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Humidity in straw bale walls and its effect on the decomposition of straw

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Preface

One day in October 2005, Martin Oehlmann was standing by the window inside his and his wife's unfinished straw bale house on the oceanfront in Brittany, France. There was a storm outside. He was observing the monstrous waves in the distance with a childlike curiosity, while the rain coming over the raging ocean was violently hitting the window panes and exterior lime plaster.

> *"Do you think the lime plaster will withstand this?"*
>
> "Well, we will see. I hope so. I think so. This is the best test. I mean all the overhangs could do anything in this sort of rain. Yes, but I'm quite confident I will put one limewash on and this will continue for few years. So this will be perfect..." Martin said.

Several weeks after this conversation, on December 1st, 2005, it stormed again, this time with even greater intensity. The storm lasted for 48 hours nonstop. Two days of rain driven by strong coastal winds caused the saturation of straw within the lime plastered western wall, so much that wet spots appeared on the inside of the building.

Will the straw have a chance to dry before it decomposes? What could have been done in order to prevent such a disaster? How to fix the damage? These questions and the answers to them summarise the purpose of this thesis.

•

This thesis explores the use of straw as a building material. In current practice, straw is compressed into bales, which are then used in the walls, either as load bearing building blocks or as superinsulation[1] used as infill in the construction frame.

A shift toward environmentally conscious building can be observed in many countries and communities, noticeably the UK, Denmark and Germany. The production of walls from local straw bales, plastered with local earth, has an incredibly low energy demand, making this building method extremely progressive. With growing environmental awareness, contemporary builders will soon be obliged to use sustainable methods during the construction of new houses. Without a doubt, straw bales represent one of the most appropriate ways of building in our endangered world. Their use not only lowers the energy demand for production of new materials, but for heating or cooling buildings as well due to their excellent thermal insulating properties.

[1]Thermal conductivity of straw measured through straw bale with density 90 kg·m^{-2} is: $\lambda = 0.6$ W·m^{-1}·K^{-1} (Andersen, 2003). Straw bale construction is compatible with superinsulation, due to the thickness of the bales (ordinarily about 360mm for straw bales laid on edge and about 460mm for straw bales laid flat.)

What are the weaknesses of straw bale construction?

The first doubts that generally come to mind in connection with straw bale walls are always related to fire and rodents. While these worries can easily be dispelled by application of good plaster onto straw (Jones, 2003), the question of the vulnerability of straw to moisture is more serious. This thesis focuses on clarifying the problem of moisture in straw bale walls. It explains the boundaries within which straw and humidity in the walls can coexist. It investigates the question of how to stay within these boundaries, so that straw bale buildings can become more innovative, more progressive and better adapted to modern climates.

In straw bale building literature, the authors usually limit the uneasy topic of moisture in straw bale walls to several rules of thumb explaining the fundamentals of moisture damage prevention. There is very little literature available that manages to provide a complex picture of moisture behaviour in straw bale walls directly connected to principles of straw decay. There is either literature explaining the decay of straw (e.g. Summers et al., 2003), or literature describing the principles of moisture behaviour in straw bale walls (e.g. Straube, 2005). Due to growing interest in this topic, there is also a number of case studies on moisture monitoring in existing straw bale buildings (e.g. Fugler, 1997).

This thesis offers a holistic approach.

- It explores the physics of moisture in walls in relation to the degradation of organic matter such as straw.
- It considers practical experience through case studies of straw bale houses.
- It compares simple design calculations for the prediction of moisture risk in building envelopes (as are often used as a guideline by contemporary civil engineers and architects) with computer simulation, developed in order to study moisture transfer in walls in great complexity.
- It looks at the relevance of using those computational methods to predict moisture performance in simple straw bale wall assemblies.
- It uses computer simulation to uncover the basic principles of moisture transfer through straw bales plastered with different materials.

The conclusions are compared to knowledge from existing situations from 27 professional straw bale builders in order to give a comprehensive guideline for future straw bale construction work.

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Chapter 1

Introduction

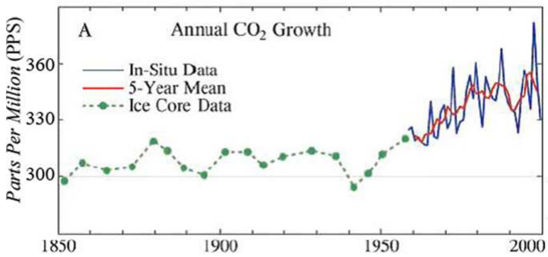
1.1 Warming

Tom and Jerry, two satellites launched into the Earth's orbit by NASA and the German aerospace agency Deutsches Zentrum für Luft und Raumfahrt (Buis, 2002), recorded the first evidence in history that the total mass balance of the Antarctic ice sheet is in significant decline. Tom and Jerry are measuring the changes in Earth's gravitational field. They had been chasing each other around the Earth, 16 times a day for four years, when in March 2006, researchers at the University of Colorado at Boulder published the results of an analysis based on the satellite's data. It proved that the rate of loss of Antarctic ice is around 36 cubic miles or 152 cubic kilometers per year[1] (Wahr, 2006).

A process called the "natural greenhouse effect" was first described by the British physicist John Tyndall in 1859. He discovered that the most common elements in the air, oxygen and nitrogen, are perfectly transparent to both visible and infrared radiation. On the other hand, air constituents like carbon dioxide, methane and water vapour are not. He declared that these imperfectly transparent gases were largely responsible for determining the Earth's climate (Kolbert, 2005):

> Energy from the sun arrives on Earth mostly in the form of visible light, which effectively heats up the Earth's surface. The greenhouse gases let the visible light pass through, but will not let the Earth's heat, in the form of infrared radiation, escape easily to outer space. The greenhouse gases absorb the Earth's heat and warm up. As they "reradiate" the heat partly to space and partly towards Earth, Earth's climate becomes livable. This complex heat exchange between Earth, its envelope, and outer space, results in a stabilized average global temperature of 13.9°C.

[1] For comparison, the city of London uses about 0.16 cubic mile or 0.68 cubic kilometer of water annually. (CLEAR, 2006)



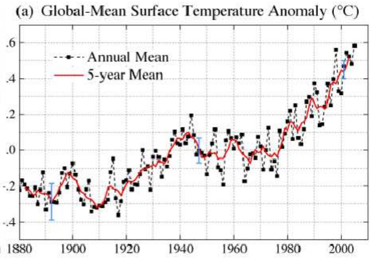


Figure 1.1: On the left — Annual growth rate of atmospheric CO2 extended back to 1850. (Hansen and Sato, 2001)

Figure 1.2: On the right — The year 2005 was the hottest year on the record. Global annual surface temperature relative to 1951-1980 are based on surface air measurements at meteorological stations and ship and satellite measurements for sea surface temperature. Error bars are estimated 2sd (standard deviation) (95% confidence). (Hansen, 2006)

As early as 1894, a little more than a century after the invention of the steam engine, the Swedish chemist Svante Arrhenius became convinced that humans were altering the earth's climate. He set up a tedious calculation. It took him a year, 14 hours a day of intensive work, to predict that it would take three thousand years of coal burning to double the carbon dioxide content in the air (Kolbert, 2005).

Since then, only 111 years later, in 2006, the CO_2 levels (at 378 *parts per million*) have increased by one third (see Fig. 1.1). An official from NASA'S Goddard Institute for Space Studies —GISS— Hansen (2006) stated that if the current trend continues, carbon dioxide levels will reach 500 *parts per million* some time in the middle of this century, making Arrhenius's prediction off by roughly 28 centuries.

500 *parts per million* of CO_2 in the atmosphere will cause a global warming of 3 degrees°C (Hansen, 2006). If this change were to take three thousand years, as suggested by Arrhenius, the many species inhabiting the Earth would probably be able to cope with it. If an increase of 3°C happens in the course of one century, Hansen (2006) warns, the Earth won't have time to adjust. The temperature shock will result in a different planet. An uncountable number of species will perish, there will be no ice in the northern seas, the ocean level will rise 90 — 880 mm and the number of refugees will number in the millions.

Unless CO_2 levels are stabilized, the point of no return will be passed within about a decade. Hansen (2006) adds: "As the movement of the giant glaciers slowly accelerates, it will attain a momentum that cannot be stopped."

1.2 Building sector

The table in Appendix B.1 shows that almost half of the world's CO_2 emissions is produced by industrialized countries (Price et al., 1999). In those countries, buildings are responsible for about 35% of total carbon dioxide emissions, the largest portion of the pie (see Fig. 1.3).

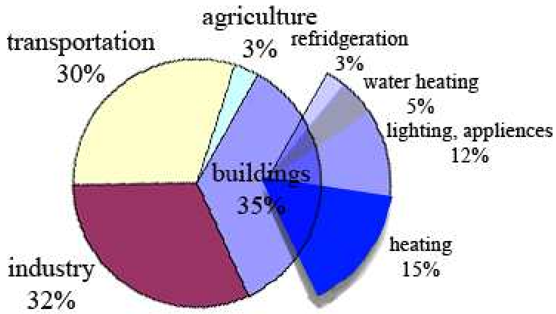


Figure 1.3: CO_2 emissions produced by industrialized countries (Price et al., 1999; eia, 2005)

The majority of carbon dioxide emitted by buildings comes from heating and cooling (eia, 2005). Fig. 1.3 shows that by changing existing building stock for highly insulated zero energy (passive) houses, a savings of about 15% of total CO_2 emissions could be achieved.

1.3 Construction materials

In 1999, the United Nations estimated that the production of new construction materials accounts for approximately 11% of global CO_2 emissions (Guy, 2004). This means that by building houses exclusively from local materials that require very little energy for their production (e.g. earth, straw and wood), another 11% of emissions could be saved. By using biomass for building, some of the current CO_2 emissions could even be stored as locked carbon in the construction.

A plant uses carbon dioxide from the air during photosynthesis while producing oxygen. Although carbon dioxide is released back into the air when a plant is destroyed (during decomposition or burning), the utilization of plant materials in construction ensures that the release of carbon dioxide is postponed for the lifetime of the construction. That is why in the short term, local natural organic materials could be CO_2 negative:

> "A net CO_2 sink is a material which contains an amount of carbon in its mass greater than the equivalent amount of CO_2 released during related raw material acquisition, transportation, manufacture and distribution" (MacMath, 2000) (see Fig. 1.4).

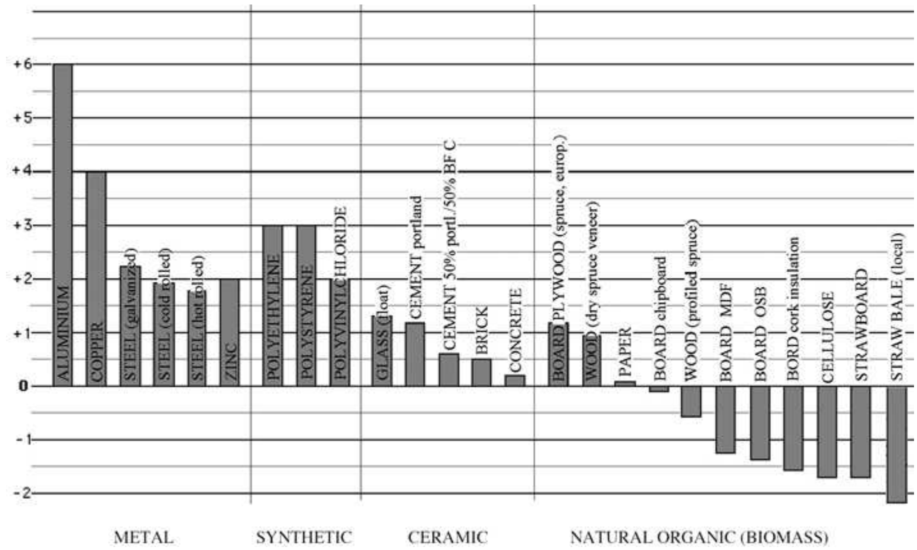


Figure 1.4: Overall CO_2 emissions by weight [kg] released by production of 1 kg of twenty-four common building materials (MacMath, 2000). The CO_2 emissions of local baled straw by weight were calculated (see below) and added to this table by author. Positive overall CO_2 emissions indicate a net CO_2 source and negative overall CO_2 emissions indicate a net CO_2 sink.

Let's calculate the approximate overall CO_2 emissions of 1kg of baled local straw[2]:

> Embodied energy of baled straw = 0.24 MJ/kg (Magwood, 2004). On average, 1 MJ of embodied energy produces 0.098 kg of CO_2 (Balderstone, 2005). This means that 1 kg of baled straw with embodied energy 0.24 MJ/kg produces $0.24 * 0.098 = 0.023$ kg of CO_2.
>
> Straw has up to 60% of carbon by weight (calculated from Appendix B, fig. B.2). Thus 1 kg of straw contains 0.6 kg of carbon. 1 kg of carbon in the presence of oxygen forms approximately 3.7 kg of CO_2 (Wilhelm, 2004). Therefore there is about $0.6 * 3.7 = 2.22$ kg of stored CO_2 in 1 kg of straw.

$$\frac{kg_{\ CO_2\ (embodied\ energy)} - kg_{\ CO_2\ (stored)}}{1\ kg_{\ baled\ straw}} = \frac{kg_{\ total\ CO_2\ emissions}}{1\ kg_{\ baled\ straw}}$$

$$0.023 - 2.22 = -\ 2.197 \text{ (see Fig. 1.4)}$$

[2]Overall CO_2 emissions will vary with different type of baling machinery, different types of straw, etc.

Above calculation means that local straw is a net CO_2 sink with 2.197 kg of CO_2 stored in 1 kg of straw. Overall CO_2 emissions of 1 kg of baled straw are - 2.197 kg.

1.4 Straw bale houses

Sections 1.2 and 1.3 summarize two great advantages of straw bale construction. Straw bale buildings are potentially CO_2 sinks. They can be made exclusively from renewable sources for the cost of a conventional house and at the same time, they can ensure insulation quality of a passive house standard without any special technology[3] (Wihan, 2005). Although insulating existing building stock with straw bales in industrialized countries seems unrealistic, as does constructing all new buildings using zero energy straw bale technology, the impact of such an act would result in a total carbon dioxide reduction of about 26%[4]. Additionally, straw is an annually renewed waste product, appearing in abundance in the most of the world and after its life span, a straw bale house biodegrades without leaving any toxic waste.

These properties put straw bales in a unique position among contemporary building materials. However, the ubiquity of straw bales can be problematic. Straw bales defy standardization, because of their variable physical properties, and therefore bales from locally harvested straw can't easily be classified as proper building material. Unless building regulations completely change their view regarding the assessment of building materials, straw bales are doomed to remain an interesting, but marginal alternative.

Building with straw bales attracts self-builders because they are easy and pleasant to work with. Nevertheless, there are great risks in unskilled handling and design. Straw bales are sensitive to moisture and vulnerable to rot. The area of moisture behavior in straw bale walls remains largely unexamined. Some research has been done and some theories are available. Along with measurements of humidity in actual walls, this thesis summarizes the existing ideas and further extends them using computer simulation to offer guidance to anyone who is interested in designing or building a faultless straw bale structure.

1.5 Thesis Overview

The second Chapter of this thesis addresses the issue of straw decay. It reviews the existing literature concerned with the decomposition of straw. At the end, the reader will become familiar with the factors affecting durability of straw in a wall, particularly with humidity (or moisture content of straw),one of the most influential factors.

[3]When using straw bales for building, heating energy consumption of the house can be reduced to close to 20 $kWh/m^2 \cdot$annum. This can be achieved without a heat exchanger and without sealing the house air tight.

[4]15% heating (see Section 1.2) + 11% material production (see Section 1.3).

The third Chapter focuses on the physical nature of humidity. It will explain the relevence of relative humidity as a physical quality determining straw decay.

The fourth Chapter further explores the connection between relative humidity and the condition of straw in a wall. It concentrates on different case studies in order to support the physical theory with practical experience.

Its first part analyzes a few selected investigations describing moisture monitoring in straw bale walls done by others.

The second part introduces two case studies monitored exclusively for the purpose of this thesis. One of them follows in a great detail the serious moisture problem in Martin and Marianne Oehlmann's straw bale house on the Atlantic oceanfront in Brittany, France, (mentioned in preface to this thesis). The other case study presents relative humidity and temperature monitoring in an earth plastered straw bale wall in Blanden, Belgium. This particular case study provides valuable data for benchmarking the mathematical models that are used in the following chapters for analysis of moisture transfer in different straw bale wall assemblies.

The fifth Chapter serves as an introduction to the complex theory behind moisture transfer in building components. It focuses on a simple mathematical model that is widely used by contemporary civil engineering practice known as Glaser's model. Glaser's mathematical model is prescribed as a norm by building standards in many industrialized countries all over the world including European countries like the UK, Germany, France, and others. It is used for the prediction of condensation inside building envelopes. At the end of this Chapter, the results of Glaser's calculation of moisture performance in straw bale walls are compared with real data measured in a real wall to reveal its lack of accuracy.

This thesis does not use Glaser's model for its final investigation of moisture behaviour in straw bale walls. There are more advanced models available that seem to be much more reliable, notably the computer model WUFI.

The sixth Chapter deals with advanced moisture transfer theory. It explains the pros and cons of the WUFI mathematical model and examines its viability as regards the simulation of moisture transfer through different straw bale wall assemblies. The comparison of the WUFI model's output with real data monitored in actual straw bale walls reveals that the WUFI model can be used for investigation of moisture transfer through basic straw bale wall assemblies with reasonable accuracy.

In the seventh Chapter, the WUFI model serves as a useful tool for a theoretical survey of moisture transfer through various simple straw bale wall assemblies. A reliable computer model is an extremely valuable tool. It enables a researcher to build a virtual straw bale house anywhere, without any great effort. It next allows the house to perform for couple of years (within a time frame of several minutes), and then the researcher can open the virtual walls and scrutinize them for any traces of moisture damage. This thesis examines, in this way, the impact of extremely cold and humid weather on a virtual straw bale house in Alaska and compares it to the influence of an extremely hot and humid climate on a fictional straw bale house in Indonesia. The results of the simulation will tell how well straw bale walls covered by various plasters perform in such diverse climates.

The end of this Chapter reveals a surprising fact concerning the saturated straw bale wall in Plozevet. The computer simulation will help to uncover its presumable drying time.

Finally, the eighth Chapter is reserved for expert opinion. A questionnaire was sent out to professional straw bale builders in order to examine the different straw bale moisture issues that they have encountered during their careers. 27 straw bale building professionals answered 22 questions which were then statistically processed and analyzed. The Chapter's summary winds up the investigations of this thesis with these well-founded opinions based on experience.

Chapter Nine summarizes the conclusions drawn from this research.

The Appendix provides some interesting material that didn't fit into the framework of this thesis. It includes, for example, an interview with the foremost British straw bale builder Barbara Jones, the author of Building with Straw Bales, A Practical Guide for the UK and Ireland and an interview with Tom Rijven, who is recognized as one of the world's leading specialists on earth plastered straw bale walls. It also includes various illustrations, tables with different material characteristics, detailed calculations, encouraging letters, submitted questionnaires and others.

Chapter 2

Decomposition of straw in a wall

A great number of inorganic elements — nutrients — (e.g. oxygen, hydrogen, carbon, nitrogen) pass through straw during its lifetime in the form of solvents. When straw grows, some of these elements become molecules, creating new organic substances in the new plant (EELS, 2005; Fogel, 2001). Decomposition reverses this process. After the harvest, straw contains a reservoir of organic elements. The breakdown of massive organic molecules into simple inorganic nutrients takes its course during the chemical process of decomposition initiated by specific *enzymes* released by *bacteria* and *fungi*, or simply — microorganisms or microbes (see Fig. 2.1).

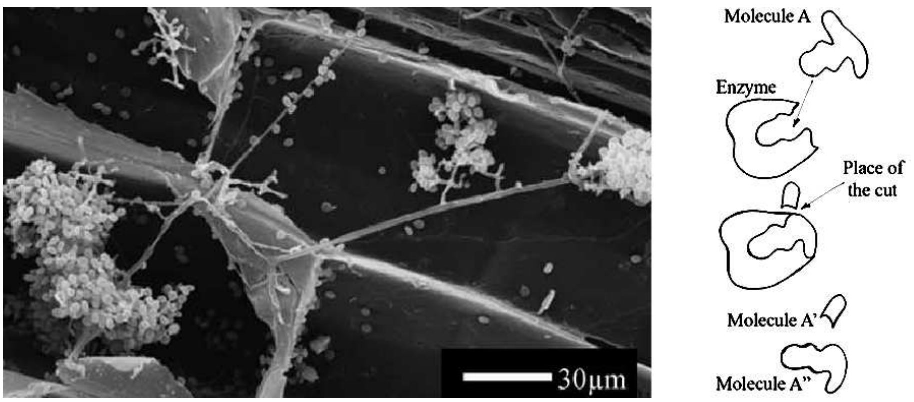


Figure 2.1: **On the left** — An image scanned by an electron microscope shows *fungal spores* and *fungal hyphae* that are beginning to be visible in the internal structure of the basal part of wheat straw after 1 week in a compost pile. (Dresboll, Magid, 2004) *Fungi* releases *enzymes*, that cause the straw tissue's *decomposition*. **On the right** — Schema of enzymatic function during *decomposition*. (Mustin, 1987)

2.1 Microorganisms in straw bales

Bacteria[1] and *fungi*[1] are ubiquitous. *Bacterial* and *fungal spores*, and *bacteria* itself, are single cell organisms, which are spread through the air or by animals. Most of them are deposited within a 100m radius and only a few travel long distances (Hawksworth, 1995).

The microbiological population living on a particular piece of land differs every year and varies from place to place (Arnolds, 1992). In general, the deciding factor for the amount of microorganisms in a particular place is the amount of available food - nutrients (Kudo, 1971).

According to research by Arnolds (1992), the diversity and density of microorganisms found in intensively cultivated, small scale fields is low in comparison to the microbial population of wild forests, natural meadows, etc... In addition to the lack of varied food (nutrient diversity), microorganisms on arable lands suffer the periodic breakdown of *fungal mycelia* that happens every year during harvest. Annual harvesting is apparently destructive for most *macrofungi* species, which are especially important for the complete structural decomposition of straw (see the Section 2.2.2). On the other hand, nitrogen-rich field fertilization might give good competitive habitat to *microfungi* and *bacteria* (Arnolds, 1992).

The microbial population that thrives on seeds, stalks and leaves at the time of harvest is of special interest to the builder, because these microorganisms will inevitably be baled with the straw (Summers et al., 2004) and transported all the way into the wall.

GrAT — The Center for Appropriate Technology at the Vienna University of Technology — is carrying out the first long term research of the occurrence of different microbial species and their quantities inside straw bale walls (Wimmer et al., 2004). Similar research over a period of two years is in progress in Germany. The German Straw Bale Association — FASBA — together with the Fraunhofer Institut für Bauphysik are searching for evidence to support general approval for straw bales as insulation (see appendix K.3). However, the results of their research aren't available yet.

From a microbiological point of view, the plant's surface – *phyllosphere* – is an extremely hostile environment with rapidly fluctuating temperature and relative humidity (Yang et al., 2001). Microorganisms are often directly exposed to strong UV radiation and they also suffer from the repeated alternation between the absence and presence of free moisture due to rain and dew (Lindow and Brandl, 2003). The *phyllosphere* itself provides limited nutrient resources. However, despite these stressful conditions, the above-ground parts of plants are usually colonized by a variety of bacteria, yeasts, and fungi. More than 85 different species of microorganisms were found on the surface of rye and wheat

[1]MEANING OF THE *EMPHASIZED* WORD IS EXPLAINED IN CHAPTER 10 — TERMINOLOGY NEEDING EXPLANATION.

by a number of studies mentioned in Yang, et al. (2001). Lindow and Brandl (2003) refer to a common occurrence of up to 10^5 bacterial cells per 1 mm^2 of plant leaf surface (equal to 10^8 cells per gram of leaf material).

Apparently bacteria make up by far the most abundant population of the *phyllosphere*. Filamentous fungi, on the other hand, are considered to be transient inhabitants, existing on living plant surfaces mainly in the form of *spores* (Lindow and Brandl, 2003). While the major microbial population is periodically washed away by rain, or killed by UV light and agents like *fungicides*, the rest seems to somehow tolerate the severe living conditions (Yang et al., 2001). Bacteria often create large aggregates on plant bodies (Lindow, 2005), which help them to establish their own temperate "nanoclimate" (see Fig. 2.2).

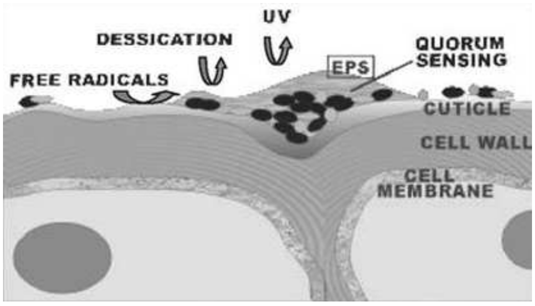


Figure 2.2: Hypothetical bacterial-habitat modification in the *phyllosphere* via the production of extracellular polysaccharide (EPS) in bacterial aggregates. The heavy EPS slime may prevent bacteria from dehydration. (Lindow and Brandl, 2003).

Plants have a natural ability to resist microorganisms during their lifespan, therefore healthy crops will barely suffer from the presence of a microbial population on their surface (Wieland, 2004). The *phyllosphere* microbial activity starts mainly with the death of a plant – in the case of straw, the harvest.

Fig. 2.3 on the left - shows the development of a microbial population on barley straw that was left to decompose in a field after harvest in New Zealand. Significant growth was recorded in the first month of monitoring, while for the following 11 months of the experiment the growth of microorganisms exhibits a steady state. According to weather data, during winter the straw received 3 times more rain than in the summer. However the fig.2.3 on the right - reveals a constant rate of decomposition unaffected by amount of active microbes.

Lynch (2000) writes that 95% of bacteria found in nature are in a *viable but nonculturable state*. Until recently scientists thought that these bacteria were dead. Instead they are in a state similar to hibernation (Oliver, 2005). Almost any bacteria can enter this state when it encounters unfavourable conditions. Oliver (2005) observed a variety of bacteria (Pseudomonas fluorescens) in soil that remained in this state for over a year.

His research indicates that if straw bale walls are kept dry, most of the

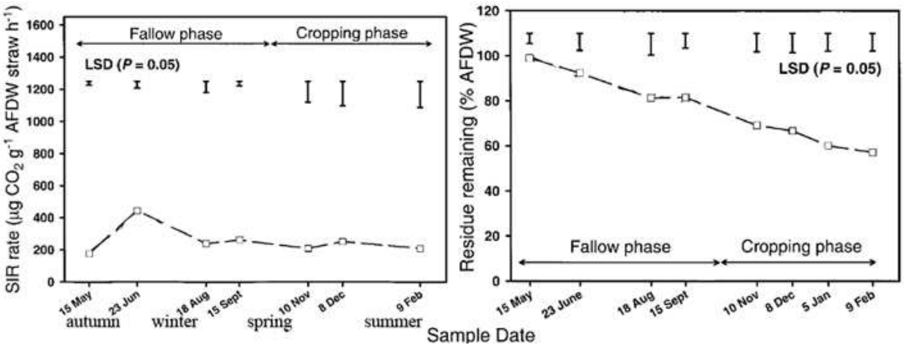


Figure 2.3: **On the left** — Substrate-induced respiration (SIR) rates from barley straw left to decay in a field for 320 days. Respiration measures the size of the potentially active microbial biomass. **On the right** — The percentage of initial barley straw remaining after 320 days of decay. Data expressed in ash-free dry weight (AFDW) basis. (Beare et al., 2002).

bacterial population could stay alive (but not active) for about a year, but probably not much longer. However, some bacterial and fungal *spores* could survive in a stable environment for years.

Most bacterial species multiply by dividing (Singleton, Sainsbury, 2001). Only a few are able to form *spores*. Conversely, fungi use *spores* for reproduction almost exclusively. There are many different kinds of *spores* and a single fungi can form more than one type during its development (Doyle, 1973).

Hawksworth (1995) writes that the *spores* of some fungal species could be dormant for up to 50 years. The *spore* activation generally requires moisture, the right temperature, oxygen and a sufficient amount of specific nutrients (Summers et al., 2004). All of those conditions must be present at once. *Spores germinate* and microorganisms grow and multiply only if this specific environment is sustained for a certain period of time (Sedlbauer et al., 2001). The environmental conditions that influence the decomposition of straw are looked at in more detail in Section 2.3

2.2 Straw physiology

At Ohio University, Rohrer and Heimlich (1998) documented a simple test. They buried wood shavings, sawdust, shredded newsprint and straw under 200mm of soil and let it decompose in the Ohio weather. After four months, the sawdust and wood shavings had disappeared almost entirely in the black soil. Shredded newsprint and straw were more closely paired in slower decomposition, although newsprint decomposed more quickly. Straw was clearly most persistent in keeping color and its strength. It was still yellow after four months in the soil.

While the relatively high decomposition resistance of straw favors straw bale building, it bothers farmers. A considerable number of scientific reports documenting tests of straw degradation is widely available. Agronomists are struggling to find the fastest and most effective way of straw composting (Beare et al., 2002). To use composted straw as a fertilizer is often seen as the easiest way of getting rid of problematic agricultural waste.

Decomposition of straw in straw bale walls has not been the subject of much research. Nonetheless, comparisons between degradation in walls and decomposition in soil can be made, as long as the major differences are taken into account (Dresboll and Magid, 2005):

- The main difference is the presence of moisture. The straw in soil or compost is usually exposed to much more water than straw in a wall.
- The relatively dry and dark environment in a wall will eliminate most of the bacteria, algae, and yeasts, because bacteria needs a high level of moisture to grow (Padfield, 2002), while algae and yeasts need, in addition to a high level of moisture, light.
- Another important difference is in microbial diversity. In general, there is a larger microbial population in soil than on the surface of the straw in a wall, where fungi will most likely be the main cause of decomposition (Beare, 2002; Padfield, 2003).
- There are also differences in nutrient values. The amount of nutrients in the soil by far exceeds the overall nutrient value in a straw bale wall, where the only source of nutrients is the low nutrient straw itself. (see Section 2.2.4).

The Rohrer and Heimlich experiment (1998) shows that straw decays at a slower rate than woodchips, woodshavings and newsprint. Another study carried out by Dresboll and Magid (2005) proved that wheat straw decomposes in the same compost pile faster than hemp and miscanthus grass. In order to find out why some types of organic matter decompose faster than others, it is useful to look at the plants under a microscope.

2.2.1 Cellular composition

All plants have a more or less similar cellular composition. The contents of the cells are vulnerable to decomposition and that is why they are naturally protected by the cell wall. During its growth, the plant cell forms a flexible *primary cell wall*, which consists of randomly arranged micro fibers of cellulose in a matrix of hemicellulose, pectins and proteins.

Once the cell stops growing, the cell wall develops structural strength in a sophisticated, multi layered system with increased resistance against enzymatic attack (Hopkins, 1999) (see Fig. 2.4). The chemical changes, which are still not completely understood (Bidlack at al., 1992; Richard, 1996) lead to the biosynthesis of lignin, an organic chemical compound that penetrates the cell wall all the way through. Micro fibers of cellulose become embedded in lignin, much as steel rods are embedded in concrete to form highly resistant and structurally impeccable "prestressed" skin (see appendix C.1). When lignification is completed, the cell dies. (Ribeiro, 2000)

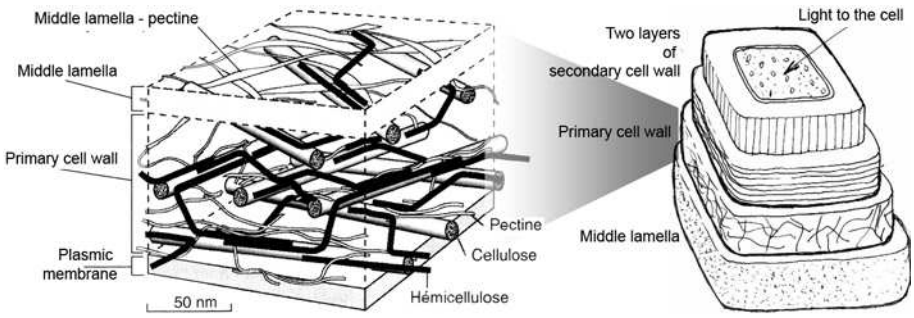


Figure 2.4: As a step into maturity, the plant cell changes its protection from a primary cell wall **(on the left)** to a fortified conglomerate of primary and secondary cell walls **(on the right)** Note the difference in cellulose micro fiber orientation in the primary and secondary cell walls. (Hopkins, 1999).

The simple structure of cellulose, with its repeated identical bonds (see appendix C.1), makes it more vulnerable to decomposition, unlike the other parts of the cell wall. Hemicellulose and particularly lignin are more difficult to break down (Richard, 1996).

2.2.2 Lignin

Lignin is composed of complex molecular links with various bonds (see appendix C.1). Its presence in a plant cell considerably reduces the rate of decomposition of the other cell wall constituents. Nonetheless, some microorganisms have developed the necessary enzymes to break lignin down (Richard, 1996; Arnolds, 1992; Kirby, 2006).

Lignin content varies between plant types, species (see appendix B.2), and different parts of the plant. The different spatial arrangement of lignified tissue even affects the biodegradability of individual cells (Dresboll and Magid, 2005). However, to make assumptions about a material decomposition rate based purely on lignin content (see appendix B.2) could be misleading.

Straw, woodshavings and newsprint

According to the table in appendix B.2, wood has a higher lignin content than straw or newsprint. Yet the wood shavings and wood chips in the Rohrer and

Heimlich (1998) experiment showed the fastest decomposition. The reason for this could be the better accessibility of the broken wooden particles to microorganisms and thus better availability of nutrients. Dresboll and Magid (2005) proved that broken tissue enhances further degradation and reduces the stability of the material. Furthermore, intact straw, with its large pores, facilitates fast drainage of moisture into the soil, while small wood shavings and wood chips tend to retain water creating a wet environment ideal for microorganism growth.

Hemp and miscanthus grass

The Dresboll and Magid study (2005) demonstrates that despite a lower level of lignification, the hemp sample showed the same rate of decomposition as miscanthus grass. Detailed pictures from an electron microscope verified that microbial penetration of hemp cells was impeded by the anatomical architecture of the thick-walled lignified hemp tissue. Dresbol and Magid concluded that decomposition is primarily limited by the anatomical structure of the plant and not by lignification itself (see Fig. 2.5).

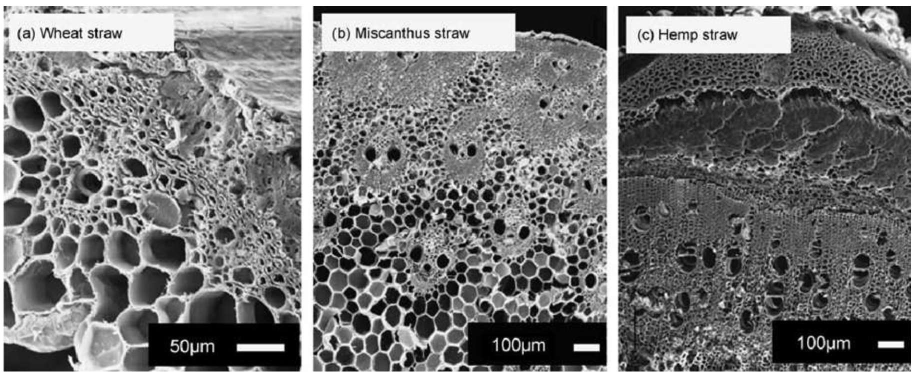


Figure 2.5: An image scanned by an electron microscope shows a cross section of the tissue of (a) wheat straw, (b) miscanthus straw and (c) hemp straw. The dense cellular composition of hemp and its higher lignification level makes it decompose at a slower rate in comparison to wheat straw. In wheat straw, the ground tissue (living cells) decrease in size towards the exterior of the stem, while the thickness of the cell wall increases. (Dresboll and Magid, 2005).

2.2.3 Silica

Silica is silicon dioxide (SiO_2) and it is the single largest constituent of ash[2] in plant material (Samson et al., 2000).

Although there is little direct experimental evidence to support this, it is believed that the high silica content in straw adds to its resistance to decomposition (Smith, 2006; Glassford, 2004; Massey et al., 2006). According to

[2] All the plant compounds that are not considered organic or water. (Wikipedia, 2006)

International Rice Research Institute (2004), rice straw does not decompose as readily as other straw, such as wheat or barley, due to much higher silica content (see Appendix B.2).

The majority of silica enters the cereal plant through the intake of monosilicic acid in water, and is deposited within a plant mainly in its leaves. Varying silica contents between straw species is often related to the photosynthetic mechanism, and to the amount of water being transpired by the plant. Decreased water usage reduces the intake of monosilicic acid, resulting in lower silica levels in a plant. Within species, the water use efficiency will fluctuate depending on the region in which the crops are grown, and on the soil type (Samson et al., 2000).

In their paper, Samson et al. (2000) mention that silica levels in plant material are highly influenced by soil type. Clay soils have higher monosilicic acid content than sandy soils, and therefore produce plants with higher silica levels.

Professional straw bale builder Tom Rijven observed that organic straw has a higher resistance to water than its nonorganic counterparts. According to Rijven, the reason is that the silica film on the surface of the stems and leaves acts as a natural water repellent (see Appendix A.2). Nevertheless, Rijven observed that when left in the sun for a while, organic straw looses its water repelling capacity. This indicates that the protective film might be based on natural waxes rather than silica. However, the natural water resistance of straw as well as question of to what extent the silica content of straw is related to its decomposition should be the objective of future studies.

2.2.4 Nutrients

Straw, like any other organic matter, contains enough nutrients to support microbial life. It provides microorganisms with carbon, hydrogen, nitrogen and other nutrients they need (Brandon et al., 1995).

Nitrogen

Nitrogen seems to be the nutrient preferred by many micoorganisms.

Nitrogen is an essential constituent of the amino acids that make proteins in organic cells. It is also a critical part of chlorophyll and is indispensable in enzymes, hormones, vitamins as well as nucleic acids DNA and RNA (Kummer, 2004).

Animals and humans get their nitrogen from plants and microorganisms, which have the ability to convert simple forms of mineral nitrogen into organic nitrogen compounds. Plants and most microorganisms take the nitrogen that they require for growth from dead organic tissue (Kummer, 2004).

Straw has a relatively low nitrogen content (see Appendix B.2). Dresboll and Magid (2005) observed that the microbes decomposing straw in a compost pile took the nitrogen necessary for progressive decomposition of straw from the surrounding nitrogen-rich clover-grass tissue. Microorganisms in straw bales grow more slowly and sustain smaller populations in comparison to microorganisms in clover-grass compost (Summers et al., 2003).

Other nutrients

Other nutrients like carbon, phosphorus, magnesium, e.g. don't typically limit straw decomposition (Summers et al., 2003).

Tissue

Different tissues contain different concentrations of nutrients, thus the quantity of nutrients varies within a single plant (Orskov, 2002).

Yang et al. (2001, p.79) write that the quality of tissue, tissue age, tissue physiological status, and the presence of tissue damage affects the composition and quantity of nutrients.

There are many different tissues in a single plant. Photosynthetic tissue, for example, is one of the most nutrient-rich tissues (Dresboll and Magid, 2005). The greener the straw, the more susceptible to decomposition (Summers et al. 2003).

Nodes contain a special tissue that is capable of developing into new plant parts. Because this tissue is more vulnerable to decomposition, nodes have a higher rate of degradation than stems (Orskov, 2002).

In cereals like wheat, oats, rye and barley, the leaves have up to twice as many nutrients as the stems. Rice, on the other hand, has stems that have a slightly higher nutritive value compared to leaves. It is clear that the amount of leaves and nodes in the straw during harvesting influences the rate of straw decomposition (Orskov, 2002) (see the Table 2.1).

Fraction	Percentage of fraction in			
	Rice	Wheat	Oats	Barley
Leaf + sheath	65.6	33.9	31.0	45.1
Internodes	20.2	46.5	56.9	44.6
Chaff	6.2	13.8	4.6	4.5
Nodes	8.0	5.7	7.3	5.7

Table 2.1: Average morphological fractions of various cereal straws. From Orskov (2002).

In order to increase stem content and reduce the leaf content of grasses, overwintering is used in the pulp and paper industries (Samson et al., 2000). Perhaps in the future, when the market for straw bale housing becomes substantial, similar strategies will be developed for the production of ideal building straw.

Water soluble nutrients in soil

Orskov (2002) wondered why the same cereal species shows up to a 30% difference in degradability from year to year until he compared degradability rates to the content of water soluble nutrients in the soil. If the amount of soluble nutrients in a particular year was higher, the straw was more easily degradable. This has a further implication in fertilization.

Fertilization

In their study, Kaboneka et al. (2002) show that fertilizer (depending on type) increases the decomposition rate of straw by up to 150% (see appendix B.3 and B.4). There is also evidence that stems benefit much more from chemical treatment than leaves (Orskov, 2002), which means that with increasing fertilization, the difference in degradability between stems and leaves of cereals (except rice — see above) decreases.

Organic straw decomposition

According to Kaboneka et al. (2002), untreated straw has the lowest rate of decomposition. Though organic straw might have more microorganisms on its surface due to lack of *fungicides*, it is apparently less attractive food.

The greater silica/wax build up on the surface of organic straw (see Section 2.2.3) and its effect on water repulsion needs to be studied further.

2.3 Environment in straw bale walls

Once the straw is in the wall, the overall building structure should provide an environment which will prevent decay. This Section reviews studies describing the interactions of microorganisms on straw with their environment. A good understanding of the physical and chemical criteria responsible for straw decay will give the builder an idea of how to make the life of microorganisms inside of straw bale walls as difficult as possible.

2.3.1 Fungicides

Straw in a wall can contain two types of *fungicides*:

- One is usually sprayed over the field to protect the straw against disease. This *fungicide* inhabits the straw surface as well as the straw structure due to cellular absorption (ITCF, 2002). The International Programme on Chemical Safety (1987) mentions a Swedish study which shows that the decomposition of straw in the field was not affected in clay soils by annual applications of up to 2 kg/ha of *fungicide*. More than 2kg/ha resulted in slightly inhibited initial stages of decomposition. Two other studies described by Liebich (1997) and Mustin (1987) proved that unless the *fungicide* was applied on straw earlier than three weeks before test, its effect was substantially degraded by straw metabolism and weather.

- The other type of *fungicide* is largely ignored not only by researchers but also by most builders. It is a *fungicide* that is applied in order to protect the straw inside a wall against vermin and decomposition. There are probably many examples of such preventive care around the world, but only few are known to the author. Platts (1997) in his study mentions straw bales powdered with lime in one building, the bales in Samuel Courge's straw bale house in the French Jura were treated with powdered lime as well.

  The effect of a *fungicide* application to a straw in a wall on the overall durability of construction is unknown. One might theorize that *fungicide* could have a powerful influence on the growth of microorganisms in a wall.

Hoflich (1977) writes that *fungicides* are most effective in eliminating fungi, in comparison to bacteria and yeast, and that it is actually fungi which are primarily responsible for the decomposition of straw.

> "An inhibition of the decomposition of straw by an application of *fungicides* is possible." he writes,
>
> "In order to stop the decomposition of straw completely it is necessary to inhibit both the physiologically active bacteria and the fungi for a longer period of time. Combinations of bactericides and *fungicides* can bring about synergistic decomposition retarding effects." (Hoflich, 1977)

Straw in the commercially produced boards "STRAMIT" (compressed straw panels) is routinely treated with a borax based substance (Bares, 2003), as is cellulose insulation. Timber shows a remarkably better resistance to harmful fungi when treated with number of available chemicals (Viitanen, 2000). *Fungicides* have become an unremarkable part of the contemporary building industry.

One of the reasons why *fungicides* aren't commonly used in straw bale construction is often their chemical origin. The use of natural material like straw leads to a higher environmental sensibility. Once people choose straw bales for the construction of their home, it is quite easy to employ other natural materials (like timber, earth, etc.) in the creation of non-toxic indoor environments. In the eyes of the occupants of straw bale houses, *fungicide* could be a poison which could spoil the "healthy home" objective. Nevertheless *fungicides* like borax, boron, and lime are of natural origin[3]. Further research is necessary to properly evaluate the potential of such easy and cheap solutions which could lead to an overall improvement in straw bale house durability.

[3]During his pilot study, Platts (1997) observed that powdered lime applied to straw bales rapidly reduces their bond with lime plaster.

Another reason why the use of *fungicides* is overlooked could be the belief that good design, well executed details, faultless plaster (or wall cover) and regular maintenance are sufficient to keep the straw bales in perfect condition indefinitely.

2.3.2 Oxygen

Straw decays most readily in the presence of oxygen. At the right temperature and moisture levels the *aerobic decomposition* process may be quite rapid (Brandon et al., 1995).

Inside a straw bale wall this is clearly not the case. Summers et al. (2003) suggest that the available oxygen within the straw bale wall will be quickly used up and replaced with carbon dioxide during active microorganism respiration (see Fig. 2.6).

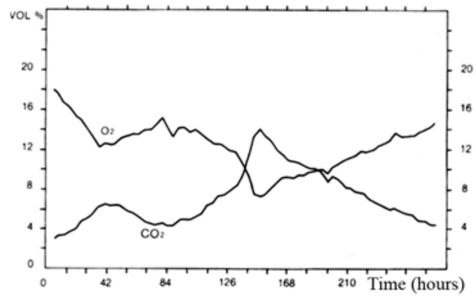


Figure 2.6: Development of oxygen and CO_2 concentrations of the air, in an enclosure with decomposing tree bark. Most fungi and bacteria require oxygen, producing carbon dioxide while utilizing the food and energy source contained in dead organic matter (Summers et al. 203). Data from CAPPAERT et al. (1987)

According to Summers et al. (2003) and Fig. 2.6 it appears that the *aerobic decomposition* in a more or less sealed environment inside a straw bale wall could to some extent gradually lead to *anaerobic degradation.*

Anaerobic degradation

In the absence of oxygen, that is, *anaerobic* conditions, straw degrades more slowly. The microbial population is probably wholly bacterial and is possibly restricted to a few types operating within a narrow tolerance range (Acharya, 1935; Brandon et al., 1995).

While *aerobic decomposition* leads to the production of organic matter, minerals and CO_2, *anaerobic degradation* results principally in the formation of acetic acids and production of the methane (Brandon et al., 1995; Acharya, 1935).

Unlike *aerobic decomposition*, *anaerobic degradation* is not as nitrogen dependent and is much more moisture demanding (see Fig. 2.7). Successful *anaer-*

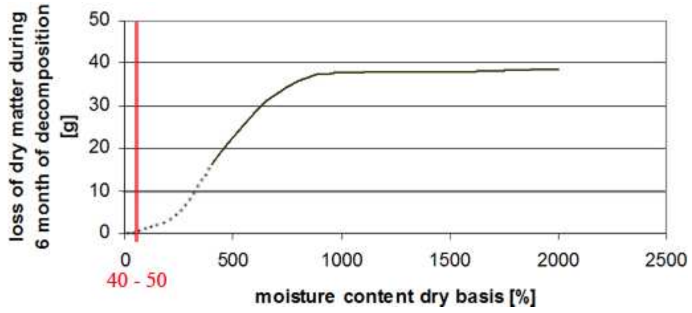


Figure 2.7: Rate of anaerobic degradation versus moisture content of rice straw (Acharya, 1935). *Dry-weight basis moisture content* of 40-50% is necessary for the initiation of *aerobic decomposition* in a straw bale wall (see Section 2.3.3). If the process becomes anaerobic at the same moisture level, the decomposition rate over 6 months will be negligible. (The dotted line projection was estimated by author.)

obic decomposition needs more than twice as much moisture than equally successful *aerobic decomposition* (Acharya, 1935; 1934).

Plaster

As with moisture, the availability of oxygen is limited by the plaster. Different plasters are differently air permeable and have diverse responses to environmental changes. For example, earth based plasters have a natural capacity to swell air-tight with increasing moisture content (Houben and Guillaud, 1994). This could slow the decomposition rate.

Different plasters also have a different impact on microbes feeding on the straw inside a wall. The water vapour condensing on straw in a wall could be enriched by liquid lime chloride filtering through from the lime plaster — a natural *fungicide*.

The influence of various types of plaster on the decomposition of straw in a wall is a subject that merits further study. The extent to which the decomposition in a straw bale wall becomes *anaerobic* is unknown. Further research could alter straw bale building technology and help to create standards in straw bale building.

2.3.3 Moisture, temperature and exposure time

The level and duration of moisture and temperature are the most critical factors for the growth of microorganisms on dead organic matter (Sedlbauer et al., 2001; Summers et al. 2003; Nielsen, 2002 ; Vitaanen 2002).

> "The amount of nutrients and (except as discussed above) the availability of oxygen are not parameters that will change once a straw bale has been placed inside a wall." (Summers et al., 2003)

Moisture and temperature in a wall, however, change in time according to external environment (weather) and interior conditions.

Time

It takes time for a previously dry *spore* to *germinate*. It takes even longer for an older *spore*. After a material is saturated with water, it takes 4 - 10 days before it is wholly covered with fungi (Nielsen, 2002). When the saturation is sustained, the growth becomes rapid. When the moisture level decreases slightly, the growth rate slows down significantly (Summers et al., 2003). And if the moisture levels after this point drop significantly, it will discomfort, but not kill the microorganisms (Padfield, 2002).

In reality, conditions fluctuate. The exterior face of an unshaded southern wall experiences the most extreme fluctuations, where wetting and drying supported by rapid changes of temperature vary greatly within the course of one day. The effect of variative moisture concentration on the growth of fungi was observed by Adan. The summary of his research by Nielsen (2002) reveals that high moisture levels alternating with low to medium moisture levels resulted in fairly constant growth. The dramatic increase of fungal growth was recorded only when these changes took place within a range of high moisture levels.

Temperature

At about 0°C, the freezing point of water, microbial life dies out.

Most of the fungi and bacteria that can be found inside a straw bale wall consider a temperature between 20 - 45°C optimal for their growth (Summers et al., 2003). This optimal temperature range differs with each microbial species and is closely related to moisture levels (Arango, 1981).

Moisture

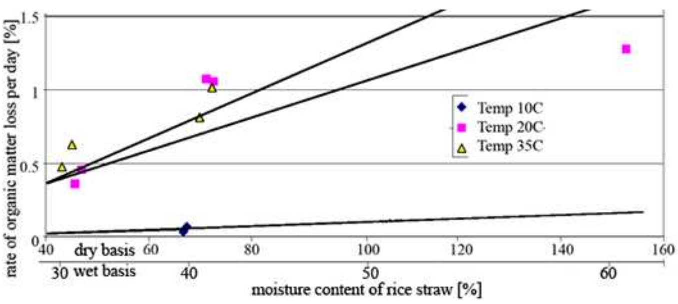


Figure 2.8: The rate of organic matter loss during *aerobic* decomposition in samples of rice straw at varying moisture contents **above** the fiber saturation point of 28% *wet basis* (39% *dry basis*). Data from Summers, Blunk et al. (2002). Note how the decomposition rate increases with increasing temperature in the same moisture conditions.

As explained above, once the decomposition in a wall is initiated, the process starts as *aerobic*. Summers et al. (2003) focused on the *aerobic decomposition* of rice straw in order to find the amount of moisture that initiates the decomposition of straw in a wall (see figs. 2.8, 2.9).

The charts illustrate that rice straw with *wet-weight basis moisture content* above 28% (*dry-weight basis* above 39% — meaning of moisture content is described later in Section 3.5) supports significant microbial growth, while rice straw with *wet-weight basis moisture content* below 28% (*dry-weight basis* below 39%) decomposes at a rate over 50 to 200 times lower (see fig. 2.9).

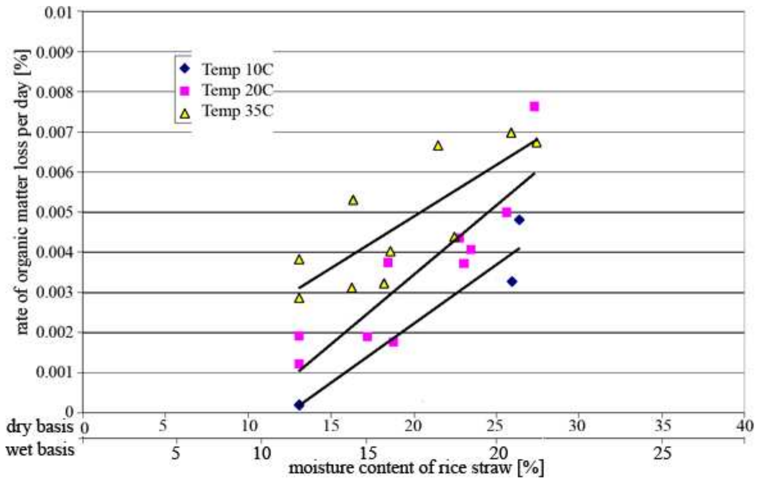


Figure 2.9: The rate of organic matter loss during *aerobic* decomposition in samples of rice straw at varying moisture contents **below** the fiber saturation point of 28% *wet basis* (39% *dry basis*). This rate is 50 to 200 times lower than the rate of decomposition described in fig. 2.8. Data from Summers, Blunk et al. (2002).

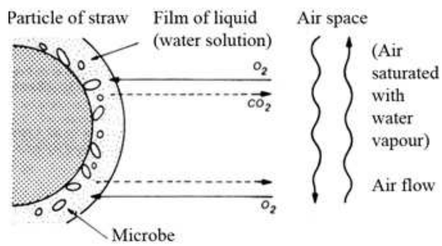


Figure 2.10: Ideal environment for *aerobic decomposition*. During extensive decomposition, the space in the cavities of the straw material is filled by air saturated with water vapor. (see Section 3.7), (Mustin, 1987)

Wet-weight basis moisture content of 28% (*dry-weight basis* of 39%) is a benchmark for the start of progressive decomposition. At this point the straw fibre is saturated with water. It corresponds to about 98% of *relative humidity* in the air surrounding the straw (see the next Chapter) and creates ideal conditions for microbial life (see Fig. 2.10).

2.4 Summary of Chapter 2

Once the conditions for microbial growth are sustained for enough time, the straw will eventually decompose completely.

> "There is always a multiplicity of decomposer fungi, which break down the organic substrates jointly." (Gams, 1992, p.198)

The above statement suggests that the microflora that cause the decomposition of straw is little affected by various agricultural practices, including the use of pesticides (Gams, 1992).

However, research suggests that fertilization increases the vulnerability of straw to decomposition; that the presence of weeds or green straw in straw bales will support a faster rate of decay; that straw bales with a high content of unbroken stems are more durable than bales with a lot of broken straw. The susceptibility of broken tissue to decomposition suggests that a wall with straw bales laid flat (with broken straw facing the plaster), will be less durable that the wall with the straw bales on edge, where the plaster (as a source of moisture) adheres to unbroken stems.

Every extra hour that the straw is left exposed to moisture in the field after the harvest can increase the risk of potential degradation.

Fungicides applied to cereals during their growth have practically no effect on the durability of straw in a wall. The influence of *fungicides* used on straw during the construction process on microorganism growth has not been the subject of available research.

The effect of plaster and related air permeability on straw bale wall degradation is unknown.

The decay of straw is negligible below 5°C and reaches an optimum at around 30°C.

28% of *wet-weight basis moisture content* (39% *dry-weight basis*) is significant for straw decomposition because at around this point the straw fibre is saturated with water and microorganisms thrive on the straw surface, causing progressive decomposition.

The summary of factors affecting durability of straw can be found in table 2.2.

straw material	**straw handling and treatments**	**owner occupancy**
• straw species • genetic factors - leaf/stem ratio - amount of nods - nitrogen concentration	**before baling** • fertilization • time of harvest (straw maturity) • time and conditions of field drying • way of baling (integrity of straw stems) **after baling** • transport • storage **during construction** • planning and performing (attention to important construction details) • way of stacking straw bales (laid flat or on edge) • fungicide application • choice of straw bale wall cover • wall surface treatments **once in a wall** • humidity (straw moisture content) • temperature • time of humidity and temperature exposure	• maintenance • inhabitant behaviour

Table 2.2: Factors affecting the durability of straw

The next Chapter shows how a *wet-weight basis moisture content* of 28% (*dry-weight basis* of 39%) corresponds to about 98% of *relative humidity* in the air that surrounds the straw fibre. It goes on to explain the extent to which the measuring of *relative humidity* in straw bale walls is appropriate to determine microbial activity.

Chapter 3

Relative humidity as a critical factor determining the condition of straw

Having considered the causes of straw rot as being largely influenced by the moisture content of straw, it is now necessary to introduce the indicator of moisture level inside the straw bale wall.

This Chapter explains why *relative humidity* is the best indicator of the moisture content of straw and points out its limitations on determining microorganism growth. It begins with an outline of basic physics, followed by a detailed description of the interaction between water molecules and materials, and finally, between water molecules and microorganisms.

3.1 Kinetic (thermal) and electrical energy

All matter consists of small particles called atoms. Atoms vibrate above the temperature of absolute zero. The higher the temperature of a body, the faster its atoms move. The kinetic energy of those vibrations is called thermal energy (Boyle 2004).

Besides kinetic energy, atoms are also affected by electrical energy. In each atom, a cloud of electrons constantly moves around the electrically charged central nuclei. They are held in the vicinity of the nuclei by an opposing electrical charge. However, positive and negative electrical forces in one atom are usually not balanced. The atoms with unbalanced consequential electrical charges are strong magnets. They can be attracted to other unbalanced atoms with opposing consequential electrical charges to form a molecule (Boyle, 2004).

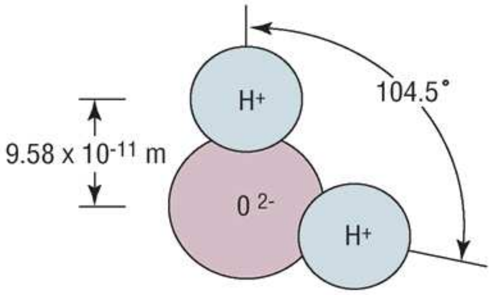


Figure 3.1: Molecule of water (Straube, 2002)

3.2 Water molecule

In a water molecule, opposing electrical charges bond one oxygen and two hydrogen atoms strongly together (see Fig. 3.1). The overall charge of the whole molecule isn't balanced either, which means that H_2O is a polar molecule and in interaction with other materials, the molecule reacts as a magnet itself. (Straube, 2002)

Some materials, called *hydrophilic*[1], contain particles with an electrical charge that attracts H_2O. When close to this type of material, water molecules in the form of vapour will cling to it. This process is called *adsorption*[1].

Water molecules are attracted to the surface of a hydrophilic body if the temperature is low, in a process called wetting. When the temperature rises, atoms become more active. As the kinetic energy of atomic vibrations gains power, water vapour molecules are pushed away from the attractive electromagnetic force of hydrophilic body. They rise and float in the air. This means the material is drying.

3.3 Water vapour pressure

If the drying material happens to be enclosed in a sealed box, more and more water vapour molecules will build up in the air trapped inside. As the water vapour concentration in the air increases, more of the water vapour molecules will collide back with the material's surface. Some of them will stick. At a fixed temperature the system will reach a state of "dynamic equilibrium," where the amount of molecules escaping from the surface equals the amount of molecules colliding back. At this point, water vapour molecules exert pressure on the walls

[1]MEANING OF THE *EMPHASIZED* WORD IS EXPLAINED IN CHAPTER 10 — TERMINOLOGY NEEDING EXPLANATION.

of the box. This is called *water vapour pressure* and is directly related to the moisture concentration on the surface of the materials (Salzman, 2000).

Water vapour pressure is traditionally used by engineers to determine moisture concentration in the air (Padfield, 1998). The higher the water vapour pressure, the higher the water vapour concentration in the air.

3.4 Saturation water vapour pressure

What if the sealed box contained liquid water instead of solid material?

In this case the water vapour molecules would be colliding with water surface. When the number of molecules escaping the water's surface reaches an equilibrium with the number of molecules returning back to it, the vapour above the water surface is said to be saturated and the pressure exerted by a consistent number of water vapour molecules on the walls of the box becomes *saturation water vapour pressure* (Wikipedia, 2006).

As the temperature increases, the average molecular kinetic energy increases. More water vapour molecules are able to overcome the intermolecular forces holding them back on the water surface (Salzman, 2000). As a result the water vapour concentration of the air increases and subsequently the saturation water vapor pressure increases (see the red curve in the Fig. 3.2).

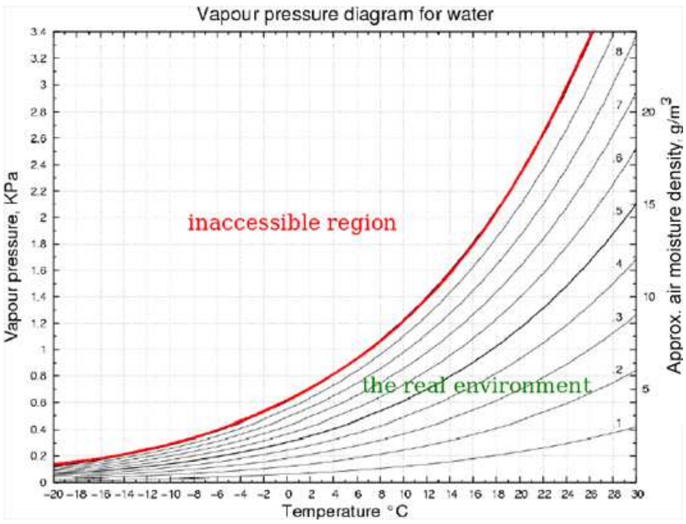


Figure 3.2: Vapour pressure diagram for water (or psychrometric chart, see also appendix C.2). Apart from the water vapour pressure, the water vapour concentration in the air could be described as *air moisture density*. **Red** curve, defines saturation water vapour pressure. (Padfield, 2005)

The red curve on fig. 3.2 shows that the capacity of air to accommodate water vapour within the same volume increases with increasing temperature.

Dew point condition and surface condensation

Usually, there is a deficit of water in the air. The area on Fig. 3.2 described as 'the real environment' represents the conditions in the air that surround the earth most of the time. For example, the typical interior temperature is 20°C with 10 g/m^3 of water vapour concentration. It exerts 1.4 kPa of vapour pressure on the interior walls (see the fig. 3.2 or follow appendix C.2). If the air suddenly cools down, there is a point at about 12°C when the air can't sustain the concentration of 10 g/m^3 anymore. It starts to dispose of its water vapour on the surfaces of solids. This is known as the dew point condition, the point at which condensation occurs. Solids become even wetter as the temperature continues to fall, because the air needs to get rid of even more of its water vapour concentration.

3.5 Moisture content

The amount of moisture in any material is defined by its *moisture content.*

> "Sometimes the *moisture content* is expressed as a moisture quantity per unit of dry or wet material" (Perry and Green, 1997).

According to this general definition, *moisture density* also falls under the term *moisture content*, which might be confusing.

Moisture density and air moisture density

$$M_d = \frac{kg_{\ moisture}}{m^3_{\ material}} \tag{3.1}$$

, where *moisture density*, M_d is the mass of moisture per unit volume of a given substance (McGraw - Hill, 2003).

In the same manner, *air moisture density* as presented in the psychrometric chart in fig. 3.2, defines the mass of moisture per volume of air [g/m^3].

$$M_{d_{air}} = \frac{g_{\ water\ vapour}}{m^3_{\ air}} \tag{3.2}$$

Dry weight basis and wet weight basis moisture contents

If the weight of a 13 kg straw bale, after thorough oven drying, stabilizes at 10 kg, the estimated amount of water in the sample was 3kg. The moisture content of the initial straw bale can be calculated like this:

$$w_d = \frac{kg_{\ water}}{kg_{\ dry\ material}} = \frac{3kg}{10kg} = 0.3 = 30\%$$

, where w_d, represents *dry weight basis moisture content.*

There is another way to calculate the moisture content of that straw bale:

$$w_w = \frac{kg_{\ water}}{kg_{\ wet\ material}} = \frac{3kg}{13kg} = 0.23 = 23\%$$

, then w_w is *wet weight basis moisture content.*

- w_d, *dry weight basis moisture content* suggests the quantity of water in a mass of dry material
- w_w, *wet weight basis moisture content* represents the quantity of water in a mass of wet material (see the Fig. 3.3).

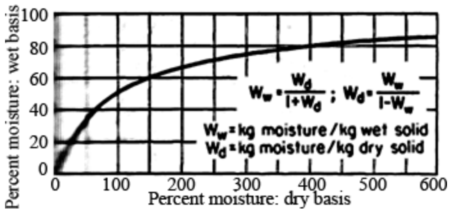


Figure 3.3: *Wet weight basis moisture content* versus *dry weight basis moisture content.* Chart is from Perry and Green (1997)

For the purposes of this thesis it is necessary to distinguish between the two kinds of *moisture content.* Even though it would be logical to prioritize the *dry-weight basis moisture content*, as the building industry prefers it, the author of this thesis has decided to emphasize *wet-weight basis moisture content.* According to Summers et al. (2003), most of the moisture meters used by straw bale builders actually measure *wet-weight basis moisture content*, which is more commonly used in the food industry and agriculture. *Dry-weight basis moisture contents*, where possible, follow in the brackets.

Air moisture content (absolute humidity)

Besides the water vapour pressure and *air moisture density*, *air moisture content* is used to define the amount of water in the air:

$$H = \frac{kg_{\ water\ vapour}}{kg_{\ dry\ air}} \tag{3.3}$$

Dry-weight basis air moisture content is often referred to as *absolute humidity* (H).

3.6 Relative humidity

The process of *adsorption*, by which material gets wet from the concentration of water vapour in the air, was described in sections 3.2 and 3.3. There is certainly a correlation between moisture concentration in the air and the moisture content of *hydrophilic* material. Parameters like *water vapour pressure*, *air moisture density*, or *air moisture content* tell how much moisture is in the air, but fail to tell to what degree the air surrounding a material makes it wet.

Here are two examples:

1. Material in a sufficiently warm environment might remain relatively dry despite high humidity levels.

   Water vapour molecules might fill the air excessively, but if their thermal energy is too high, none of them will stick to the material's surface. In that case *water vapour pressure*, *air moisture density*, or *air moisture content*, will show high readings, but the moisture content of the material will remain low.

2. At low temperatures, even a very low water vapour concentration in the air will make the material wet.

   If there are only a few water vapour molecules in the air, at low temperatures their kinetic energy might be so low that they will cling to the material making it wet. Despite low readings of *water vapour pressure*, *air moisture density*, or *air moisture content*, the moisture content of the material will be high.

In addition to *water vapour pressure*, *air moisture density*, or *air moisture content*, the researcher needs to know the material's surface temperature in order to discover the wetting potential of the water vapour concentration in the air. Only then he is able to classify the dew point condition, for which he needs a psychrometric chart (see appendix C.2). If the dew point condition in the air is approaching, than he knows that the material is getting considerably wet (see the Section 3.7).

While all the parameters mentioned in the previous three sections describing water vapour concentration in the air tell only half of what a researcher needs to know, the *relative humidity* manages to tell the whole story in one figure.

Relative humidity shows clearly how close the air surrounding a material is to a limit (RH = 100%), which manifests itself as dew and fog[2] For the straw bale builder, *relative humidity* serves as an indicator of potential damage of straw. Summers et al. (2002) showed that extensive straw decomposition appears only when *relative humidity* of the air in a wall remains above 98% (see Chapter 2).

[2]When liquid water starts to condense on numerous dust particles in a cold atmosphere, clouds (fog) appear (Thompson, 2000).

The percentage of relative humidity is defined by following equation:

$$RH = 100 * \frac{p}{p_s}, \tag{3.4}$$

where (RH) is *percentage of relative humidity*, (p) is the partial vapour pressure in air and (p_s) is saturation vapour pressure (the vapour pressure of air above the water's surface) at a given temperature (Perry and Green, 1997; CIBSE, 2002) .

The *relative humidity* doesn't necessarily refer to water vapour pressure. Padfield (1999) considers the units in which the ratio is expressed to be insignificant, because the ratio will always remain the same. However, CIBSE (2002), Guide C, strictly differentiates between the ratio defined by vapor pressure (by CIBSE (2002) called *Relative Humidity*), and the ratio relating to the air moisture content (by CIBSE (2002) called *Percentage Saturation*). Those two characteristics give slightly different values for the same specific conditions.

For example:

20°C warm air with 8.85 g/kg of moisture content, exerts 1.4kPa water vapour pressure (CIBSE, 2002)

Temperature = 20°C

Air moisture content: 8.85 g $_{moisture}$ / kg $_{dry\ air}$

(Saturation air moisture content for 20°C = 14.75 g $_{moisture}$ / kg $_{dry\ air}$ (CIBSE, 2002))

Percentage saturation = $\frac{8.85\ g_{\ moisture}/kg_{\ dry\ air}}{14.75\ g_{\ moisture}/kg_{\ dry\ air}}$ **= 60%**

Water vapour pressure = 1.415 kPa

(Saturation water vapour pressure for 20°C = 2.34 kPa (see Appendix C.2))

Relative humidity = $\frac{1.415\ kPa}{2.34\ kPa}$ **= 60.56 %**

The difference is: 60 - 60.56 = 0.56%. The dataloggers used for the research of this thesis work with an accuracy ±3.5%[3] (LASCAR, 2005). In order to simplify an already complicated issue, this thesis follows the assumption made by Padfield (1999), which is accurate enough for its purposes.

Relative humidity has another advantage over *water vapour pressure*, *air moisture density* and *air moisture content.* It can be easily measured:

- by whirling hygrometer. Relative humidity is defined as a temperature value subtracted from measurements by wet bulb and dry bulb thermometers (Thompson, 2000).

[3]This specifies the overall error in the logged readings, for relative humidity measurements between 20 and 80% RH

- by hair hygrometer. This measuring technology is based on the fact that human or horse hair changes its length according to relative humidity. Hair movement is transmitted by levers to the calibrated display. (Singleton and Sainsbury, 1978)
- by capacitive electronic sensors - dataloggers (see Chapter 4).
- by wooden disc moisture probes. The resistance to electric current is measured between two wires connected to a wooden disc which absorbs the moisture from the air. The wetter the wood, the lower the resistance. The relative humidity is then estimated from a calibration in laboratory conditions (Goodhew et al., 2004).

In addition to showing how close the environment is to dew point condition with a simple device, relative humidity is extremely useful because of its remarkable relation to moisture content in *hygroscopic* materials.

3.7 Relative humidity versus moisture content of hygroscopic materials

Before discussing the reactions of materials to changes in *relative humidity*, it is important to distinguish between *hygroscopic* and *nonhygroscopic* materials.

> *Nonhygroscopic* material is non-absorbent, it remains dry; while *hygroscopic* material gets wet in contact with water.

While the inner structure of *nonhygroscopic* material (e.g. glass, metal) is unaffected by changes in the percentage of *relative humidity*, *hygroscopic* material (e.g. wood, brick, straw, plasters, renders, and most other building materials) tends to attract water vapour molecules from the air at the surface of its complicated inner pore system (Kunzel, 1995).

The surface area of *hygroscopic* material is usually very large. It includes all the inner pores and capillaries. Straube (2002, p.38) writes that "the interior surface area of gypsum board is about 50 ft^2/ounce (164 m^2/kg - ed. author); of cement paste about 5000 ft^2/ounce (16400 m^2/kg - ed. author), and even more for wood or cellulose".

The moisture content of all materials surrounded by air with 0% *relative humidity* is zero (Perry and Green, 1997).

From 0% to around 50% *relative humidity, hygroscopic* materials get wet due to *adsorption*, described in detail by Section 3.2.

In contact with air at about 50% *relative humidity*, water molecules have already *adsorbed* to the material's surface in a layer one or several molecules thick. Any further increase in *relative humidity* results in condensation due to a process called *capillary condensation* (Kunzel, 2004).

Capillary condensation

As mentioned in Section 3.4, surface condensation happens in an environment containing water saturated air (with *relative humidity* of 100%). However, on the microscopic level, condensation occurs in the smallest pores of *hygroscopic material*, already in an environment with a much lower *relative humidity* (from 50% onwards) due to curved water surface (Kunzel, 2004). This process is called *capillary condensation*.

Curved water surfaces in the shape of menisci form inside very narrow tubes called capillaries due to the attracting forces between the molecules of water and molecules of the surface matter forming the capillary (see the Fig. 3.4, on the right).

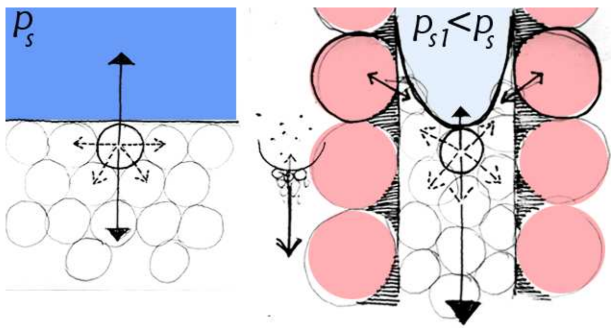


Figure 3.4: **On the left**—the sketch shows the approximate molecular configuration of a flat water surface. The force holding the water molecules together is not sufficient to keep all those molecules on the water surface. There is a definite number of water molecules that are able to escape. They become water vapour molecules, which exert saturation water vapour pressure p_s in the immediate surroundings above the water's surface. **On the right**—molecules create a curved water surface in the narrow tube (capillary) due to the attracting forces between the molecules of water (white circles) and molecules of matter forming the capillary (pink circles). The water molecules forming a curved meniscus are surrounded slightly more by their neighbours than the water molecules on the left sketch, thus they are bonded more strongly together. The curved shape lets fewer molecules escape the water surface, resulting in a lower number of molecules in the air and thus lower saturation water vapour pressure p_{s1} (see Section 3.4).

Picture 3.4 compares the intermolecular forces between liquid water molecules forming on flat (on the left) and curved (on the right) water surfaces. In case of curved menisci, (on the right) any water molecule on the surface is surrounded by a greater number of neighbouring molecules, which results in a greater attractive force towards the water vapour molecules above. More water vapour molecules cling to curved water surface than would cling to the flat surface. Thus fewer water vapour molecules above a curved water surface result in environment with lower water vapour pressure p_{s1}. That is why condensation on a curved water surface happens in environments with *relative humidity* below the value of 100% (100% relative humidity corresponds to conditions of condensation on flat water surfaces).

The curvature of water surface is determined by the radius of capillary. The narrower the capillary, the stronger the curvature, the greater the attractive force and the lower the saturation water vapour pressure (Perry and Green, 1997).

Sorption isotherm

*What happens when 1 kg of dry straw is suddenly exposed to air with relative humidity of **70%** at 25° C?*

According to the psychrometric chart (appendix C.2), air with relative humidity of **70%** at 25°C manifests water vapour pressure of 2.2 kPa.

When dry straw is exposed to an environment with 70% relative humidity, its smallest pores fill with water and then larger ones with larger curvature of menisci. The *capillary condensation* continues until the saturation water vapour pressure at the menisci of certain pore sizes (p_{s1} on fig. 3.4) corresponds to the water vapour pressure of the current 2.2 kPa in the air.

In this way equilibrium between the moisture content and the relative humidity is established. The graph on fig. 3.5 shows that at 70% *relative humidity* dry-weight basis moisture content of straw is 15%. This means that 1 kg of dry straw gained 0.15 kg of water:

$$w_{d_{straw}} = \mathbf{15\%} = 0.15 = \frac{0.15\ kg_{\ water}}{1\ kg_{\ dry\ straw}}$$

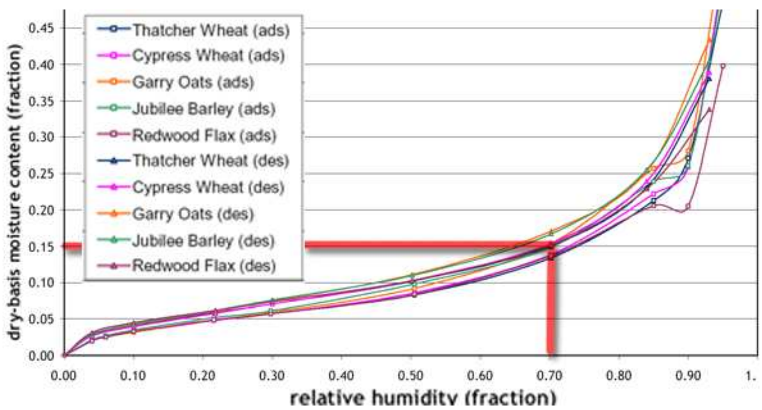


Figure 3.5: The sorption isotherms of different types of straw were obtained in laboratory and describe the relationship between *dry-weight basis moisture content* of straw and the *relative humidity* of the air that surrounds it. For example at 70% of relative humidity dry-weight basis moisture content of straw stabilizes at 15%. **(ads)** means adsorption, **(des)** means desorption. Measured by Hedlin. From Bigland-Pritchard (2005).

By adding still more water vapour to the air, the *relative humidity* increases and more pores within a material become filled with water, resulting in higher material moisture content. After a while, the new equilibrium between material moisture content and *relative humidity* is set. The range of equilibrium between various material moisture contents and corresponding values of relative humidity defines a curve called the sorption isotherm (see the Fig. 3.5). The curve is unique for each material due to differences in number and size of a material's pores (Straube, 2002).

The beauty of the sorption isotherm resides in its independence regarding temperature in the range of 15—50°C (Perry and Green, 1997). This fact is demonstrated by a comparison between the previous and following examples:

*What happens when 1 kg of dry straw becomes suddenly exposed to air with the same relative humidity as in the previous example (**70%**), but this time at 15° C?*

> According to the psychrometric chart (appendix C.2), at **70%** *relative humidity* water vapour molecules dissolved in air with a temperature of 15°C exert 1.2 kPa of water vapour pressure, which is half as much in comparison with the previous example (there are half as many water vapour molecules in the air at 15°C in comparison to number of water vapour molecules at 25°C).
>
> By lowering the saturation water vapour pressure (due to lowering the temperature), the water vapour molecules will be able to condense onto the menisci of capillaries with wider diameters than in the previous example. The range of pore sizes available to capillary condensation increases.
>
> Even though there are half as many water vapour molecules available in the air, the resulting amount of water in the straw sample will again stabilize at 0.15 kg, because in the environment with lower saturation water vapour pressure, there are more pores available for capillary condensation. The equilibrium, **70%** of RH versus roughly **15%** of $w_{d_{straw}}$ remains the same regardless of temperature (see the red marks on fig. 3.5).

However, outside the 15—50°C range, the sorption isotherm will differ with changing temperature (Perry and Green, 1997). The interest of this thesis is the moisture transfer in a straw bale wall and particularly its effect on microbial growth, which causes the decomposition of straw. Because progressive decomposition happens in a temperature range of 20—45°C (see Section 2.3.3), the sorption isotherm in Fig. 3.5 is adequate for further reference.

Hysteresis

The equilibrium moisture content depends on the direction in which the equilibrium is approached.

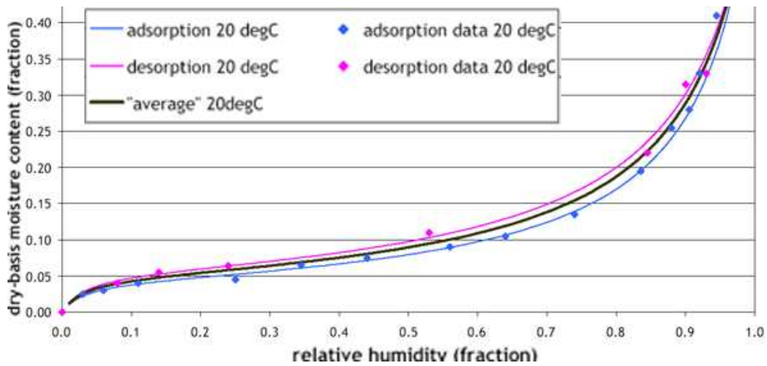


Figure 3.6: Sorption and desorption curves for straw measured in laboratory by Stroemdahl, Hailwood-Horrobin. From Bigland-Pritchard (2005).

When material reaches an equilibrium between moisture content and *relative humidity* at a certain level of *relative humidity* by desorption during drying, its moisture content will be slightly higher than that measured after reaching equilibrium at the same value of *relative humidity* by absorption during wetting (see fig. 3.6). This phenomenon is called *hysteresis* (Perry and Green, 1997).

> "The hysteresis effect is not totally understood, but it is generally assumed that the higher moisture content for desorption is due to a "ink-bottle-effect", where moisture gets trapped inside the small pores." (Pheukuri, p. 19, 2003)

The fig. 3.6 shows that for straw (as well as for most building materials, (Künzel, 1995)) the hysteresis effect is not very distinct and it is considered to be insignificant for the purposes of this thesis. The material storage function will be further characterized by sorption (absorption) isotherm.

3.8 Relative humidity versus water availability to microorganisms

The cell short of water is in danger of collapse because of a lack of internal pressure. Microorganisms on porous *hygroscopic* materials like straw frequently struggle to get as much water as possible from the surrounding environment, unless the environment is saturated.

> "The degree to which the actual RH is lower than 100% can be regarded as a measure of the difficulty any organism has in getting water into its cells." (Padfield, pg. 3, 2002)

3.8.1 Microorganisms and liquid water

Normally, there is some liquid water in narrow capillaries, but high surface tension, described in previous Section, interferes with the ability of microorganisms to draw water into their cells. Nevertheless, microbes are able to overcome high surface tension in order to "drink" from those narrow tubes even in environments with *relative humidity* lower than 100%. They do it by lowering the saturation vapour pressure within their cells in a process called *osmosis*. *Osmosis* creates suction pressure so that water can diffuse through the channels in the cell walls from the surrounding liquid, or, in principle, from the surrounding humid air (Calamita, 2005; Padfield, 2002).

Osmotic regulation of the cell fluid

During *osmosis*, microorganisms synthesize hygroscopic chemicals like glycerol, manitol and various sugars, which make dilute solutions in their cells. The molecules of those solutes (dissolved materials) have greater attractive force on water molecules within a solution than water molecules would impose on each other in pure liquid water (see the fig. 3.7).

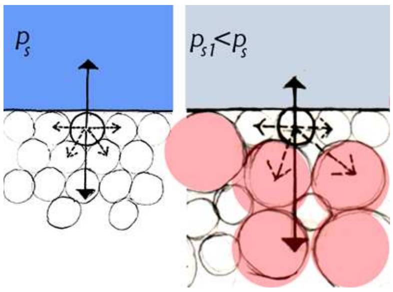


Figure 3.7: **On the left**—approximate molecular configuration of a flat water surface. **On the right**—Intermolecular forces on a surface of a solution. **Pink** circles represent molecules of a solute, **white** circles are molecules of water.

> "Increased interactive force between molecules of water and molecules of solution results in decreased tendency for water to escape into the vapour phase." (Padfield, 2002)

As a consequence, there is a smaller number of water vapour molecules above the surface of the solution, which results in decreased saturation water vapour pressure.

Once the molecules of a solute are present within a microbe, their attractive forces will draw the water molecules through the cell wall to the inside. The process is similar to surface condensation, the only difference is that due to presence of a solute, osmosis works in environments with relative humidity lower than 100%.

Perhaps later, when ambient *relative humidity* rises again, the living organic cell can "digest" the excessive hygroscopic chemicals to reestablish the equilibrium of saturation water vapour pressure in their cells with the partial water vapour pressure in their immediate surroundings (Padfield, 2002).

Solutions in narrow capillaries

The principal of interaction between saturation water vapour pressure and water concentration in solutions works outside the cells as well. The pores of *hygroscopic* materials rarely contain pure water. Water always makes some kind of solution[4]. The greater the concentration of solute, the greater the forces by which water molecules hold on to the liquid mass of a solution, and thus the greater difficulty a microorganism will have in getting water into its cells.

In reality, there is a combination of forces in the capillary-like pores of hygroscopic material. In addition to the high surface tension, water molecules are held back from microorganisms by molecules of solute in a solution (see Fig. 3.8).

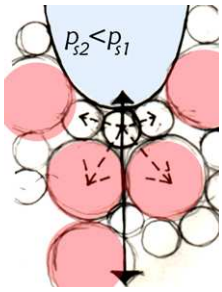


Figure 3.8: The intermolecular forces further increase when the influence of a solute is combined with the higher surface tension of curved surface in a narrow capillary (see Section 3.7). **Pink** circles represent the molecules of solute, **white** circles are the water molecules.

3.8.2 Microorganisms and water vapour

> "The whole concept of osmotic equilibrium depends on liquid equilibria across a semi-permeable membrane. When one side of the semi-permeable cell wall is bathed in air with a given partial water vapour pressure, but no solute, the situation is far from that which the theoreticians have so elegantly explained." (Padfield, pg. 17, 2002)

Padfield (2002) further suggests that while microbes in contact with a liquid water solution in a humid (not saturated) environment are able to survive under

[4]For example: the *hygroscopic* material itself could be soluble, microscopic dirt on the material's surface could dissolve into the water, etc.

certain circumstances, microbes in contact only with air of an equivalent humidity might have considerable difficulties in capturing water vapour molecules.

> "One characteristic of water in the air is that it is very dilute, compared with water of equivalent activity in a solution, or in the capillary pores of a solid. The water concentration in a saturated potassium nitrate solution, as is commonly found in the masonry of the cellars of older buildings, will be approximately 900g/l. The water vapour in air at equilibrium with this solution (95% RH) is, at 20°C, 0.016 kg/m^3 = 0.016 g/l. The difference in concentration is dramatic. One might suspect that kinetic, rather than equilibrium thermodynamic considerations, would limit the usefulness of water vapour to the stressed organism." (Padfield, pg.6, 2002)

Even though *relative humidity* represents the concentration of water vapour molecules in the air (see Section 3.6), Section 3.7 explained how *relative humidity* directly corresponds to liquid water availability to microorganisms in pores of *hygroscopic* material. It was mentioned that after a certain period of time the *relative humidity* reaches an equilibrium with the moisture content of the material and microorganisms are able to draw water from the capillaries because of *osmosis*. In that case *relative humidity* becomes the appropriate measure and there is no reason to be concerned with microorganisms drawing moisture directly from air.

However, *relative humidity* in actual straw bale walls often changes so quickly that the moisture content of straw is hardly ever able to reach an equilibrium with the relative humidity of the surrounding air.

Bigland-Pritchard (2005) investigated the moisture content development of a dry sample of straw placed in an environment with a constant higher relative humidity level. According to his crude experiment it took 10 to 13 hours for the moisture content of the straw sample to reach 90% equilibrium with the relative humidity of its surrounding environment.

Indeed, as Jolly (2000) demonstrated in his paper, microbes in a straw bale wall might often be dependent on water dissolved just in the air, especially in an environment with fluctuating relative humidity (see the next Section).

3.9 Relative humidity versus moisture content of straw in an actual wall

One of the most important observations concerning the relationship of *relative humidity* and moisture content of straw in a wall was made by Jolly (2000). While monitoring relative humidity inside actual straw bale walls, he took complementary wet-weight basis moisture content readings of straw at the location of the relative humidity sensor. He wondered if simultaneous moisture content and relative humidity data from the same place would correspond to the "general sorption isotherm of straw", provided to him by Oregon University (a similar sorption isotherm to the one in fig. 3.5). After comparison of his field data with the data obtained in laboratory conditions, he wrote:

> "In the field, moisture contents were consistently lower than what would be predicted (using "general sorption isotherm of straw" - ed. author) by the recorded RH levels.
>
> Depending on the monitor location. ... the difference between the predicted values and the measured values was generally 1%-2% less in measured moisture content. When diurnal variances in RH were observed, moisture contents always coincided most closely with minimum daily RH values." (Jolly, p.4, 2000)

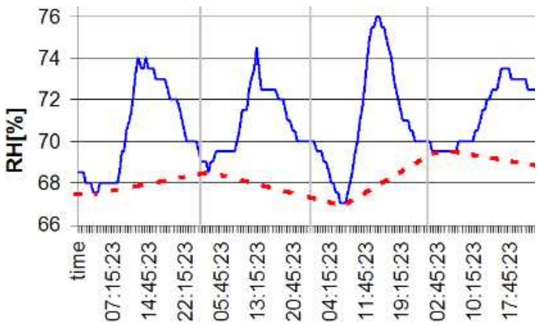


Figure 3.9: 4 days of relative humidity monitoring, done inside a straw bale wall just under the exterior earth plaster in Blanden, Belgium. Measured relative humidity is **continuous blue line**. As Jolly (2000) suggests, the **red dash line** represents the estimated level of straw moisture content.

In accordance with Jolly's conclusions, the red dashed line in fig. 3.9 represents the *relative humidity* that corresponds to the estimated straw moisture content level. It fluctuates slightly around the value of 68%, which then becomes the actual measure of liquid moisture availability to microorganisms in that particular case (see Section 3.8).

Jolly's (2000) investigation shows that water vapour often diffuses through a wall independent of the movement of liquid. In the case of the Blanden wall on fig. 3.9, the *relative humidity* value corresponding to the concentration of water vapour in the air peaks for short periods of time at about 75%. This is a much higher value than the 68% that matches the liquid water availability in material.

> "A central question therefore is how much does a high relative humidity in the pore volume encourage mould growth in the absence of an accessible liquid phase..." (Padfield, pg. 7, 2002)

The above statement represents a topic needing further investigation.

3.10 Influence of relative humidity on microbial life

Even though the previous Section showed how uncertain relative humidity might be in indicating the moisture availability to microorganisms (especially in cases with fluctuating *relative humidity*), building science tends to stubbornly repeat that high *relative humidity* is largely responsible for microorganism growth. Padfield (2002, p.19) summarizes:

> "The German building standard states that 80% RH is the upper limit for safe conditions. Innumerable secondary sources give values between 65% and 80% as the limit for biological growth in buildings."

Straube (King, 2006) writes:

> "Fungal growth can begin on most surfaces when the storage moisture results in local relative humidity of over about 80% after many months. Corrosion and decay require high levels of humidity (well over 90%) and temperatures over 15°C to proceed at dangerous rates. It is for those reasons that the *relative humidity* around a material should be controlled..."

However, Padfield (2002) suggests that the material's pore structure, pore size distribution, the nature of the solution forming in its pores and other environmental factors which are still not clearly understood seem to have a comparatively powerful influence on the viability of microorganisms stressed by low water availability.

3.11 Summary of Chapter 3

Fig. 3.10 summarizes the relationship between straw moisture content and the *relative humidity* of surrounding environment. It was derived from several sorption isotherms of straw (including the isotherms from fig. 3.5). It includes the influence of moisture content on the rate of microbial growth observed by Summers et. al. (2003) as was described in Chapter 2. The graph also shows the influence of relative humidity on condensation in capillaries of different diameters. It explains the range of adsorption and capillary condensation and indicates where the straw starts to be in contact with liquid water.

The graph in fig. 3.10 corresponds to a steady state condition which is in reality almost never achieved. Due to dynamic changes of *relative humidity* in real walls, Jolly (2000) suggests that moisture content of straw corresponding to a particular level of relative humidity will be actually 1-2% lower than the moisture content indicated by the graph 3.10. In cases with fluctuating *relative humidity*, the moisture content of straw will most likely correspond to the lower values of *relative humidity* (Jolly, 2000).

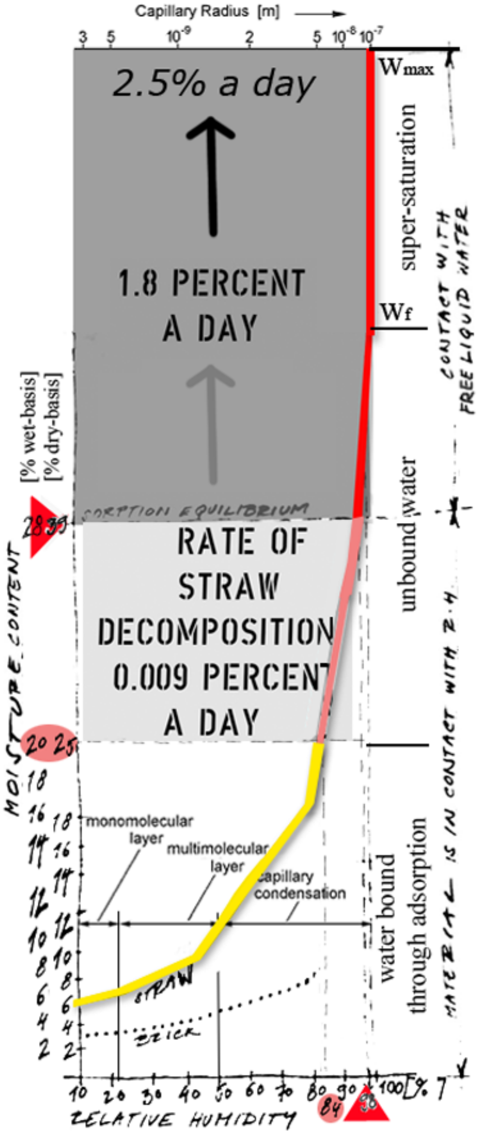


Figure 3.10: **General sorption isotherm of straw** At around 28% of *wet-weight basis moisture content* (39% of *dry-weight basis*), and about 98% of sustained relative humidity straw is saturated with water. As Summers et al. (2003) have proved, straw moisture content in equilibrium with sustained relative humidity levels below 98%, leads to negligible microorganism growth. They further recommend that only bales with bulk *wet-weight basis moisture content* below 20% (*dry-weight basis* below 25%) should be used in wall construction. This value corresponds to sustained relative humidity of about 84%. Free saturation w_f corresponds to *relative humidity* of 100%. Because of air pockets trapped in the pore structure, free saturation is a lower figure than the maximum water content w_{max} which is determined by the porosity. The rate of decomposition represents an average value within a range of moisture content. Based on Summers et al. (2003), Kunzel (1998), the general straw sorption isotherm was estimated by the author based on general sorption isotherms by Jolly (2000) and Wimmer (2001) and from a sorption isotherm of wheat straw (Minke, 2005).

With the graph, 3.10 and knowledge of straw moisture behaviour in dynamic conditions, one can measure *relative humidity* and use it as an indicator of straw condition in the wall.

However, the *relative humidity* isn't necessarily the only parameter facilitating microbial life.

> "High relative humidity is the factor most often cited as facilitating micoorganism growth, but a survey of the literature reveals a more complicated, and by no means fully understood, interplay of environmental influences." (Padfield, 2002)

Furthermore Padfield (2002) mentions that while the mechanism by which cells are able to draw water from a liquid solution (osmosis) has been well documented, the process by which cells draw water vapour directly from the air is almost unknown. This makes the study of microbial growth on straw in a wall especially difficult, because as building scientists have found, water vapour often diffuses through a wall independent of the movement of liquid. It suggests that microbes in a straw bale wall might be often dependent only on water dissolved in the air, especially in an environment with fluctuating relative humidity.

Chapter 4

Case studies

The previous two chapters presented in some detail the theory of straw deterioration. This Chapter will review available research that examines the moisture conditions triggering microbial growth in the actual walls of existing straw bale houses. Furthermore, it introduces two case studies provided exclusively for this thesis. The measured data will be compared with the theory presented so far and simultaneously serve as a basis for the following considerations of a theory of moisture transfer in the straw bale walls which will be explained in later chapters (see chapters 5, 6).

Figure 4.1: Pilgrim Holiness Church in Arthur, Nebraska was built out of straw bales in 1928 (Wanek, 1998). *"These buildings typically were constructed with 1-2' roof overhangs* (300-600mm - ed, author) *and were originally plastered with earthen materials and later replastered with cement-based plaster."* (Swearingen, 2005)

Even though the first straw bale buildings have successful performance records that stretch over hundred years, they are situated in ideal conditions, such as the dry Nebraska plains (see fig. 4.1).

More recently, the modern straw bale building revival has brought straw bale construction into more humid climates (Platts, 1997). The oldest straw bale houses built in Nova Scotia, Ireland or Scandinavia, for example, are no more than few decades old. To open their walls and test the straw for humidity has been a subject of great interest.

4.1 Overview of existing moisture monitoring in straw bale walls

Despite the interest in wall moisture monitoring among the majority of straw bale builders, there are only a few studies available that give a broad picture of moisture migration in existing straw bale structures. The analysis presented in this Section focuses on a number of investigations that were carefully selected to meet the following criteria:

1. the survey included sufficient data about the monitor installation, building (construction details), site (exposure to elements) and climate
2. the monitoring equipment was calibrated
3. the survey was part of academic research

Inventory of selected investigations

In the late 1990's, Canadian Mortgage and Housing Corporation commissioned comprehensive research into the moisture conditions of straw in walls and floors (CMHC, 2000). It included:

- the development of simple and affordable "wooden block" moisture meters (CMHC, 1996)
- a pilot study of moisture performance in stuccoed walls of four straw bale structures in Quebec — 7 to 10 years old (Platts, 1997)
- an investigation of moisture control in twelve samples of straw bale floors
- detailed monitoring of moisture conditions in walls of nine straw bale houses in Alberta (Jolly, 2000)
- a report of moisture monitoring on straw bale houses in Nova Scotia (Henderson, 1998)[1]
- research of humidity levels in straw bale walls of five houses in British Columbia (Gonzales, 1999)[1]

Additionally, subsequent analysis covers another two case studies:

- a study supported by the state of California covering in great detail the hygrothermal performance of straw in the earth plastered walls of a Californian winery (Straube and Schumacher, 2003).

[1]The studies of Henderson (1998) and Gonzales (1999) focused directly on cases in high humidity and high precipitation climates.

- research presenting moisture content measurements in walls of a lime plastered, unheated, straw bale storage building situated on the north eastern edge of Dartmoor in Devon, England (Goodhew et al., 2004).

A summary of the monitored data mentioned above can be found in Appendix B.0.3. It covers 17 structures in 92 monitoring locations, with 133 sensors[2] monitoring either relative humidity or direct moisture content of straw. Some of the sensors measured temperature as well.

A few marginal studies are additionally mentioned in the following text in order to further diversify or support the investigation of this thesis.

4.1.1 Response of straw bale walls to atmospheric humidity

In their study, Straube and Schummacher (2004) show that ambient relative humidity is capable of penetrating the straw bale wall. They assume that a sustained high level of relative humidity (70-85%) should be reduced, because it eventually imposes high stress on straw within walls. Unfortunately, their study doesn't examine any straw samples in order to consider the effect that sustained high ambient relative humidity has on the condition of straw.

Similar evidence was provided by Jolly (2000). He monitored a house built on the Canadian west coast in an area of high atmospheric relative humidity loads. The moisture content readings in the walls indicated unacceptable conditions regarding microbial growth. Again, no samples of straw were examined to support the statement. Jolly writes:

> "Although the north wall is well protected from precipitation, high moisture content readings persisted during the summer months. This is likely a situation where high moisture content within the wall coincides with high atmospheric RH levels. The builder of this house felt that the exposure may be overprotected by vegetation (forest within 4 m of the wall) and a reduction in air circulation may be affecting drying." (Jolly, p.52, 2000)

Straw with high moisture content usually occurs only in the surface area under the wall cover (plaster) which faces high relative humidity levels. One marginal case study in the moist climate of the Pacific Northwest, in Oregon, USA (Still, 1999) mentions how interior warmth reduces relative humidity all the way to the outer side of the wall:

> "Our average external relative humidity last winter hovered around 85%. The buried-in-straw sensors near the outside of the bales reflected this very high relative humidity. All the sensors near the

[2]In some locations up to three sensors were installed, one in the straw facing the exterior, one in the straw facing the interior of the wall and one sensor in the middle of the wall.

inside of the bales showed greatly reduced RH. The interior warmth seems to be passing through the wall and warming the sensors buried 4 in (100mm - ed. author) from the interior sheet rock. The warmer temperatures result in readings of decreased relative humidity. The external sensors were often closer to the temperature of the outside air. So, these sensors reflected relative humidity that was in relation to the wintertime average near the outer surface of the bale" (Still, 1999)

However, Goodhew et al. (2004) monitored the moisture content of straw in an unheated building, where high levels of relative humidity showed very similar readings in the interior and exterior of the building (see yellow and red curve in fig. 4.2). It was expected that when the relative humidity behaves in a similar manner on the both sides of a wall, the straw moisture content throughout the wall will follow accordingly (see purple curves on fig. 4.2).

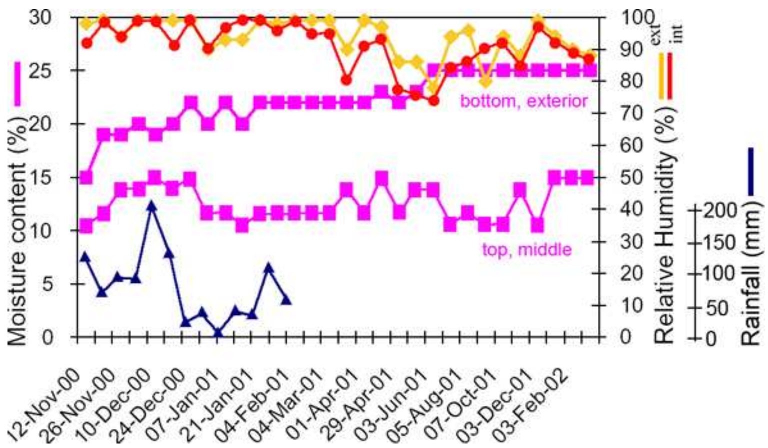


Figure 4.2: The south wall of an unheated building in Devon, England was exposed to rain penetration. The **upper purple curve** shows moisture content (presumably wet-weight basis) readings in exterior side at the wall's very bottom and the **lower purple curve** indicates the mid-bale location at the top of a wall. The figure shows simultaneously a high level of ambient relative humidity measured at both sides of a wall (**yellow and red**) and fragment of rainfall data over winter 2000-2001 (**dark blue**). Some sort of response of moisture content to the decrease of ambient relative humidity was recorded at the top of the wall with an approximate 3 month delay, but the effect is fairly subtle and shouldn't be seen as conclusive. However, the response of the same location to rainfall seems to be immediate and much more obvious. This graph was adapted from Goodhew et al. (2004) by author.

According to the data presented in fig. 4.2 Goodhew (p. 1446, 2004) writes:

"There is little direct correlation between the variance of exterior and interior relative humidity levels and corresponding variances of the moisture content readings within the bales. However, over longer time periods any theories concerning time lag of moisture movement through straw-bale walls maybe better determined."

If there is no evident correlation between the straw moisture content and changes in ambient relative humidity, what was then the main force behind moisture migration through the wall in this case? The dark blue curve in the left corner of fig. 4.2 gives a possible explanation.

> "A better correlation between the average rainfall close to the building and the moisture content of the upper part of the wettest wall was observed. There was no evidence of water ingress due to faulty render of roofing coverage to suggest that wind-driven penetrating dampness was responsible for this association." (Goodhew at all, p. 1447, 2004)

It appears that atmospheric relative humidity doesn't in fact prove to be the dominant moisture load. Aside from the accidental leak of water within a wall, the strongest influence on moisture levels in straw bale walls is wind-driven rain (Straube and Schumacher, 2004).

4.1.2 Response of straw bale walls to rain and sun

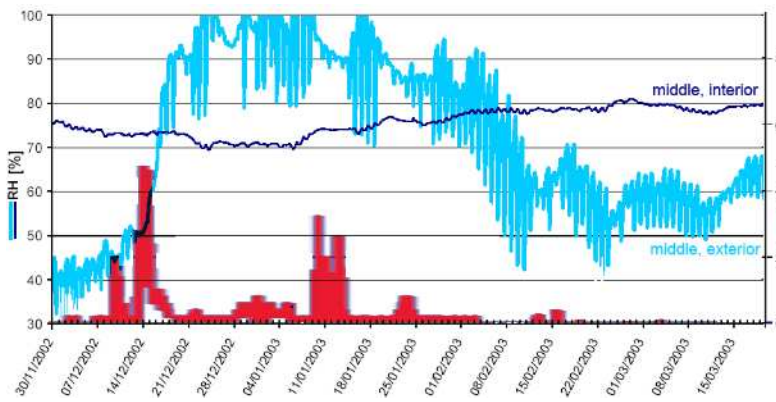


Figure 4.3: Californian winery. Mid-height of the south wall. There was heavy rain and wind from the south just before Christmas 2002 (**red** colour), and the RH sensor, placed in the straw under the exterior earth plaster, responded dramatically (**light blue** colour). The other RH sensor in the same wall, at the same height, but facing the interior earth plaster, shows increased relative humidity redistributing itself slightly throughout the wall (**dark blue** colour). Image adapted from Straube and Schumacher (2004) by author.

While analyzing a vast amount of relative humidity and temperature data collected over one year in the walls of a Californian winery, Straube and Schumacher (2004) arrived at the conclusion that earth plastered straw bale walls respond very strongly to wetting by rain (see fig. 4.3). In spite of large overhangs, the readings within a wall exposed to driving rain showed rapidly occuring peaks in relative humidity, while in other walls, not affected by rain, the relative humidity inside bales changed very slowly, often over weeks.

Furthermore Straube and Schumacher (2004) proved that the wetting due to driving rain is redistributed to the center of the wall as a part of the drying process (dark blue curve on fig. 4.3).

> "Rain control for earth plastered strawbale buildings is clearly essential. Rain causes the greatest and quickest increase in RH. Drying can occur quickly after rain events if conditions allow it, but serious wetting will often require at least 4 to 8 weeks to dry." (Straube and Schumacher,p. 15, 2004)

The wall hit by driving rain in this study was the southern wall and the drying in the sunny and extremely dry Californian climate took 8 weeks (see fig. 4.3). The drying depends on ambient relative humidity as well as the temperature, which is highly affected by solar gains. As Straube and Schummacher (p. 15, 2004) write:

> "The sun can heat even the back of heavy earth plaster surfaces to 20 °C above outdoor air temperature."

However, different drying patterns occur in cold and wet climates, for example in the UK. Walls exposed to permanent shade, or to long periods of rains, high ambient humidity and low temperatures need to be protected from driving rain by all means.

In damp and cloudy Dartmoor, England, an unheated building showed degrading straw at the bottom of southern wall after only approximately two years of its existence due to moisture that was unable to dry out (Goodhew et al., 2004). Wind-driven rain penetrating the lime render caused gradual moisture content build up. The complete absence of drying at this particular location is apparent from fig. 4.2 in the previous Section. Unfortunately, the authors don't specify the construction details at the foot of the wall. To draw a conclusion from their case, it would be useful to know if the wall footing under the bottom course of bales was drained properly.

4.1.3 Vertical variations of humidity in straw bale walls

Assumedly, moisture has tendency to gravitate to the lower parts of a wall. Such phenomenon is apparent from fig. 4.2 and seems to occur especially in walls that aren't exposed to extensive sunshine (Jolly, 2000; Gonzales, 1999; Goodhew, 2004).

The readings of relative humidity in the straw under the exterior plaster of the eastern wall of the Californian winery (Straube and Schumacher, 2004), heated regularly by morning sun, reveal the opposite. Relative humidity reached its highest values at the top of the wall, while the bottom and the middle showed much lower, almost identical, readings (see fig. 4.4).

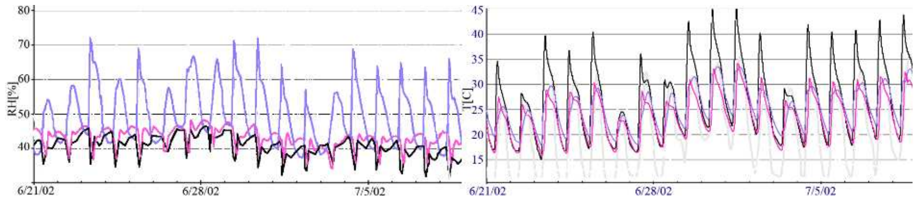


Figure 4.4: Relative humidity (**on the left**) and temperature readings (**on the right**) under the exterior plaster in the eastern wall of a Californian winery. A **Blue** curve indicates the readings at the top of the wall, a **black** curve shows the middle-height values, a **purple** curve corresponds to the bottom of the wall and the **light grey** is the outside temperature. From Straube and Schumacher (2004).

The temperature data demonstrate how the middle height of the wall heats up to 45 °C, every morning due to its unobstructed sun exposure. The upper and lower part stays cooler, because, as Straube and Schumacher (p. 12, 2004) write:

> "The top sensor is more protected from the sun by the overhang, and the bottom sensor is connected to the massive and earth-connected concrete footing wall."

The temperature could be the key to the high relative humidity levels at the top of the wall. It is possible that the vapour coming from drying straw and drying exterior plaster at the middle height level migrates to the top of the wall, where it cools down and thus shows rocketing peaks of relative humidity.

Hammer (see Appendix K.1) monitored moisture content in the western wall of small unheated storage building in California during the rainy season and discovered a similar phenomenon:

> "Generally, the straw moisture content (presumably dry-weight basis - ed. author) was well under 16%, but the top half of the west wall had alarmingly high readings of 18-39%. It was determined that the joints between bale stacks acted as 'chimneys', allowing the west sun to heat air in the bales, with whatever moisture it had wicked from the plaster or entered through small cracks, and drive it up to the top of the wall where it was trapped by a layer of plastic which was unwittingly installed as a second line of defense under the metal flashing wall cap. Uncapping the wall, removing the plastic, and drilling ventilation holes in the plywood top plate has apparently solved the problem."

Hammer's testimony confirms that the majority of moisture damage in straw bale walls comes from fundamental design flaws. The attention to proper detailing during construction of straw bale building is crucial in preventing any serious moisture problem.

4.1.4 Construction details

Platts (1997) investigated four 7-to 10-year old straw bale structures in Quebec, Canada in order to determine any traces of moisture damage in their walls. He opened the stucco and checked the straw for microbial activity and moisture content. In a discussion of his study, Platts (p.11, 1997) writes:

> "Substantially troubled zones in the stuccoed bale walls were marked by faint surface telltales and perhaps generally can be found and remedied. Better yet, we think the problem of excessive moisture can be avoided altogether at the design and construction stage..."

Rising damp

One of the moisture problems discovered by Platts (1997) referred to rising damp in a six year old straw bale wall. It was covered from both sides with 50 mm thick cement stucco and footed on a deep rubble trench foundation without any polyethylene film or other dampproof course (see fig. 4.5).

Figure 4.5: "White mould indicates advanced rotting of supersaturated straw - moisture content off scale. 1m above this location, straw was moist and deteriorating with measured moisture content about 38-43%" (presumably dry-weight basis - ed. author). From Platts (1997).

The rubble trench foundation happened to drain a lot of water, due to the sloping site situated on a hill. Platts (p.6, 1997) explains:

> "What we have, though, is an upside-down concrete bottle with its open mouth a few inches above water or vapour at 100% RH... ...And it's filled with straw."

The example described above proves that the layer of rubble creating a capillary break between the moist earth and straw bales isn't sufficient to provide protection against rising damp. If the bottom of the trench foundation is exposed to water, water vapour migrates into the air between the stones and causes straw decomposition at the foot of the wall.

Window sill

Platts (1997) measured straw moisture content in a 10-year old lime plastered north facing wall, just under a window sill that was flushed with plaster without any drip edge. The readings through the wall from exterior to interior were: 25-25-22-20% (presumably dry-weight basis), angling the moisture probe downward, the moisture content readings became: 25-30-35-30%. The sample of straw from this location showed obvious signs of degradation (see fig. 4.6).

Figure 4.6: A wall opened under the corner of the window sill without a drip edge reveals musty smelling, weak, moist straw. From Platts (1997).

During driving rain, a window surface provides an accumulated amount of water running down the window sill. If there is no drip edge on the window sill, moisture soaks through the plaster, wetting the bales under the window.

Figure 4.7: No drip edge on the window sill is a bad practice in straw bale construction. Photo of lime plastered straw bale house in Maine, USA by Beals (2004).

4.1.5 Sheet moisture barriers

Sheet moisture barriers are commonly used to protect a wall assembly against moisture damage. They can be applied either under the interior surface of a wall to shield its core against water vapour originating from inside a house, or they are used under the outside wall face, to avoid moisture problems caused by the elements.

Generally, professional straw bale builders are against the use of sheet moisture barriers in plastered straw bale buildings, because moisture barriers applied directly on straw inhibit the physical connection between straw and plaster. Swearingen (2005) writes that the decision to use a sheet moisture barrier over straw bales in a plastered wall affects its strength and integrity.

He explains that when plaster is executed directly onto a straw bale, an intersection of straw and plaster creates a thin layer with a strong bond, due to which the whole wall assembly starts to behave structurally as a single element – a light stress-skin panel. The complete structural effect is accomplished when the plaster is executed directly on straw bales from both sides (inside and out). Furthermore the plaster-straw bond has the advantage of being flexible, so that any movement of straw bales is accommodated without transfer of stress to the plaster. This helps to prevent stress-related plaster cracking.

There is another major reason why sheet moisture barriers are not accepted in straw bale construction. The results of some investigations show that sheet moisture barriers don't particularly improve moisture protection of straw bale wall assemblies. Some even say that moisture barriers might have a damaging effect on straw in a wall.

Exterior sheet barrier — Tyvek

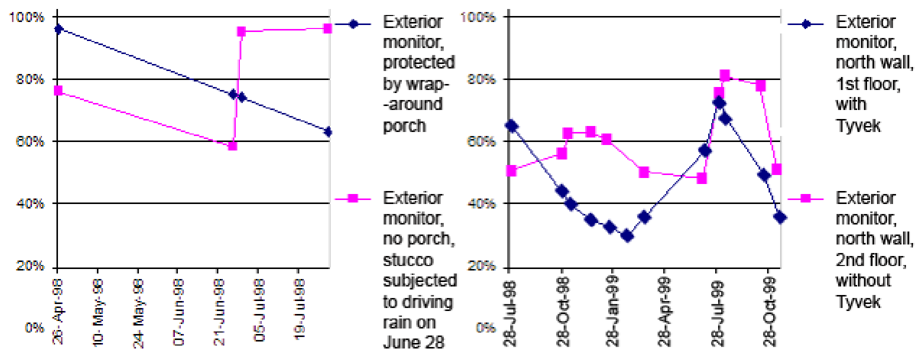


Figure 4.8: **On the left** are readings of relative humidity from two monitors buried in straw just under a Tyvek exterior moisture barrier that was plastered by cement stucco. One location was affected by driving rain (**purple** curve), the other was not (**blue**). It was protected by a porch. The graph shows that Tyvek was not effective at blocking the driving rain. **On the right** (different straw bale house) are two relative humidity readings taken at different heights in the northern wall just under the cement stucco. One location had Tyvek (first floor level - **blue** curve), the other one did not (second floor level - **purple** curve). This graph proves that Tyvek doesn't inhibit the drying of straw behind it (Platts, 1997).

Moisture sheet barrier products such as Tyvek block liquid moisture while transmitting water vapour. Tyvek was used under exterior plaster as protection against driving rain and back splash on two straw bale houses monitored by Jolly (2000) (see fig. 4.8).

The first house had an exterior of straw bale walls wrapped in Tyvek and then plastered by cement stucco. Jolly (2000) made an interesting observation when comparing moisture conditions in the wall Section affected by driving rain and the wall Section protected by the porch. The rain-affected straw showed a considerable increase in relative humidity, to an almost unacceptable level, even though the straw was protected by Tyvek. Assuming that Tyvek blocks liquid moisture, the extensive wetting must have been related to transfer of water vapour from wet stucco through Tyvek into straw. The implication in this case seem obvious: The efficiency of the exterior moisture barrier Tyvek, as protection against exterior wetting, in this case failed (see fig. 4.8 on the left).

The graph in fig. 4.8, on the right, presents data collected in the northern wall of the other house studied by Jolly (2000). This time Tyvek covered only the exterior wall of the first floor. There was no sheet moisture barrier applied between the straw and exterior cement stucco at the second floor level. Although direct comparisons between those two locations are impossible due to the application of stucco during different months (this fact considerably influenced the monitored data), at the time of monitoring, the relative humidity in straw didn't seem to be affected by Tyvek. In his commentary to the graph above (see fig. 4.8 on the right) Jolly (p.31, 2000) writes:

> "It does seem relatively clear that a highly permeable sheet moisture barrier (in this case, Tyvek) does not inhibit drying under normal conditions"

There isn't enough data to support any strong conclusions. Further research needs to be done. The investigation of Jolly (2000) suggests that straw bales covered by the exterior moisture sheet barrier "Tyvek" don't benefit from it. Plastered Tyvek doesn't protect the straw from the driving rain and at the same time, it allows the straw to dry as if it were not really there.

Interior vapour barriers

A vapour barrier eliminates the air exchange between the interior and exterior of a house which is caused by vapour diffusion through the materials. It is usually an aluminum or plastic sheet applied on the interior "warm" side of a wall. It shouldn't be confused with an "air" barrier. Air barriers prevent the air exchange caused by air flow - infiltration. Air barriers are necessary in any heated building and are sufficiently provided by interior plasters, and well sealed joints between walls and floor slab, windows, and ceilings (Straube and King, 2006).

As far as the author of this thesis is aware, the effect of an interior vapour barrier on moisture conditions in straw bale walls has not been the subject of any serious research. However, discussion about their use in the straw bale building industry is widespread.

The majority of straw bale builders who answered the questionnaire (see Section 8.2.5) believe that diffused interior water vapour (coming from bathing, cooking, laundry drying, etc.) will not cause any harm. A strong argument supporting this belief comes from a study by Canadian Mortgage and Housing Corporation (CMHC, 1996) done on timber framed, dry walled structures. The main investigator of the study, Bob Platts (1998) wrote to The Last Straw journal:

> "So, full-thick insulated, flued older houses in Canada, including blown cellulose jobs, very rarely suffer rotting walls from indoor-source moisture, lack of "vapour barrier" be damned. (We can make dogmatic statements like this because we've investigated about 16000 houses across our country, including a 14000-house cross section done with infrared thermography.) Now, if the fledgling straw bale industry can begin to investigate its rich field history, our Nebraska heritage will also confirm that, though some will have signs of excessive indoor RH, few will have gross air leaks (due to continuous plaster wall finish - ed. author) and so few will exhibit wet wall spots. No vapour barrier, no need for one; let's move on."

Installation of vapor barriers has been widely popular since the 1960's in construction of standard timber frame, well insulated houses. Vapour barriers quickly became routine, and were adopted by building codes and the majority of timber frame building contractors throughout the world. However, the tendency towards comparing the moisture behaviour of a straw bale wall to that of a timber frame wall is misleading. Moisture performance of a plastered straw bale wall is much more closely related to masonry than to a timber frame wall. In an article for The Last Straw journal, Straube writes:

> "Vapour can only diffuse into the (well plastered straw bale - ed. author) wall at a reasonably slow and measured rate, and the quantities are low enough that the wall can absorb and subsequently release the moisture. This behaviour is similar to that of a traditional solid masonry or adobe wall." (Straube and King, 2006)

It has been demonstrated by centuries of practice that adobe or masonry walls don't require a vapour barrier installation for their successful moisture performance. In his article, Straube concludes that, in the case of plastered straw bale walls, vapour barriers are not necessary "...or in fact desirable" (Straube and King, 2006).

Plastered straw bales don't need extra protection from the interior of the house, however, complicated assemblies of prefabricated straw filled wall panels are sometimes thought to require them (see fig. 4.9).

Figure 4.9: One of the first prefabricated straw bale houses in Breitenfurt in Austria. Wall section **on the left**: **1**— light, silicate based exterior plaster, **2**— cement based wood wool panel (heraklith), **3**— diagonally clad timber, **4-6**— straw bales between double timber studs, **7**— diagonally clad timber, **8**— vapour barrier, plastic sheet, **9**— gypsum plasterboard, **10**— interior plaster. Image of exterior of the house under construction is **in the middle** and interior, prior to sheeting with "vapour" barrier, is **on the right**. Section is from Wimmer et al. (2001) and images from www.baubilogie.at.

Since the year 2000, Austrian architects have been developing a unique straw bale "passive house"[3] technology with an attempt to increase the enclosure's airtightness by installing a vapour barrier (this measure is also supposed to reduce the amount of wetting in the wall).

4.1.6 Air infiltration

Piepkorn (2000) assumes that the interior of a house that is wrapped in vapour barrier could act like an air balloon, because the vapour pressure doesn't have a chance to equalize evenly through the enclosure. Vapour pressure could build up inside a house and any small break in the vapor barrier system, almost like a perforated tire tube, could allow a startling amount of humid interior air to find its way into the wall.

> "The volume of moisture will be anywhere from ten to hundred times more at that location (behind perforated vapour barrier - ed. author)." (Piepkorn, 2000)

In building envelopes, it is not only a vapour barrier due to increased vapour pressure that contributes to moisture problems, but on smaller scale any air barrier (e.g. plaster) makes a vapour pressurized enclosure that might lead to trouble. Any discontinuity or crack in an air barrier creates a passage for humid air and causes moisture infiltration in plastered straw.

[3]Generally, a building falls within the "passive building standard", if its annual heating energy consumption meets the target of 20 kWh/m^2. Contemporary building practice believes that in order to meet passive house standard, homes need to be equipped with heat exchanging air conditioning, which requires air tight building envelopes (Wihan, 2005).

The impact of air infiltration on humidity in a straw bale wall was documented during monitoring in Plozevet, Brittany, France (this case will be introduced in great detail further in this Chapter). A perfectly sealed monitor in the middle of a wet straw bale wall in Plozevet showed more or less stable values of relative humidity until the monitor was taken out for data download. The re-entry of the monitor wasn't done properly and the hole in the lime plaster wasn't sealed well. In this case, because the straw in the wall was very humid, infiltration of interior air through the badly sealed plug into the monitor location contributed to drying (see fig. 4.10).

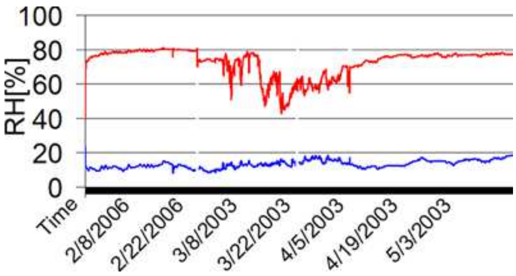


Figure 4.10: Monitoring in wet wall at mid-bale depth in straw bale house in Plozevet, Brittany, France. The chart shows a fragment of the data collected for this thesis (see Section 4.2.1). The monitor was adequately sealed in the lime plastered straw only during first month of monitoring. At the beginning of March, the monitor was taken out of the wall for data download and after its reentry into the same position, it wasn't properly sealed. The data from March til mid April were affected by infiltration from interior air. In the middle of April, the monitor was well sealed to give stable mid-wall depth readings again.

It could be expected that in normal conditions (with dry straw in a wall and humid air), any crack in an air barrier (e.g. plaster) could cause significant wetting.

4.1.7 Air convection

Air infiltration introduces air carrying water vapour into a construction. The convective flows of humid air then occur in the air gaps and air pockets within a wall.

The effect of air convection in straw bale walls was mentioned in Section 4.1.3, when Hammer (see Appendix K.1) observed migrating moisture in "chimneys" behind the exterior plaster, causing condensation and straw rot under the impermeable roof (top) plate built on top of the wall.

Another anecdote regarding air convection was recorded by Magwood (see Appendix L). He writes:

> "We often see patterns of moisture accumulation behind the exterior plaster on houses we have built. At first these scared the heck out of me! But having spent some time opening up walls in these places

> and testing and observing the straw, I don't feel that it is a problem. These spots occur where the straw in the wall is not as well packed, ie, where air is more free to circulate. Any moisture in this moving air condenses on the back of the plaster and soaks through as it dries out of the plaster. We most commonly see these spots when a streak of cold weather is followed by a day of much warmer temperatures. I speculate that on the continuously cold days, this moisture is transpiring into the very dry air very quickly, so doesn't accumulate in the plaster. A bit of warmer, damper weather will slow this drying and the moisture hangs out in the plaster a bit longer. The moisture meter inserted into this damp spot does not give worrying figures (usually under 15%), but the figures are higher than in the dry-appearing sections of wall. I haven't found any discoloured or deteriorated straw in these places, but don't know what another 50 years of cycling will do.
>
> Most of this moisture enters the wall from gaps in the interior plaster. It is especially important to seal up electrical boxes and the plaster seam with the ceiling and/or top plate. Making sure that the bales do not have voids or unstuffed areas will prevent moisture from accumulating in concentrated areas."

Newport Partners (2004) state that the movement of water vapour by air flow can transfer large amounts of moisture through building construction.

Dalgliesh (2005), Straube and Schumacher (2003) also suggest that the impacts of air convection flow within a wall assembly are of great importance.

A good example of construction with a potential for inner convection currents is the North American classic: timber frame. The gaps between the drywall interior and exterior cladding are pathways for humid air to enter. Spaces created between studs and imperfectly installed insulation create an ideal space for convective flows. Solid masonry walls, on the other hand, don't allow for much air convection.

As for natural convection flows, plastered straw bale walls seem to be somewhere in between these two extremes.

Andersen (2004) suggests that there are considerable air convective currents in plastered straw bale walls. In his paper, he summarized several independent studies on the thermal performance of straw bale walls. He discovered that the thermal transmittance (U-value) on large wall sections of completed plastered straw bale wall assembly is unexpectedly poor in comparison to thermal transmittance through a single straw bale. The major cause for thermal loss within a straw bale wall assembly were air penetration and natural convection flows.

> "A computational fluid dynamics model helped to uncover that the natural convection does not occur predominately through the straw itself. The natural convection can occur within the gaps between the

straw and the surface treatments on both the interior and exterior sides." (Christian et al., 1998)

Christian et al. (1998) conclude that with all the spaces between the bales well sealed (stuffed with loose straw) and the careful application of interior and exterior plaster, straw bale wall builders can build "natural convection free."

Natural convection free straw bale building

Additionally, the gaps between straw bales can be largely eliminated by compression. This is the unquestionable advantage of load bearing straw bale building technique. With great vertical compression, the horizontal gaps between courses disappear. However, if the bales are in courses laid flat (rather than on their edge), they tend to expand sideways with vertical compression, due to the position of their tying strings (see fig. 4.11).

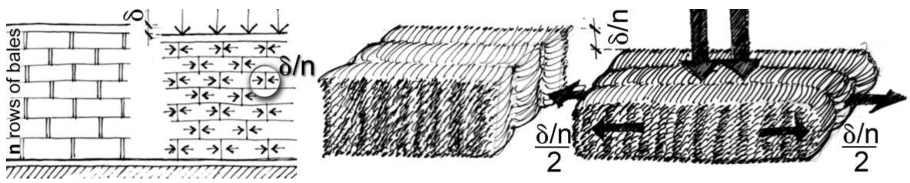


Figure 4.11: When **n** bale high load bearing wall with straw bales laid flat is squeezed by vertical compression, the overall settlement is δ. The volume of settlement δ depends on the density of the bales. Settlement over 1 bale height is then $\delta/\mathbf{n}$. Because the strings retain their size, reduced height results in extended length. That is why the gap between two bales will become by $\delta/\mathbf{n}$ narrower.

Jones (2002) writes that a 7-bale high wall built with dense building bales (about 100 kg·m^3) will compress up to 50mm. This means that every bale in each row will be compressed by $50/7 = 7$mm. According to fig. 4.11, the strings will allow a 7mm length extension for each bale.

Length extension acts as an automatic gap sealer. Because the overall wall settlement depends on the density of bales, this system becomes even more effective when using bales that were not initially compressed well.

That is why well plastered, load bearing straw bales, laid flat, with all the gaps carefully stuffed with loose straw, will not only give the straw the best possible protection from rotting due to elimination of natural current air flows, but also improve the house's overall thermal performance.

4.1.8 Moisture balance

Padfield (see Appendix K.2) suggests that straw has an enormous water vapour storage capacity, which will protect it against long periods of locally high RH. This is good news, because as long as the moisture within straw is allowed to dry out, considerable moisture load doesn't necessarily cause a problem (see fig. 4.12).

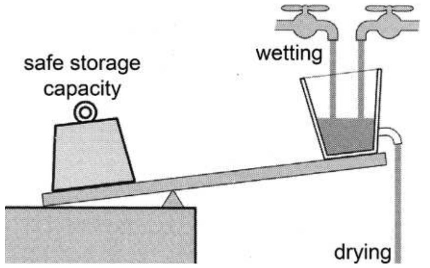


Figure 4.12: Straube writes: *"A building material's ability to store moisture is important as it represents the amount of time that can separate wetting and drying events before problems begin."* (King, p.142, 2006)

The drying potential seems to be key (King, 2006). More than 100 years of experience with straw bale building keeps proving that good attention to detail will minimize wetting of straw in walls, while their cover in breathable (permeable) plasters will allow for sufficient drying (see fig. 4.13).

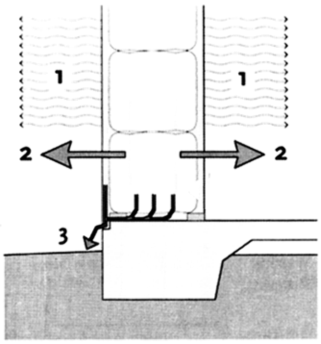


Figure 4.13: Drying of a straw bale wall enclosure. Except for evaporation from the wall surface (**1**) and vapour transfer driven by diffusion and air leakage through breathable plasters (**2**), excessive moisture is also removed from straw by proper drainage (**3**). (King, p.142, 2006)

4.2 Monitoring in straw bale walls done exclusively for this thesis

So far, Chapter 4 analyzed results of monitoring in straw bale walls done by others. The rest of this Chapter is going to complement existing research with new investigations in two different straw bale buildings. One is in Blanden, Belgium and one in Plozevet, France.

4.2.1 Case study I. Plozevet, France

Case study I. was introduced in the preface to this thesis. It provides an interesting case of serious moisture damage. Two days of rain driven by strong coastal wind caused saturation of the straw within a lime plastered wall.

Construction Details

Date of build
2005—2006

Design and realization
Self built and self designed. The house respects the look of traditional local masonry architecture. It has 1 story plus inhabited attic space, and was built as a two-family house, available as a summer rental. Plozevet is a favourite French holiday destination during July and August.

Foundation
Shallow trench concrete foundation with insulated slab. The first course of bales ranges between 30—100mm above ground.

Figure 4.14: Straw bales on the edge are used in the walls as well as in the roof. The red arrow points at the future location of the monitor. Photography by Martin Oehlmann.

Strucure

The walls and roof are insulated with straw bales as infill in a loadbearing frame made out of prefabricated I-beams (see fig. 4.14)

Weatherproofing

The straw bale walls are lime plastered (outside and inside). Straw bales in the roof are also lime plastered. The ventilating air gap between the plastered straw and roofing is closed by timber boarding with traditional slate roof on top.

Heating

Radiant floor heating hasn't been used yet. The woodstove and significant passive solar gains have been sufficient to heat the interior during the winter.

Climate

Figure 4.15: The red arrow points at straw bale house in Plozevet, Brittany, France

The coastal microclimate is influenced by the ocean. The weather often changes a few times a day. It is sunny most of the year, nevertheless rain showers are very common, often with strong winds. In autumn, winter and spring severe storms occur. They often last for several days.

Average yearly temperature

10.8 °C, measured in Brest (Studemund-Halevy, 1994)

Average yearly precipitation

1200 mm, measured in Audierne (Meteofrance, 2005)

Disastrous storm

The 48 hours of horizontal rain driven by very strong coastal wind happened on December 1st and 2nd 2005 and caused several large wet spots on the interior plaster of the western wall.

Monitoring

Lascar EL-USB-2 humidity, temperature and dew point USB data logger[4] and used to monitor conditions inside the straw bale wall.

The monitor was placed in the western wall under the window at the location of one of the former wet spots on January 25th 2006. It was inserted from the interior of the house approximately 180mm deep into the wall (the mid-depth of the wall, see fig. 4.16). At that time the wet spots on the interior lime plaster had already dried out even though the inside of the house smelled strongly of rotting straw.

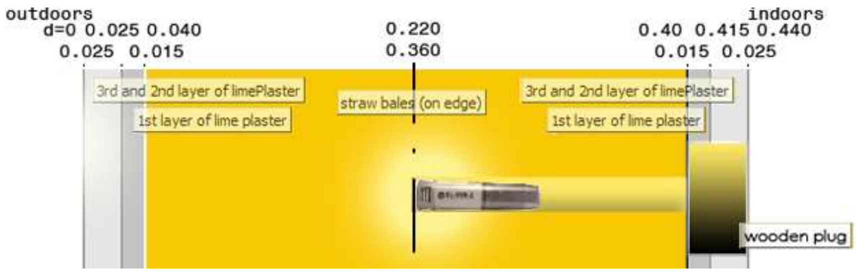


Figure 4.16: Section through the wall shows monitor placement.

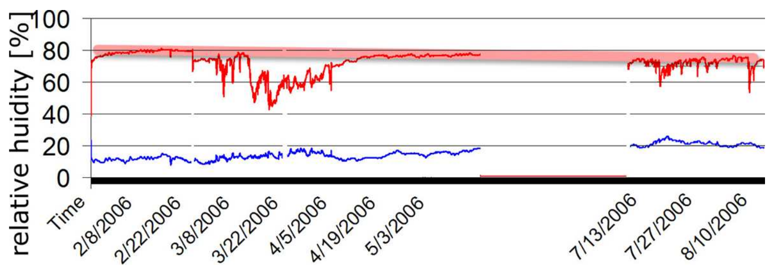


Figure 4.17: The graph shows relative humidity (**red** curve) and temperature (**blue** curve) development in the middle of the wall during the 8 months of monitoring. From February until March and from July until August the relative humidity readings are unstable because the monitor location was affected by air infiltration from the house's interior. The datalogging was interrupted from June 1st until July 9th 2006.

[4]For the monitor's accuracy see Appendix B.0.1. The monitor was calibrated (see Appendix D).

Presumably, just after the storm, the straw at the monitoring location was saturated and the relative humidity was 100%. According to fig. 4.17 relative humidity at the beginning of monitoring read 80% which means that during the first (unmonitored) 8 weeks after the storm, the straw in the wall managed to dry out considerably. 20% of relative humidity drop was probably caused by moisture redistribution in the straw within the volume of the wall. Otherwise, the drying seemed to be a very slow process. 8 months after the storm, the straw still shows 75% relative humidity. The thick pink line on fig. 4.17 indicates the average value of drying at about 1% of relative humidity per month.

During February, April and May, the plug covering the datalogger in the wall was sealed airtight by silicon sealant. That is why the relative humidity in the middle of the straw bale wall during those three months seems to be relatively stable. In February, March and then in July and August, the wall opening accommodating the monitor was loosely covered by a leaking cap. The swings in relative humidity thus most likely correspond to air infiltration of the monitor location from the interior environment (see fig.4.1.6).

The datalogging was interrupted from June 1st to July 9th 2006 (see fig. 4.17).

Condition of straw: January 25th, February 17th 2006

The first sample of straw fibre was taken on January 25th 2006 during the installation of the monitor. The straw taken from mid-wall-depth showed no sign of deterioration, although it was humid to the touch and smelled of mold.

Figure 4.18: February 17th 2006 (12 weeks after the damage). Both samples smelled strongly of mold. **On the left** is a sample taken approximately 50mm from the exterior plaster. The straw has large dark spots on the stems. The nodes are completely black. **On the right** is sample taken approximately 100mm from the exterior plaster. About half of the nodes are darkened. The stems have a healthy colour.

Other samples were taken on February 17th 2006 from the same location as the sample from January 25th- the cavity accommodating the monitor. The condition of the straw sample from mid-wall-depth had not changed since January 25th . It was humid, but looked healthy. Deeper into the wall towards the exterior, the straw gradually began to show signs of decay (see fig. 4.18).

The condition of straw next to the exterior plaster was particularly alarming. However, just a few centimeters deeper into the wall, the degradation of straw matter decreased significantly (see fig. 4.18).

Straw recovery

The measures for straw recovery taken by the owner were risky. Alarmed by the rotting straw just under the exterior plaster, Martin Oehlmann decided to enclose the walls from the outside. This precaution inhibited further wetting caused by the frequent driving rain of winter, but at the same time it certainly prevented the wall from drying (see figs. 4.17 and 4.19).

Figure 4.19: Straw bale house in Plozevet, Brittany, France. **On the left**—February 2006—The red arrow points at the approximate position of the monitor in the western wall. At the time of the storm, the monitored bale was approximately 400 mm above the ground (see fig. 4.14). **On the right**—July 2006—Since March 2006, the lime plastered house has been further protected from frequent storms by timber cladding. A storage shed was built at the place of the greatest damage. The shed created a space allowing for ventilation so that the wall covered by it could dry out more easily. At the same time, the shed and the timber cladding (although ventilated) prevented drying, which could have been considerably improved during spring and summer due to sun and wind exposure.

Condition of straw: September 20th 2006

On September 20th, 2006 the owner opened the exterior plaster at approximately the location of the monitor. Despite 10 months of exposure to the high relative humidity level of about 70%, the straw taken at mid-wall-depth looked healthy. At the depth of 100 mm from the exterior plaster, the straw showed almost no sign of decomposition except for a few darkened nodes. The straw next to the exterior plaster was black in places, but just a few centimeters deeper its condition improved significantly. All samples were humid, smelled of rot and showed no sign of having decomposed further (see fig. 4.20) since the last examination of straw condition in February 2006.

Figure 4.20: September 20th, 2006 (10 months after the damage). Both samples smelled of mold. **On the left** is a sample taken approximately 30mm from the exterior plaster. The black straw shows signs of decomposition. The nodes are completely black. **On the right** is a sample taken from mid-wall-depth. After 10 months in an environment with a high humidity level (above 70%) the straw is not visibly damaged.

Lime plaster failure

In Plozevet, lime plaster was mixed on site from the following ingredients:

- Local red sharp sand — well washed and well graded about 3—4mm.
- Hydraulic lime (hydraulique) Boehm, Natural NHL5.
- Hydrated lime (air-lime, airienne) Decochaux, St. Astier.
- Local water.

There is no difference between the interior and exterior plaster on the straw bale walls in Plozevet. They were made from the same mixes and applied identically:

First coat (closest to the straw):

July 14th 2005 — August 1st 2005.

Applied partially by spraying machine, partially by trowel and partially by hand.

1 lime (1/2 hydraulic, 1/2 hydrated) : 3 sand in a layer 10—20mm thick.

Second coat:

September 17th- 20th 2005.

Applied with a trowel after the first coat created a hard crust.

1 lime (hydrated) : 3 sand in a layer about 10—20mm thick.

Third coat:

October 1st-6th 2005
Applied by a trowel after the second coat created a hard crust.
1 lime (hydrated) : 3 sand in a layer about 3-5mm thick.

Simon Ayres, the director of Lime Green, the British lime producer who promotes healthy, breathable buildings, was interviewed for this article, as well as Barbara Jones of Amazon Nails, the UK's foremost straw bale building specialist, in order to give their expertise on Plozevet's lime plaster (see Appendix A.1 and A.4). While crumbling a sample of plaster from Plozevet in their hands, they both independently agreed that the plaster didn't go through enough carbonation to protect the straw from the driving rain.

For sufficient protection from driving rain, Jones suggests that the last coat of lime plaster needed to have a chance to carbonate for at least three months, but the duration varies according to the weather conditions. Ayres, who seems to know the rough weather at the coast of Brittany well, suggests that under those specific conditions the third coat of plaster made of (air, or hydrated) lime would need to carbonate for at least five months to give the straw sufficient protection from driving rain.

According to Ayres, the carbonation of lime is a chemical process that happens only in an environment with temperatures above 8°C. Since the completion of the exterior plaster on 6 October 2005 till the event of the storm on 1-2 December 2005, 2 months had elapsed. 16 days out of those 2 months had an average daily temperature below 8°C (Meteo, 2005), which means that the last protective layer of lime plaster was able to carbonate before the incident for only about 1 and a half months. Additionally, Ayres says that effective carbonation requires a moderate level of ambient humidity. In this case, the carbonation process was further slowed by frequent driving rain during November 2005 which kept the plaster soaking wet for long periods of time. Furthermore, temperatures in the middle of November 2005 were often below freezing (Meteo, 2005), causing serious plaster disintegration in places.

Jones has been lime plastering straw bale buildings in harsh climates such as Wales, Scotland and Ireland since the mid- nineties and all of those buildings seem to perform remarkably well. Amazon Nails use lime putty in their plaster mixes. However, Jones is not quite sure if the properly made and cured lime plaster itself would be able to withstand driving rain directly by the Atlantic ocean. In extreme cases, such as Plozevet, she would recommend giving the house additional protection from the wind by trees, or until trees grow, a natural screen of some sort.

Resume

On December 2nd, 2005 the straw throughout the whole wall section at the location of the monitor was saturated with water. Since then the interior of the house was regularly heated by wood stove to maintain a more or less stable temperature of about 16°C. The exterior of the west and north facing walls was exposed to further wetting by frequent wind driven rains until March 2006 when the house was protected by timber cladding.

The monitor at mid-wall-depth showed an almost constant relative humidity value of about 75% during the 8 months of monitoring. 10 months after the damaging storm, the straw at this exact location hadn't started to visibly deteriorate. This seems to prove the theory which suggests that straw in an environment with 75% sustained relative humidity is not able to provide sufficient water for microorganism growth.

Because of the driving rain that continued to wet the exterior plaster for another three months after the damage, the straw closer to the exterior of the wall sustained a much longer period of very high relative humidity. The straw just under the exterior plaster began to decompose. Apparently, the decomposition stopped after the exterior of the building had been clad in timber.

4.2.2 Case study II. Blanden, Belgium

Case study II. provided monitoring of moisture conditions in very simple wall assembly (earth plaster—straw—earth plaster) during winter 2005—2006. This survey was designed solely for the study of moisture transfer in straw bale walls discussed in the next three chapters. It will provide real data for comparison with the data obtained by mathematical models. This way the complicated theory behind moisture transfer in straw bale walls can be evaluated on the basis of practical experience.

The straw bale house in village of Blanden is fully exposed to the weather (see fig. 4.21). The majority of neighbouring houses are made of brick, have two stories and gable roofs.

Figure 4.21: Straw bale house in Blanden, Belgium. Photography by Herwig Van Soom.

Construction Details

Date of build
2001—2002

Self built and self designed by an architect. The house has 2 stories plus a large outdoor terrace under the roof. The majority of the interior is a double story living room. There is also a kitchen downstairs. All the bedrooms and one bathroom are upstairs.

Foundation
Trench concrete foundation with insulated slab. The first course of bales is about 100—200mm above ground.

Strucure
Round timber columns three stories high carry the 2nd floor, roof terrace and roof timber joists creating a load bearing timber frame construction. The straw bale walls were built as self bearing, independently of the timber frame. They were afterwards anchored to the frame by long screws for stability reasons. The southern wall is partially glazed, partially timber clad. Opaque areas are insulated by mineral wool. Mineral wool is also used as horizontal insulation under the roof terrace. There is a lightweight corrugated metal roof on top of the frame at the height of 9m above the ground.

Weatherproofing
The straw bale walls are earth plastered (outside and inside). Commercially produced earth plaster (CLAYTEC, Lehm Unterputz) was mixed with water and sprayed in three layers onto both sides of straw bales. The southern facade is protected by about 4m and the western facade by about a 3m roof overhang. East and north facades are left unprotected.

Heating
The house is heated by a warm air distribution system, which is supported by significant passive solar gain in winter.

Climate

The weather in Blanden is mild. The winds are broken by the surrounding buildings and according to the owner there are almost never northern or eastern winds blowing in this locality.

Average yearly temperature (Bruxelles)
9.8 °C (ISHS, 2005)
Average yearly precipitation (Bruxelles)
675 mm (ISHS, 2005)

Monitoring

5 x Lascar EL-USB-2 / humidity, temperature and dew point USB data logger[5] and were installed in the straw bale house in Blanden on December 6th 2005. The monitoring was carried out until 1 May 2006.

Figure 4.22: Relative humidity and temperature data inside the bathroom's external wall in the family house in Blanden were monitored by three dataloggers. #1 was placed in the straw just under the exterior earth plaster, #2 in the middle of the bale and #3 in the straw just under the interior earth plaster. 2 other dataloggers were placed externally. Monitor #4 in the interior of the bathroom and monitor #5 outside.

Internal monitors #1,2,3 were placed inside the wall in a hole drilled from the interior of the house's bathroom (see figs. 4.22 and 4.23 red arrow). The space between the internal monitors was tightly filled with straw and the opening was sealed with fresh earth plaster.

Figure 4.23: Monitors #1,2,and 3 fit into one channel that was drilled across the earth plastered exterior straw bale wall in bathroom of the family house in Blanden (see the **red** arrows). **On the right**, there is a view along the wall towards the ceiling. Monitor #4 was placed directly under the ceiling (see the **yellow** arrow).

Monitors #4 and #5 were positioned externally. Monitor #4 measured interior conditions just under the ceiling in the bathroom (see fig. 4.23 yellow arrow) and monitor #5 provided exterior data.

[5]For monitors' accuracy see Appendix B.0.1. All monitors were calibrated (see Appendix D).

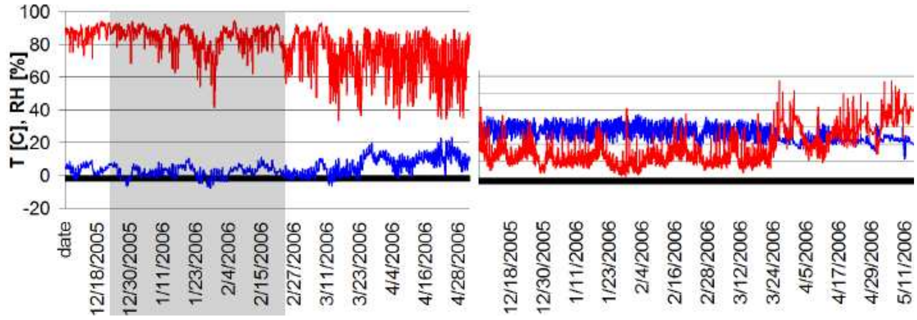


Figure 4.24: Relative humidity (**red colour**) and temperature (**blue colour**) data were measured by outdoor monitor #5 (**on the left**) and monitor #4 placed inside the bathroom (**on the right**) in Blanden, Belgium. **Grey colour** indicates the time period of 60 days (from 24 December to 24 February) chosen for averaging the values of RH and T according to BS 5250 (1995) (see the next Chapter).

In this case, the straw bale wall has to bridge temperature and relative humidity differences that occur between the bathroom environment (see fig. 4.24 on the right) and the winter environment outdoors (fig. 4.24 on the left).

Horizontal distribution of humidity in the straw bale wall

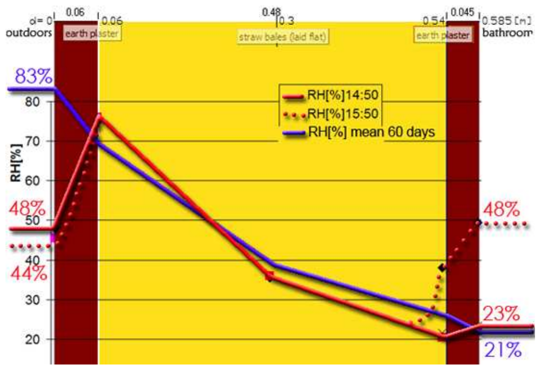


Figure 4.25: Measurements in the exterior bathroom wall in Blanden.The **red continuous line** demonstrates the relative humidity measured January 29th at 14:50. The **Red dotted line** indicates the change in relative humidity throughout the wall, after the window was open, one hour later at 15:50. The **Blue curve** represents the mean values of relative humidity over 60 winter days (from December 24th to February 24th).

Fig. 4.24 shows how at each moment, the straw bale wall bridges dynamically changing relative humidity and temperature.

The red curves on fig. 4.25 capture two snapshots when, in the course of one hour, interior relative humidity changed from 23% to 48% due to the open window and exterior relative humidity dropped from 48% to 44%. The blue curve on fig. 4.25 represents the mean values measured over 60 winter days (calculated from 24 December till 24 February). The juxtaposition of the mean 60 day values with the immediate measurements indicates that the variations of relative humidity within the straw portion of a wall are minimal. The dynamic changes (daily fluctuations) of ambient relative humidity are registered mainly within the interior and exterior earth plaster (see fig. 4.25).

Resume:

After being part of the wall for 5 years, the straw samples taken out during monitor placement were found to be completely dry, healthy, with a fresh smell. Although the wall is facing the interior of the bathroom, relative humidity throughout the wall turned out to be surprisingly low (especially close to the interior) due to the low levels of interior relative humidity (see fig. 4.24). Low relative humidity in the bathroom during winter was caused by relatively high interior temperature sometimes reaching over 30°C.

4.3 Summary of Chapter 4

The summary of the monitoring investigated by this thesis can be found in Appendix B.0.3. Out of all the cases available for this research (see Section 4.1), the most frequent cause of unacceptable moisture content levels in straw bale walls (close to 100% of relative humidity of air surrounding straw) was wind driven rain—seven cases. In one case the unacceptable moisture content levels were caused by sustained high ambient relative humidity.

Even though wind driven rain raises moisture levels in straw bale walls relatively quickly, the straw often manages to dry out without imposing any serious damage. The actual decomposition of straw caused by wind driven rain was recorded only in two cases. Serious decay of straw was caused by rising damp in three cases and in one case by a leaking window sill. All of this damage could have been avoided by proper design and careful execution.

One of the two case studies monitored exclusively for the purpose of this thesis, case study I. (see Section 4.2.1), showed how easily proper protection of straw bale walls could be underestimated. It provided straw samples in order to demonstrate that despite 10 months in an environment with sustained high relative humidity (above 75%), the great majority of straw in the wall didn't start to visibly mould.

The other case study, case study II. (see Section 4.2.2) provided useful data to support the research in next chapters concerning a theory of moisture transfer in a straw bale wall.

Chapter 5

Moisture transfer in a straw bale wall, steady state calculation

Previous chapters considered the theory and practice of straw degradation in a wall in some detail. They examined the moisture requirements for mold growth and relative humidity as its main indicator. Analyzes of case studies revealed that the risk of water penetration within a straw bale wall can in each case be minimized by proper design and careful execution. However, another concern of this thesis is the evaluation of moisture behaviour within different straw bale wall assemblies in different conditions by mathematical model. Therefore, it is necessary to introduce the main principles of mathematics behind moisture transfer in straw bale walls.

> "Moisture transfer in porous media involves a complex interaction of different transport mechanisms, their driving forces, and the effects of available capacity and possible temperature gradients" (Pheukuri, p. 17, 2003).

While the next Chapter will consider all the possible influences on moisture transfer using an accurate mathematical model, it will be beneficial to start with a simple analogy. This Chapter focuses on only one of the aspects of the moisture transfer mechanism through a wall: on water vapour diffusion with water vapour pressure as its driving force.

Even though scientists doubt that the water vapour by itself has any major significance in the moisture transition through a building envelope (Padfield, 1998), a mathematical model for the prediction of water vapour condensation in a wall has been widely adopted by norms and standards all over the world.

For example, the British standard BS 5250 (1995)[1], European norm EN 13788 (2002), German standard DIN 4108, as well as CIBSE (1999)[2] recommend testing external building envelopes for condensation due to water vapour movement using a simplistic theoretical model developed in the 1950's in Germany by H. Glaser (Sanders, 2005). His model is based on the assumption that condensation inside a wall occurs where the value of calculated water vapor pressure within a wall reaches its saturation level.

Glaser's mathematical model will serve as an introduction to the theory under investigation.

5.1 Principle of Glaser's model; Introduction to the theory of moisture transfer

Mathematical (or theoretical) models are based on mathematical theory and physics. They are equations describing certain natural phenomenon. The creator of the model, who forms the equations, decides what factors are relevant to the problem, observes their mutual relationship and describes it in mathematical language. It is an evolving process. Once a model answers a given question, it should be critically examined. If the model doesn't reflect the observed reality of the phenomenon with satisfactory accuracy, the equations are modified.

> "Generally the success of a model depends on how easily it can be used and how accurate are its predictions." (Edwards & Hamson, 1990)

The success of Glaser's model resides in its simplicity. The model assumes that buildings are enclosures that behave like sealed boxes (see the experiment described in Section 3.3). A source of water (e.g. bathroom, kitchen, laundry room) inside of such an enclosure generates water vapour molecules in the air. Free water vapour molecules exert pressure on the interior of a building envelope. There is a water vapour pressure on the envelope from the outside as well. However, due to the differing climate conditions outdoors, water vapour pressures on each side of a wall differ. This difference is called the water vapour pressure gradient and results in a flow of water vapour across the external wall.

The flow of water vapour molecules happens only through a building envelope that is made of *permeable* materials. In wall assemblies containing a continuous layer of *non permeable* material, like plastic, metal or glass, the exchange of water vapour between the interior and exterior of a building doesn't happen. Nonetheless, porous *hygroscopic* materials are *permeable* and the water vapour migrating through their volumes is prone to condensation.

Water vapour gradually condenses in the pores of *hygroscopic* material with increasing relative humidity due to capillary condensation, as was described in Chapter 3. Glaser's model doesn't consider capillary condensation. It simply

[1] Code of practice for control of condensation in buildings

[2] Guide A - Environmental Design

expects that a permeable material remains completely dry until dew point condition is reached somewhere within a material (for an explanation of dew point condition, see Section 3.4).

Besides water vapour flow across building envelope, Glaser's model allows for a flow of thermal energy. The difference between the temperature outside and inside of a building (temperature gradient) drives heat from the warmer side to the colder side of a wall. Let's assume that in winter, in a *heating climate*, the interior surface of an external wall is gaining heat. As the *permeable* material of that wall cools towards the cold exterior, the material (which, according to Glaser's model, is still completely dry) might at a certain point become cold enough to cause water vapour to condense within a wall. It is only at this point and at that exact place that Glaser's model considers a permeable material wet (100% relative humidity). This type of condensation is known as interstitial condensation.

The purpose of Glaser's model is to predict the long term build-up of interstitial condensation (CIBSE, 1999). Architects and engineers usually use it at the design stage of a building, particularly when choosing the materials to be used in the building's envelope. The prediction of interstitial condensation based on Glaser's method often determines the feasibility of external walls in future houses. It is a widely used tool and therefore useful to question its accuracy and relevance.

5.2 Designing straw bale walls in Blanden; Prediction of interstitial condensation build up using Glaser's model

This Section uses a calculation based on Glaser's model for the prediction of interstitial condensation in external walls in the way that designers and architects are advised to use it by British Standard BS 5250 (1995) and CIBSE, Guide A (1999)[3]. The temperature and relative humidity monitoring that was done for this thesis inside the existing external straw bale wall of the bathroom in the family house in Blanden, Belgium (see case study II., Section 4.2.2), gives the following calculation a point of reference.

At first the prediction will be made as though the house in Blanden hasn't been built yet and is still in the design stage. Later the model's results will be compared with real monitored data. This way, Glaser's model will not only provide a good exercise that leads to a better understanding of moisture transfer through a wall, but the juxtaposition of its results with the data and measurements of the existing wall in the occupied building will give a clear picture of model's accuracy.

[3]The author used CIBSE, Guide A (1999) - Environmental Design - as a guideline for the following calculation. However, CIBSE refers to BS 5250.

5.2.1 Design input data

As input data, Glaser's model requires values defining conditions inside and outside of the wall as well as values that characterize the materials of the wall assembly under investigation.

Outside and inside design conditions

To obtain accurate results, the right calculation input is crucial . This especially applies to Glaser's model, because its input of outside and inside design conditions requires a great deal of intuition. The problem is that Glaser's model counts on a "steady state" environment. In order to keep it simple, the calculation only considers a case where relative humidity and temperature remain unchanged on both sides of a wall - steady, whereas in real life, indoor and outdoor conditions vary on a diurnal basis (see fig. 5.1).

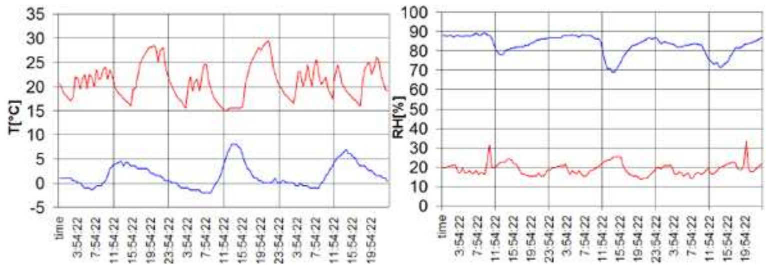


Figure 5.1: 3 days (from January 8th to 10th 2006) show swings of temperature **(on the left)** and relative humidity **(on the right)** on a diurnal basis. **Red** indicates conditions inside of the bathroom and **blue** the conditions outdoors. The data represent a small sample of the data collected for this thesis over winter 2005-2006 in Blanden, Belgium (see case study II., Section 4.2.2).

As for outside and inside conditions, the steady state model requires just four values, one value of relative humidity and one of temperature for each side of a wall. They should be chosen with consideration for potential interstitial condensation. For the reasons mentioned earlier in Section 5.1, the highest probability of interstitial condensation within a building envelope in a *heating climate* is in winter. The fig. 5.1 shows monitoring over 3 winter days in Blanden, Belgium in the exterior and interior of a bathroom in an occupied family house (see case study II. Section 4.2.2). The relevant question is:

> *What single temperature and relative humidity value best represent reality?*

The British Standard BS 5250 (1995) suggests using the average values that pertain in winter for a 60-day period as the outside design conditions.

$$2°C, 83\% \text{ RH}$$

are the average values of relative humidity and temperature measured in Blanden (see case study II., the grey area on fig. 4.24) over a 60 day period from December 24th to February 24th. They were chosen to represent winter 2005 - 2006 for the following calculation of interstitial condensation prediction.

Inside design conditions can't be measured if the house isn't yet built.

These values need to be estimated. British Standard BS 5250 (1995) suggests following indoor, bathroom (referred to by British Standard as *moist-wet occupancy*), design conditions:

$$15°C, 85\% \text{ RH}.$$

Summary of design conditions:

conditions	T [°C]	RH [%]	$\Longrightarrow$	vapour pressure[a] [Pa]
outside	2	83	$\Longrightarrow$	589
inside	15	85	$\Longrightarrow$	1440

[a]From CIBSE (2001) Guide C

Table 5.1: Outdoor and indoor design conditions to be used in the model.

The "design" temperature gradient across the wall in Blanden is 15 - 2 = 13°C and the "design" vapour pressure gradient is 1440 - 589 = 851 Pa. It will drive the water vapour from the interior towards the exterior.

Characteristics of materials in the wall assembly under investigation

Besides indoor and outdoor design conditions, Glaser's model requires data specifying the materials of the wall assembly, in particular their resistance to heat flow and water vapour flow. These values are specific for each material and can be obtained from information provided by the manufacturer or from various brochures and tables for civil engineers (for example from CIBSE (1999) Guide A).

An obvious analogy exists between heat flow and water vapour flow, suggesting that both phenomena are based on the same principle.

Under steady state conditions:

the rate of heat transfer per unit area of a material is:

$$\Phi = \frac{\Delta t_s}{R} \tag{5.1}$$

the rate of water vapour transfer per unit area of a material is:

$$q_m = \frac{\Delta p_v}{G} \tag{5.2}$$

, where Φ is *heat transfer rate* per unit area [W·m^{-2}], Δt_s is the *temperature gradient* [°C] and R is the *thermal resistance* [m^2·K·W^{-1}]

The *thermal resistance* is defined as:

$$R = \frac{d}{\lambda} \quad (5.3)$$

, where λ is the materials ***thermal conductivity*** [W·m^{-1}·K^{-1}] and d is the thickness of the material (CIBSE, 2001).

, where q_m is *water vapour transfer rate* per unit area [kg·m^{-2}·s^{-1}], Δp_v is the *vapour pressure gradient* [Pa] and G is the *vapour resistance* [N·s·kg^{-1}]

The *vapour resistance* is defined as:

$$G = \frac{d}{\delta} \quad (5.4)$$

, where δ is the materials ***vapour permeability*** [kg·m·N^{-1}·s^{-1}] and d is the thickness of the material (CIBSE, 1999).

The vast majority of sources agree that a material's resistance to heat flow represents *thermal conductivity*. However, the resistance to water vapour flow is expressed differently by different sources. Respectively as: *vapour permeability*, *vapour resistivity*, *water vapour diffusion coefficient*, or *water vapour diffusion-equivalent to air layer thickness*. A brief overview of these parameters and the units commonly used to specify a material's resistance to heat flow and water vapour flow is provided by table 5.2.

material's characteristic	parameter	symbol	unit
resistance to heat flow	*thermal conductivity*	λ	[W·m^{-1}·K^{-1}]
resistance to water vapor flow	*vapour resistivity*	r	[GN·s·kg^{-1}·m^{-1}][a]
	vapour permeability	δ	[kg·Pa^{-1}·m^{-1}·s^{-1}][b]
	water vapour diffusion coefficient	μ	[-]
	water vapour diffusion-equivalent to air layer thickness	s_d	[m]

[a]some sources use [MN·s·g^{-1}·m^{-1}] = [GN·s·kg^{-1}·m^{-1}]
[b]some sources use [kg·m·N^{-1}·s^{-1}] = [kg·Pa^{-1}·m^{-1}·s^{-1}]

Table 5.2: Parameters and the units commonly used to specify a material's resistance to heat flow and water vapour flow.

All of the different parameters indicating a material's water vapour resistance basically express the same value. The basic definitions are discussed in the following text:

Reciprocal value to *vapour permeability* (δ) [kg·m·N^{-1}·s^{-1}] (see 5.4) is ***vapour resistivity*** (r) [GN·s·kg^{-1}·m^{-1}]:

$$r = \frac{1}{\delta \ * \ 1\ 000\ 000\ 000} \tag{5.5}$$

Vapour diffusion coefficient (μ) [-] indicates how much less *vapour permeable* is the layer of a material in comparison to the layer of air with the same thickness:

$$\mu = \frac{\delta_{air}}{\delta_{material}} \tag{5.6}$$

, where $\delta_{air} = 1.884{\cdot}10^{-10}$ kg·Pa^{-1}·m^{-1}·s^{-1} at T = 5°C and at ambient atmospheric pressure of 101.325 kPa (Tywoniak and Kulhanek, 1995).

The great advantage of *vapour diffusion coefficient* μ is its temperature independence. In general, vapour permeability δ is dependent on temperature. While both, δ_{air} and $\delta_{material}$ change proportionately with temperature, μ remains constant.

Water vapour diffusion-equivalent to air layer thickness (s_d) [m] quantifies (for comparison's sake), the thickness of motionless air layer that has equivalent μ to μ of given material ($\mu_{air} = \mu_{material}$):

$$s_d = \mu * d \tag{5.7}$$

, where d [m] is thickness of material and μ [-] is materials *vapour diffusion coefficient* (Tywoniak and Kulhanek, 1995; Time and Uvslokk, 2003).

s_d is also temperature independent.

A more detailed explanation of these expressions and terms is given in EN ISO12572:2001 (Time and Uvsløkk, 2003).

Following Glaser's model, a calculation based on BS 5250 (1996) will use *vapour resistivity* (r) [GN·s·kg^{-1}·m^{-1}] as the parameter defining resistance to water vapour flow[4].

[4]However, the computer simulation model explored in the next Chapter requires a *vapour diffusion coefficient* (μ) [-].

Wall assembly

Figure 5.2: Section through the external bathroom straw bale wall in Blanden (see case study II., Section 4.2.2). The straw bales are laid flat $\Longrightarrow$ the heat and water vapour flow are parallel to the straw fibre. A commercially produced earth plaster (CLAYTEC, Lehm Unterputz) was mixed with water and sprayed in three layers onto both sides of the straw bales.

The material characteristics of the straw bale wall assembly in Blanden (see fig. 5.2) required for Glaser's model are presented in table 5.3. The values were taken from Appendix B.0.2.

element	thick-ness d [mm]	thermal conductivity λ [W·m^{-1}·K^{-1}]	vapour resistivity r [GN·s·kg^{-1}·m^{-1}]	thermal resistance R [m^2·K·W^{-1}]	vapour resistance G [GN·s· kg^{-1}]
internal surface	—	—	—	0.12	0
earth plaster	60	0.83	53.1	0.072	3.186
straw bale	480	0.085[a]	13.3	5.65	6.38
earth plaster	45	0.83	53.1	0.054	2.39
external surface	—	—	—	0.06	0

[a]According to independent research on the thermal conductivity of straw, when heat flow is parallel to straw fibre, $\lambda_{\ straw\ parallel}$ = 0.05 - 0.082 W·m^{-1}·K^{-1} (Andersen, 2004). However, testing on the plastered wall proved that over the whole wall section, plastered straw bales show considerably lower thermal resistance which corresponds to $\lambda_{\ straw\ parallel}$ = 0.085 W·m^{-1}·K^{-1}. The reason is unknown. There is some speculation that the convection currents in gaps within a straw bale wall effect its thermal resistance, as does the unclear boundary between the straw and plaster (Andersen, 2004).

Table 5.3: External bathroom straw bale wall in Blanden. Materials and their characteristics used as input in Glaser's model.

5.2.2 Calculation of interstitial condensation using design conditions

Once both temperature and water vapour gradients across a wall structure are known, as well as *vapour* and *thermal resistance* of all of the wall's elements (layers), any intermediate value of vapour pressure, or temperature can be easily calculated.

In this calculation, the construction is represented as number of resistances in a series with fixed points at each end (on one end inside design conditions, and on the other end outside design conditions).

$$t_1 - \boxed{R_1} - t_2 - \boxed{R_2} - t_3 - \boxed{R_3} - t_4 \cdots t_{n-1} - \boxed{R_{n-1}} - t_n$$

$$p_{v1} - \boxed{G_1} - p_{v2} - \boxed{G_2} - p_{v3} - \boxed{G_3} - p_{v4} \cdots p_{v(n-1)} - \boxed{G_{n-1}} - p_{vn}$$

The temperature and water vapour pressure at each contact area between two layers of different materials (at the connecting line), can be calculated by:

$$t_j = t_1 + \frac{(t_n - t_1)\sum_{i=1}^{j-i} R_i}{\sum_{i=1}^{n} R_i} \qquad (5.8)$$

$$p_{vj} = p_{v1} + \frac{(p_{vn} - p_{v1})\sum_{i=1}^{j-i} G_i}{\sum_{i=1}^{n} G_i} \qquad (5.9)$$

, where t_j is the temperature of the contact area j [°C], R_i is the thermal resistance across the layer i [m^2·K·W^{-1}], p_{vj} is the vapour pressure at the contact area j [Pa] and G_i is the vapour resistance across the layer [N·s·kg^{-1}].

Saturated vapour pressure p_{svj} corresponding to the calculated temperature t_j of the connecting line j, is obtained from a psychrometric chart (see Appendix PsychrometricChart), or CIBSE (2001) Guide C.

If the saturation vapour pressure value is higher than the value of calculated vapor pressure at the j contact area

$$p_{svj} > p_{vj} \qquad (5.10)$$

, there is no interstitial condensation in that area.

If the calculated vapour pressure at the j contact area equals or exceeds saturated vapour pressure at that area, there is interstitial condensation occurance:

$$p_{svj} \leq p_{vj} \qquad (5.11)$$

In reality, water vapour pressure can't reach a higher value than saturated vapor pressure (see Section 3.2). In case of interstitial condensation occurrence, the j connecting line is assumed to be saturated. The construction must at that point be divided into two subconstructions, with saturated vapour pressure and calculated temperature at that point as design conditions for a new calculation.

Blanden - design conditions; Calculation of interstitial condensation occurrence

The following diagrams summarize input data that were specified in Section 5.2.1:

outside — surface — plaster — straw — plaster — surface — inside

2°C — 0.12 — 0.072 — 5.65 — 0.054 — 0.06 — 15°C

589 Pa — 0 — 3.186 — 6.38 — 2.39 — 0 — 1440 Pa

For example, the temperature between straw and plaster towards the outside of the building according to 5.8 will be:

$$t_{\ straw/plaster} = 2 + \frac{[15-2]*[0.12+0.072]}{0.12+0.072+5.65+0.054+0.06} = 2.42\ ^{\circ}C$$

and vapour pressure according to 5.9:

$$p_{v\ straw/plaster} = 589 + \frac{[1440-589]*[0+3.186]}{0+3.186+6.38+2.39+0} = 816\ Pa$$

Calculation results in each contact area, including comparisons of partial water vapour pressures with saturated water vapour pressures for interstitial condensation occurrence are presented in the following table:

contact area or connecting line	location of connecting line	temperature t_j [°C]	vapour pressure p_{vj} [Pa]	saturation vapour pressure[a] p_{svj} [Pa]	condensation
1 outside	—	2	589	706	no
2	surface/plaster	2.26	589	718	no
3	plaster/straw	2.42	816	727	**yes**
4	straw/plaster	14.75	1269	1670	no
5	plaster/surface	14.86	1440	1696	no
6 inside	—	15	1440	1704	no

[a]From Appendix C.2, or from CIBSE (2001) Guide C - vapour pressure adequate to corresponding temperature and 100% RH.

The calculation predicts condensation between the straw and the outer layer of earth plaster. In order to find out if this is the only point of interstitial condensation occurrence, it is necessary to divide the construction into two subconstructions in the saturated contact area, where partial water vapour pressure (above the saturated one) is replaced by saturated water vapour pressure:

a)

$$589\text{ Pa} - \boxed{0} - \boxed{3.186} - 727\text{ Pa}$$

b)

$$727\text{ Pa} - \boxed{6.38} - \boxed{2.39} - \boxed{0} - 1440\text{ Pa}$$

and calculate again:

contact area or connecting line	location of connecting line	temperature t_j [°C]	vapour pressure p_{vj} [Pa]	saturation vapour pressure[a] p_{svj} [Pa]	condensation
subconstruction a)					
1 outside	—	2	589	706	no
2	surface/plaster	2.26	589	718	no
3	(fixed point)	2.42	727	727	**yes**
subconstruction b)					
3	(fixed point)	2.42	727	727	**yes**
4	straw/plaster	14.75	1245	1670	no
5	plaster/surface	14.83	1440	1696	no
6 inside	—	15	1440	1704	no

[a]From Appendix C.2, or from CIBSE (2001) Guide C - vapour pressure adequate to corresponding temperature and 100% RH.

No other saturated contact areas were detected.

The following calculation predicts the amount of moisture buildup in the location of the interstitial condensation occurance.

Blanden - design conditions; Calculation of interstitial condensation buildup

The amount of condensation in subconstruction a) can be determined from equation H.2:

$$q_{m_a} = \frac{727 - 589}{3.186 * 10^9} =$$

$$= 43.3 * 10^{-9} \ kg \cdot m^{-2} \cdot s^{-1}$$

and similarly the amount of condensation in subconstruction b):

$$q_{m_b} = \frac{1440 - 727}{(6.38 + 2.39) * 10^9} =$$

$$= 81.3 * 10^{-9} \ kg \cdot m^{-2} \cdot s^{-1}$$

The rate of condensation is the difference between the moisture flowing from the inside to the contact area q_{m_b} and the moisture flowing from the contact area to the outside q_{m_a}:

$$q_m = q_{m_b} - q_{m_a} =$$

$$= (81.3 - 43.3) * 10^{-9} = 38 * 10^{-9} \ kg \cdot m^{-2} \cdot s^{-1} =$$
$$= 0.14 \ \ g \cdot m^{-2} \cdot h^{-1}$$

The question that suggests itself at this point is:

Does the moisture accumulated in winter due to interstitial condensation have a chance to dry out over the summer?

5.2.3 Calculation of drying in summer using design conditions

The calculation of evaporation (summer drying) is equivalent to calculation of interstitial condensation (see 5.2.2). The only difference is in the input data, respectively, the calculation of evaporation uses summer exterior design conditions.

Blanden - design conditions; Calculation of evaporation

Monitored summer conditions in Blanden are not available . Therefore, the BS6229 (2002) recommends including the estimated average outside summer design conditions in the calculation described above:

$$18^{\circ}\mathrm{C},\ 65\%\ \mathrm{RH}.$$

and calculate the rate of evaporation. If the amount of condensation doesn't exceed amount of evaporated water, the prediction considers the building structure to be convenient.

Calculation of the rate of evaporation q_e is analogous to calculation of condensation build up (see Section 5.2.2) and can be found in Appendix G.0.4.

5.2.4 Summary of results

condensation rate	+0.14	$g \cdot m^{-2} \cdot h^{-1}$
evaporation rate	-1	$g \cdot m^{-2} \cdot h^{-1}$

The evaporation rate over the summer is more than 7 times greater than the winter condensation rate. Over the year there shouldn't be any moisture gain between the straw and outside earth plaster of the straw bale wall under investigation.

5.2.5 Straw bale wall in Blanden; prediction's accuracy

Even though Glaser's model showed that winter condensation would sufficiently evaporate over summer, it predicted that in winter, condensation would continue to deposit 0.14 g of moisture in every 1m^2 of surface area every hour, between the straw and external earth plaster.

Let's compare the model's output with reality. That is to say, with the actual data measured inside of the existing bathroom wall in Blanden. The relevant data was provided by monitor #1 (see case study II.,Section 4.2.2), which was placed directly in the area of predicted condensation occurrence: in the straw just under the exterior plaster.

According to the prediction (see Section 5.2.4) it was expected that the datalogger would often measure, in that particular place, relative humidity of 100% which corresponds to saturation or, in other words, to liquid moisture occurrence, or occurrence of condensation. Fig. 5.3 shows that in reality the relative humidity in this area never reached 100%.

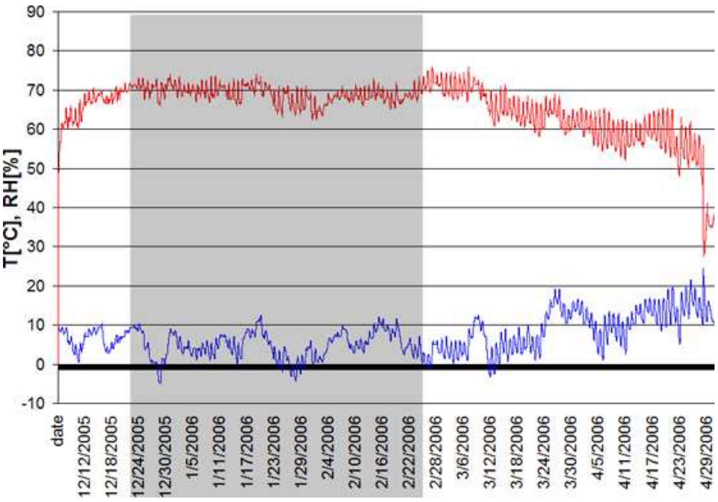


Figure 5.3: December 6th, 2005 - May 1st, 2006. Monitor#1 (see case study II., Section 4.2.2) was placed in the exterior wall adjacent to the bathroom of the family house in Blanden, in the straw just under the exterior plaster. It was decided that December 24th, 2005 - February 24th 2006 (grey area) would represent winter conditions over which average values would be calculated (see Section 5.2.1). **Red**—relative humidity, **blue**—temperature.

The average winter relative humidity over the 60 day period measured by the datalogger under the exterior plaster was:

$$69\% \text{ (see fig. 5.3).}$$

The maximum monitored relative humidity over the whole winter 2005-2006 peaked at:

$$76\% \text{ (see fig. 5.3).}$$

In reality, the interstitial condensation in the critical area between the straw and exterior earth plaster never happened. So why did Glaser's model predict it?

In order to answer this question, it is necessary to consider the relevance of the design's estimated input data.

Accuracy of design's estimated input data

The outside design conditions used as input for the prediction were based on real monitoring in Blanden over the winter. There can be no doubt about the accuracy of these data.

On the other hand, inside design conditions were estimated. Following the recommendations of the British Standard BS 5250 (1995), the prediction counted on average values of:

$$15°C, 85\% \text{ RH. (see Section 5.2.1)}$$

How does this estimation compare to the conditions in the real bathroom of the occupied house in Blanden?

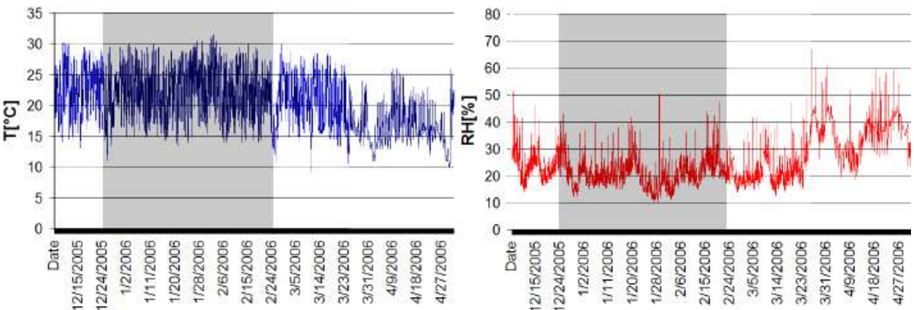


Figure 5.4: December 6th, 2005 - May 1st, 2006 in the interior (bathroom) of the family house in Blanden. The grey area shows a 60 day period (December 24, 2005 - February 24, 2006) over which real average winter inside conditions were calculated. **Red**—relative humidity, **blue**—temperature.

According to the datalogger placed in the interior (bathroom) of Blanden house (see fig. 5.4), the average winter indoor conditions over the 60 day period are:

$$22°C, 21\% \text{ RH.}$$

There is a large discrepancy between indoor design conditions based on estimation by the BS 5250 (1995) and the real conditions measured in the bathroom of an occupied straw bale house.

The mean internal relative humidity value of 21% is a very low value for a bathroom environment. A closer look around the bathroom in the straw bale house in Blanden reveals the reason for this. It was achieved due to a high mean internal temperature that kept the bathroom at around 22°C most of the time. The entire house is heated by warm air and a large diameter, main heat distribution pipe leads through this bathroom. In the evenings, this pipe heats the air up to 30°C (see fig. 5.1) and prevents high relative humidity levels. Another factor that presumably cuts down the water vapour concentration is the earth plastered straw bale walls, which have considerable water vapour absorption capacity (Padfield, 1998).

In comparison to the prediction, the reality is more favourable in terms of interstitial condensation occurrence. Due to low readings of interior relative humidity, the actual moisture levels inside the wall will be much lower than predicted, making the prediction in this case unreasonably overestimated.

Before looking at the general limitations that the prediction based on Glaser's model has in practice, it is useful to apply Glaser's model to the same wall, but this time with accurate, real input data.

5.3 Straw bale wall in Blanden; Benchmarking of Glaser's model

In this Section, Glaser's model will calculate the condensation occurrence in the straw bale wall using the same procedure as in Section 5.2.2. The only difference is that this time, the calculation will be based on real interior bathroom conditions.

5.3.1 Real input data

The average indoor conditions in the bathroom in Blanden are:

22°C, 21% RH (see Section 5.2.5).

Real outdoor winter conditions in Blanden remain the same as in the calculation with design conditions:

2°C, 83% RH (see Section 5.2.1).

By aligning the model's input with real measured data, it will be possible to compare calculation results in each intermediate layer of the straw bale wall assembly with adequate monitoring, and thus assess the calculation's accuracy.

5.3.2 Calculation of interstitial condensation using real conditions

Calculation of interstitial condensation occurrence in the straw bale wall in Blanden based on real data can be found in Appendix G.0.5

5.3.3 Summary of results

The calculation based on real conditions didn't indicate interstitial condensation occurrence in the straw bale wall in Blanden.

Besides the two external monitors monitoring outside and inside (bathroom) conditions in Blanden, three monitors (#1,2,3) were internal. They were buried inside the straw bale wall (see case study II., Section 4.2.2).

While comparing the calculation results of Glaser's model from Appendix G.0.5 with the output from the internal monitors (considered as a mean value over 60 winter days of monitoring, see Section 4.2.2), the accuracy of model becomes apparent (see table 5.4 and fig. 5.5).

		calculated				measured		
contact area	d[a] [m]	T [°C]	P_v [Pa]	$\Longrightarrow$	RH[b] [%]	data logger	T [°C]	RH [%]
outside	0	2.0	565	$\Longrightarrow$	83	5	2.0	83
plaster/straw	0.06	2.6	570	$\Longrightarrow$	81	1	4.7	69
middle of bale	0.3	12.2[c]	576[d]	$\Longrightarrow$	53.5	2	14.6	38.4
straw/plaster	0.54	21.8	582	$\Longrightarrow$	26	3	22.2	25.4
inside	0.585	22.0	589	$\Longrightarrow$	21	4	22.0	21

[a]distance from surface of exterior plaster

[b]from Appendix C.2, or from CIBSE (2001) Guide C - vapour pressure adequate to corresponding temperature gives RH.

[c]linear relation: $\frac{21.8-2.6}{2} + 2.6 = 12.2$

[d]linear relation: $\frac{582-570}{2} + 570 = 576$

Table 5.4: The comparison between the calculated results of Glaser's model (from Appendix G.0.5) and the real monitored data from all five monitors. The data from monitors were used as average values over 60 winter days of measuring (from December 24th to February 24th, 2006).

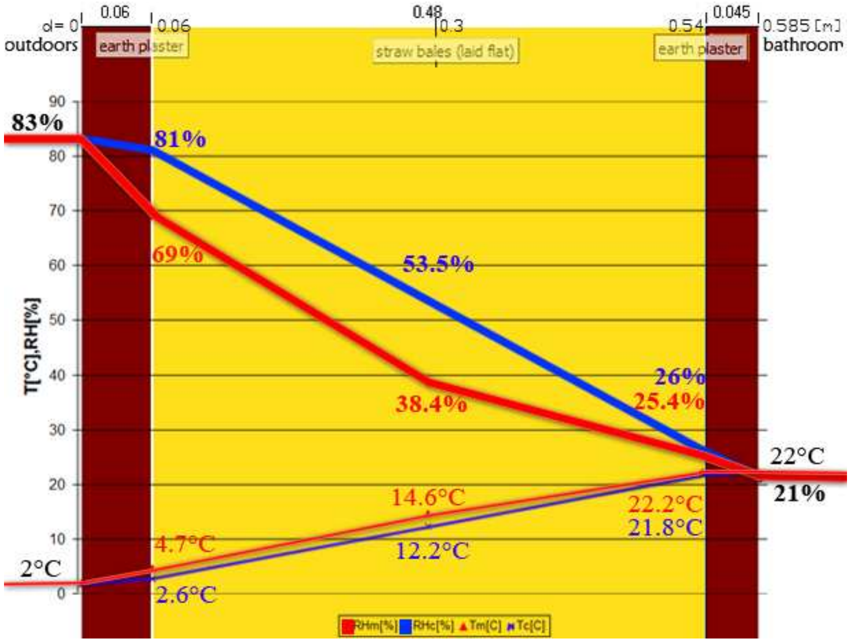


Figure 5.5: Relative humidity (graph **above**) and temperature (graph **below**) distribution across the straw bale wall in Blanden as monitored by dataloggers (**Red**, RH_m, T_m) in comparison to the results of Glaser's model (**blue**, RH_c, T_c).

Whereas Glaser's model simulating heat flow through the wall is quite accurate (see the temperature distribution through the wall on the lower graph on fig. 5.5), the model indicating water vapour flow doesn't match reality with satisfactory precision (see the upper graph on fig. 5.5).

The relative humidity calculated by Glaser's model (see the upper blue curve on fig. 5.5) refers to the relative humidity of humid air diffusing through completely dry material. This doesn't actually happen. The humid air constantly interacts with the hygroscopic material due to the material's adsorption and capillary condensation (see Chapter 3). The real, monitored, relative humidity (see the upper red curve on fig. 5.5) corresponds to equilibria between humid air and moist material. The distribution of moisture in the straw is in fact far from being linear, as Glaser's model suggests. Straw gets exponentially more wet the closer it gets to the exterior, but it never develops enough moisture content to threaten significant decomposition (see Chapter 2). The exterior part of the bale remains reasonably dry. The moisture performance of exterior earth plaster makes an interesting point. In compliance with the observations of Padfield (2002), the real measured data show that 60 mm of exterior earth plaster functions as an excellent humidity buffer, capable of keeping the exterior face of the straw bales 12% less humid than anticipated by the model.

5.4 Limitations of the steady state calculation using Glaser's model

In reality, moisture transfer consists not only of vapour diffusion, but of liquid water transfer as well.

Glaser's model counts solely on vapour diffusion, with vapour pressure gradient as its driving potential. Water vapour pressure is a driving potential of vapour diffusion only in isothermal conditions (when the ambient temperatures are equal on both sides of a wall). In reality, the ambient conditions affecting a building envelope are rarely isothermal and the process driving the water vapour through the wall becomes more complex (Ficker, 2003).

The major limitation of Glaser's model lies in the assumption that *vapour resistivity*, δ always stays constant throughout the wall component. In fact δ value changes with temperature (Ficker, 2003), with relative humidity or moisture content (Vinha et al., 2002), with direction of driving potentials and with their mutual interaction (Peuhkuri et al., 2003).

Glaser's model doesn't consider capillary condensation and the related storage capacity of building materials.

Glaser's model doesn't consider the dynamic changes in ambient relative humidity and temperature that characterize real, actual conditions.

5.5 Summary of Chapter 5

Glaser's model is simple to use and understand, however, it is inaccurate. Large deviations from reality could easily occur if the model is supplied with inaccurate input data, as was demonstrated in Section 5.2.5. The input data recommended by norms and standards are generally overestimated in order to secure results for the worst case scenario.

Section 5.3 showed that under equal boundary conditions, Glaser's model doesn't agree with the measured relative humidity in the actual wall in Blanden. Glaser's model doesn't consider the material's moisture buffering capacity (or moisture storage - see the next Chapter), which appear to have a large impact on the overall moisture performance of the wall. In reality, the excellent buffering ability of the exterior earth plaster lowers the overall relative humidity level in the straw. Additionally, the distribution of relative humidity throughout the homogeneous straw material isn't linear, as the model suggests. The interior half of the wall is drier and gets gradually wetter towards the exterior.

Glaser's model is used by building science for the prediction of interstitial condensation occurrence. The research on straw bale walls (see Chapter 4) shows that interstitial condensation due to vapour diffusion through a wall assembly isn't a substantial threat to the integrity of plastered straw bale walls anyway, so the use of Glaser's model in order to avoid possible condensation in plastered straw bale walls is misleading.

Despite its shortcomings, Glaser's model serves as the ideal tool for an initial preview of moisture transfer theory. Bigland-Pritchard, (2005) for example, used Glaser's model in his dissertation for preliminary analyzes of humidity occurrence in different straw bale wall assemblies. There is no reason to think that professionals in the construction industry will suddenly stop using Glaser's model because of its pessimistic results. Given its popularity, it is likely that it will continue to be widely utilized. As for assessments of humidity performance in plastered straw bale walls, it would be be helpful to give a researcher some guidance on how to get the most accurate and useful results out of this tool. The following recommendations are based on the research in this Chapter:

- Boundary conditions are much more significant for reliable calculation results than material properties. That is why it is important to give the model as much accurate input of the ambient conditions as possible.
- In some cases, CIBSE Guide A (1999) recommends using overall extreme design conditions for the prediction of short term condensation buildup. When modeling straw bale walls, it is much more useful to use average values over the continuous (most extreme) 60 day period (as it was done in this Chapter) in order to asses long term moisture performance in straw bale walls. The overall extreme design conditions tend to appear over too short a period to notably affect the humidity of straw in a plastered wall.

- In the case that Glaser's model predicts condensation between straw and exterior plaster, the results are most likely exaggerated. The model doesn't take into account the moisture buffering capacity of the wall's materials. The excellent moisture buffering capacity of straw and earth appears to have a significant effect on moisture transfer within straw bale walls.

In order to understand moisture transfer in a straw bale wall at a more detailed level, it is now necessary to introduce a more powerful and accurate tool - a mathematical model based on computer simulation.

Chapter 6

Moisture transfer in straw bale wall, dynamic simulation

Although Glaser's model is capable of simultaneously describing heat and moisture transfer in building components (Glaser's is a hygrothermal model), it is too simplified for any serious research. This Chapter looks into moisture transfer theory in greater complexity. It introduces advanced hygrothermal model WUFI Pro 4.0 IBP[1].

After its validation at the end of this Chapter, the WUFI model is used in the next Chapter as a tool for analyzing various straw bale wall assemblies under different ambient conditions.

6.1 Overview of hygrothermal computer models

The goal of steady state modeling using Glaser's model in the previous Chapter was to determine the possibility of interstitial condensation occurance in a particular wall assembly.

> "While this problem is computationally tractable, it has also been recognized as one of the least important parts of the overall moisture picture since it is limited to diffusion. More recent models have worked to encompass a variety of other transport modes and effects while lifting the constraints of one-dimensional steadystate analysis." (Newport Partners, p. 92, 2004)

Due to the growing complexity of mathematical models, which utilize physics, and due to the large amount of data that needs to be precisely calculated, it

[1]Available from: http://www.hoki.ibp.fraunhofer.de/wufi/bezug_e.html

is necessary to employ computers to obtain a modeling environment which corresponds to reality with greater precision. Computer simulation has become a recent trend in moisture transfer science. There are number of well validated advanced hygrothermal computer models available not only to scientists, but also to architects and engineers.

Straube and Burnett (2001) organized the hygrothermal models into two basic categories.

- Glaser's model together with its extensions such as EMPTIED and SHAM belong, according to Straube and Burnett, (2001) to **simplified models**.DIAL and DRAL (Ficker, 2003)fall into the same category.
- A more advanced category includes **detailed computer models** such as: WALLDRY, TRATMO, MATCH, MOIST, TCCD2, FSEC, WUFI, WUFIZ, and LATENITE. Besides those mentioned by Straube and Burnett (2001), there are still models like MOISTURE-EXPERT, hygIRC and DELPHIN that should be included in the "detailed hygrothermal computer models" category (Tariku and Kumaran, 2006).

6.2 Choosing a model for analysis of hygrothermal behaviour in plasered straw bale wall

There are many aspects influencing the researcher's choice of suitable hygrothermal computer model, but in general there are three major issues that need to be considered:

1. *Dimension:*
   - Whether a model is one, two, or three dimensional: whether it performs calculation at one point of the wall (1D—usually horizontally through the whole wall section—like Glaser's model or WUFI Pro 4.0 IBP), or whether it considers two (2D—planar) or even three dimensional (3D—spatial) performance within a particular building assembly.
2. *Time:*
   - Whether a model describes hygrothermal behaviour in ambient conditions that don't change over time (steady state) or whether it considers the input of changing ambient conditions (dynamic hygrothermal behaviour).
3. *Accessibility to researcher:*
   - Whether a model asks for data that is readily available;

- whether a researcher needs a special skill to run the model (programming skills, etc.);
- whether a model has an intuitive and well arranged interface;
- whether a model gives a complex output data that is easy to interpret.

> "The extent into which these issues are taken into account is usually considered to be the measure of the sophistication of the model." (Straube and Burnett, p.6, 2001)

The following table 6.1 compares the level of sophistication between Glaser's model and WUFI.

category	Glaser	WUFI
dimension		
	1D = *	1D = *
time		
	steady state = *	dynamic = ***
accessibility to researcher		
availability of input data	***	**
ease of use	**	**
interpretation of output data	**	***
usefulness of output data[a]	*	***
summary		
out of 18* possible[b]	10*	14*

[a]this category is the main factor in assessing the model's practicability and thus it renders Glaser's model practically useless

[b]the higher the number of stars, "*" the more sophistication the model exhibits

Table 6.1: As for sophistication, * poor; ** good; *** excellent. Glaser's model proved to be moderately sophisticated (with 10*), while WUFI's sophistication level (received 14*) is very good.

The computer model WUFI Pro 4.0 IBP is generally held in high esteem (Straube and Burnett, 2001). It is a one-dimensional, dynamic and easy-to-use hygrothermal computer model designed for building professionals and architects who don't necessarily have in-depth knowledge of the physics of moisture behaviour. For those reasons, it was chosen for the investigation in the next Chapter.

Although operating WUFI doesn't require theoretical knowledge of moisture behaviour, a good understanding of it is helpful to arrive at a critical assessment of the model's results. Furthermore, when dealing with unusual cases, such as straw bale insulation, it is helpful to consider the model's strengths and weaknesses regarding that particular case in detail.

A knowledge of theory will prepare a researcher for potential problems encountered during the simulation process.

6.3 WUFI, advanced moisture transfer theory

> "The moisture transfer within an external wall of heated space is a complex matter. Moisture movement through the wall is supported by air flow, gravitation, hydraulic pressure, osmotic and electrokinetic effects." (Kunzel, 1995)

A list of all the physical mechanisms (known to the author) that contribute to overall moisture transfer through the building envelope is introduced in table 6.2.

type of mechanism		level of contribution	considered by WUFI	see Appendix
moisture storage				
(moisture buffering	in region A	***	***	H.1.1
capacity)	in region B	***	**	H.1.2
	in region C	*	-	H.1.3
moisture transfer				
vapour transfer	water vapour diffusion	**	**	H.2.1
	thermal diffusion	*	-	H.2.1
	effusion	*	-	H.2.1
	convection[a]	***	-	H.2.1
liquid transfer	capillary conduction	*	*	H.4
	soret effect	*	-	H.2.2
	surface diffusion	***	***	H.2.2
	seepage flow	*	-	H.2.2
	hydraulic flow	*	-	H.2.2
	electrokinetics	*	-	H.2.2
	osmosis	*	-	H.2.2
moisture transfer below frost level				
	water vapour diffusion	*	-	H.5.1
	surface diffusion	***	***	H.5.2
heat storage and heat transfer				
	moisture dependent λ	**	**	H.6.1
	h.t. with phase change	***	***	H.6.3
surface transfer coefficients				
(advanced theory)	heat and vapour coeff.	*	*	H.7.1
	solar and rain factors	*[b]	***	H.7.2

[a]Here lies the weakest point of WUFI model. It doesn't consider air convection in its calculation, even though air convection is a significant factor in overall moisture transfer performance of any building construction (Straube and Burnett, 2001).

[b]solar and rain influence is not important, because the wall assemblies under investigation won't be affected by solar radiation or rain.

Table 6.2: All the mechanisms contributing to overall moisture transfer through the building envelope are discussed in great detail in Appendix H. The level of contribution (* = negligible; ** = moderate; *** = significant) of each mechanism is evaluated in terms of the degree of WUFIs consideration of each problem (- = not considered at all; * = insufficiently considered ; ** = considered; *** = well considered).

Table 6.2 helps to uncover the possible strengths and weaknesses of the WUFI hygrothermal model. It estimates the degree of contribution that a single mechanism imposes on overall moisture transfer through a building component and simultaneously, it shows the level of WUFI's consideration of that particular problem. A detailed explanation of each mechanism, including a discussion of WUFI's involvement with it, is provided in Appendix H.

According to the table 6.2, WUFI sufficiently covers all of the important issues concerning moisture transfer except one — air convection.

6.3.1 WUFI and air convection

The greatest weakness of the WUFI model is its failure to acknowledge vapour penetration into the construction due to infiltration through gaps, cracks and various imperfect details. Newport Partners (2004) state that compared to water vapour diffusion (the only form of moisture transfer considered by Glaser's model), the movement of water vapour by air flow can transfer much larger amounts of moisture through building construction. Consequently, moisture movement through hollow spaces within a wall isn't considered by WUFI either.

> "The detailed simulation of heat and moisture transport in air layers (including convection, turbulence etc.) is much more complicated and is outside WUFI's scope." (WUFI, 2005)

Research on straw bale buildings by Andersen (2004) proves that there are considerable convective air currents in plastered straw bale walls, due to air pockets between straw bales. However, building "natural convection-free" straw bale walls is possible, if not always achieved in practice (see Section 4.1.7).

It is necessary to take natural convection into account when analyzing the results of the WUFI model, since by ignoring air convection, WUFI counts on perfect, "natural convection-free" straw bale construction.

6.3.2 WUFI and straw

Another reason why WUFI could be unreliable for the purposes of this thesis is its questionable relationship with organic fibrous materials.

WUFI is tailored for the calculation of moisture transfer within porous mineral materials like renders, bricks, porous stones and concrete. Though the WUFI manual (2005) says that moisture transfer through fibrous organic matter like hemp, reed or straw isn't generally different from the moisture transfer in porous mineral materials, it also mentions that determining a liquid transfer coefficient for organic fibrous matter might be difficult or even impossible, because it could change its consistency in high moisture content levels (during caking, for example). It is advisable to take WUFI's results showing high moisture contents in straw (90% relative humidity and more) as conservative estimates.

In this thesis, the liquid transfer coefficients of straw will be ignored, since WUFI doesn't consider liquid transfer in normal conditions anyway. Liquid transfer starts to influence the calculation results only after the material is fully saturated and that isn't relevant for fibrous organic materials, since they need to be protected from saturation.

6.4 Straw bale wall in Blanden; Benchmarking of WUFI model

This Section introduces a WUFI simulation for a specific example. WUFI calculated a relative humidity and temperature profile through a wall section built on a computer screen to match the material parameters and geometry of an existing straw bale wall in Blanden, Belgium. The temperature and relative humidity in the real wall had been measured over winter 2005-2006 by three internal wall monitors. An additional two monitors measured interior and exterior ambient conditions (see case study II., Section 4.2.2). Using the monitored data of ambient relative humidity and temperature as an input, WUFI calculated the relative humidity and temperature profile for the simulated wall section over the entire monitoring period. The monitored data is then compared to the calculated data and in this way asseses the model's accuracy, or in other words, benchmarks the model for use in the next Chapter.

6.4.1 Input data for WUFI simulation

Wall assembly, monitor positions and grid

Fig. 6.1 presents the wall assembly in Blanden as it was set in WUFI's dialog:

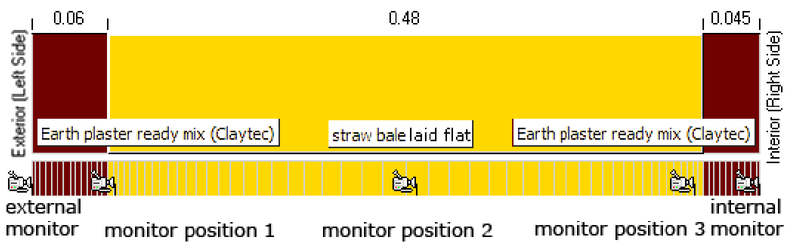


Figure 6.1: Section through the northern external straw bale wall in Blanden. Straw bales are laid flat, $\Longrightarrow$ the heat and water vapour flow are parallel to straw fibre. Commercially produced earth plaster (CLAYTEC, Lehm Unterputz) was mixed with water and sprayed in three layers onto both sides of the straw bales. The horizontal strip in the middle of this figure shows a "mean" calculation grid with monitor (camera) positions. Note that the grid is finer at the material's boundaries. The yellow strip at the bottom shows the section through just straw with the grid and monitor position in detail.

Assessment of the monitor position and grid is discussed in detail in Appendix I.4.1 and I.4.2.

Material data

In the case of the Blanden wall, there are only two materials creating the wall assembly: earth plaster and straw. Basic and optional parameters required by WUFI software are summarized in table 6.3.:

material characteristic	units	earth plaster CLAYTEC Lehm Unterputz[b]	straw[a]
basic values			
bulk density	[kg·m^{-3}]	1600	100
porosity	[m^3·m^{-3}]	0.3[c]	0.9[d]
specific heat capacity of dry material	[J·kg^{-1}·K^{-1}]	850	2000
thermal conductivity of dry material	[W·m^{-1}K^{-1}]	0.7	0.085
water vapour diffusion coefficient	[-]	8	2
optional parameters			
sorption isotherm		(Minke, 2006)	fig. 3.5
water absorption coefficient[e]	[kg·m^{-2}·s$^{-\frac{1}{2}}$]	0.068[f]	-
moisture dependent:			
- thermal conductivity[g]	[W·m^{-1}K^{-1}]	-	-
- water vapour diffusion coefficient	[-]	(Andersen, 2004)	-[g]
typical built in moisture[h]	[kg·m^{-3}]	1	9

[a]heat and moisture flows are parallel to straw fibre
[b](Claytec, 2006)
[c]Estimated from porosity values of other plasters (see Appendix B.0.2) and porosity of earth bricks (Fernandes, 2003).
[d]Estimated from similar organic fibre materials from the WUFI database.
[e]determines liquid transfer coefficients - suction and redistribution [m^2·s^{-1}]
[f](Straube, 2003)
[g]For lack of available data, WUFI will not allow it.
[h]Estimated from final moisture content, when running the model once, with completely dry materials at the beginning.

Table 6.3: Basic values are necessary for WUFI calculation. Optional parameters support more accurate calculations. Data taken from Appendix B.0.2 and from table 5.3 if not specified otherwise.

Other input data

The wall in Blanden was chosen to minimize requirements for extensive input data. Some weather data that are difficult to collect (for example driving rain load and solar radiation on the wall surface), were excluded from this calculation. The examined wall is north facing. This fact completely eliminates the effect of solar radiation. Furthermore, due to almost nonexistent southern wind in the Blanden area, the northern wall under investigation almost never receives driving rain and that eliminates the need for rain load data.

Outside and inside ambient (climate) conditions as well as coefficients influencing surface moisture transfer and other necessary parameters required by

WUFI software are summarized in table 6.4. The table is a result of a detailed discussion in Appendix I.

input data	[units]	actual value	see Appendix
time step			
	[h]	1	I.1
climate data			
exterior			
rain load	[$l\cdot m^{-2}\cdot h^{-1}$]	-[a]	I.2
solar radiation	[$W\cdot m^{-2}$]	-[a]	I.2
long wave atmospheric counterradiation	[$W\cdot m^{-2}$]	-[a]	I.2
barometric pressure	[kPa]	93.36[b]	I.2
temperature	[°C]	monitored	I.2.1
relative humidity	[%]	monitored	I.2.1
interior			
temperature	[°C]	monitored	I.2.2
relative humidity	[%]	monitored	I.2.2
surface transfer coefficients			
exterior			
vapour diffusion thickness	[m]	0	I.3.1
short wave radiation absorptivity	-	0[a]	I.3.2
long wave radiation emissivity	-	0	I.3.3
rain water absorption factor	-	0[a]	I.3.2
heat transfer	[$W\cdot m^{-2}\cdot K^{-1}$]	17	H.7.1
water vapour transfer	[$kg\cdot m^{-2}\cdot s^{-1}\cdot Pa^{-1}$]	$75\cdot 10^{-9}$	H.7.1
interior			
heat transfer	[$W\cdot m^{-2}\cdot K^{-1}$]	8	H.7.1
water vapour transfer	[$kg\cdot m^{-2}\cdot s^{-1}\cdot Pa^{-1}$]	$25\cdot 10^{-9}$	H.7.1
wall component			
orientation	-	-[c]	I.4.3
inclination	[°]	-[c]	I.4.3
height of the component	[m]	-[c]	I.4.3

[a]The wall in Blanden isn't exposed to rain or sun.
[b](ISHS, 2005)
[c]The data influenced by solar radiation and rain penetration[a].

Table 6.4: The rest of the input data required by WUFI simulation software. More detailed information is available in Appendix I.

6.4.2 Calculation of moisture transfer with the WUFI model

WUFI calculates the dynamic heat and moisture transfer in building components using coupled differential equations that are discussed in Appendix J.

Not unlike Glaser's model (see Section 5.2.2), WUFI calculates temperature and relative humidity on boundaries of a single element. On boundaries, the values are shared by two neighbours, and then the values change across the element influenced by element properties. While Glaser's model counts on linear transfer of heat and moisture through one material, the WUFI model shows nonlinearity through one material due to the transient development of heat and moisture transfer. For this reason, WUFI subdivides the material layers of a building component into even thinner layers (elements) on the grid (see Appendix I.4.2).

> "WUFI uses the method of 'finite volumes'. This method first formulates the differential equations in terms of balance equations for heat and moisture and then derives the algebraic equations in a way which makes sure that the heat and moisture balances remain preserved for every element of the numerical grid. That is, the variation of a physical quantity in each grid element is strictly consistent with the amount of that quantity that flows into or out of the element through the element boundaries ("conservative discretisation") (see fig. 6.2 - ed. author)." (WUFI, 2005)

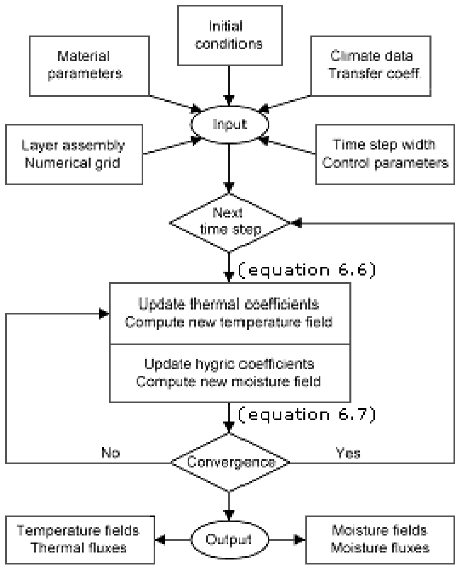


Figure 6.2: Flow chart for the WUFI model. From WUFI (2005)

6.4.3 Summary of results

At the end of each calculation, WUFI exports the output of relative humidity and temperature data in given monitor positions into a .tex file. Those calculated values and the values downloaded from dataloggers (also in .tex format) are then easily compared in charts (see the following sections).

February 19th 2006 — March 12th 2006

Before analyzing the data over the whole monitoring period(from December 7th 2005 till May 1st 2006), let's first examine the convergency between the measured and calculated data in greater detail. This way, the model's accuracy becomes obvious immediately.

Only a fraction of the entire data file, the 21 day period (from February 19th 2006 to March 12th 2006), was randomly chosen to provide an example for closer analysis (see fig. 6.3).

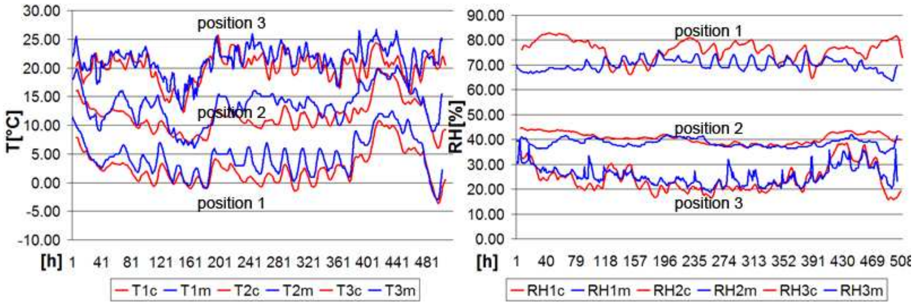


Figure 6.3: Output of WUFI simulation (see the **red curves**) in 3 specific monitor positions (1 is close to the exterior, 2 is in the middle and 3 is towards the interior (see fig. 6.1)), compared to real measured data (see the **blue curves**) in the same positions inside the wall in Blanden. The graph shows a fraction of the complete relative humidity and temperature data. It represents the monitoring over the randomly chosen 21 day period (from 19 February 2006 till 12 March 2006). There is overall agreement in trend and values, with the exception of relative humidity at monitor position 1.

The fig. 6.3 shows temperature and relative humidity "time" profiles in all three internal monitor positions (see figs. 4.22 and 6.1). Note that the relative humidity at position 2 (in the middle of the straw bale) gives relatively stable values compared to values of relative humidity in the straw close to the outside of the wall (monitor positions 1 and 3). The shapes of blue (monitored) and red (calculated) curves show similar trends and values. The overall agreement between experimental and simulated results is very good except for the poor convergency of relative humidity values at monitor position 1 — in the straw just under the exterior plaster.

December 7th 2005 — May 1st 2006

Monitor position 1

Fig. 6.4 describes the profiles of calculated and measured data at position 1 (in the straw just under the exterior plaster) over the whole monitoring period from December 7th 2005 to May 1st 2006. While the calculated temperature agrees with the monitored values, the relative humidity shows major inaccuracies. During the first half of the monitoring, the measured relative humidity data are much lower than the data calculated by WUFI. While WUFI calculates a maximum value of 86% relative humidity, in reality the relative humidity at this position hardly ever reaches 75%. During the second half of monitoring the measured and calculated data are closer to each other.

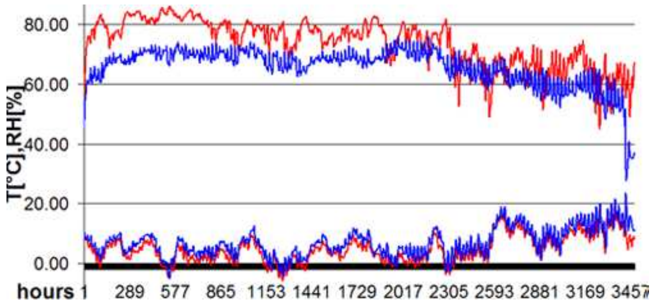


Figure 6.4: Output of WUFI (**red curves**) compared with the real measured data over the whole time of monitoring in the wall in Blanden (**blue curves**) at monitor position 1 in the straw just under the exterior plaster. Here the calculated values of relative humidity (**upper part** of the graph) disagree with the monitored values, while the temperature data (**lower part** of the graph) are in a good convergency.

The most probable reason for error in the relative humidity calculation at position 1 is the inaccuracy of the external climate input data that have a major influence on this position. The external input of relative humidity and temperature was provided by datalogger #5 mounted to the wooden beam just under the metal roof, far from the dataloggers in the wall — internal monitors # 1,2,3 (see fig. 6.5).

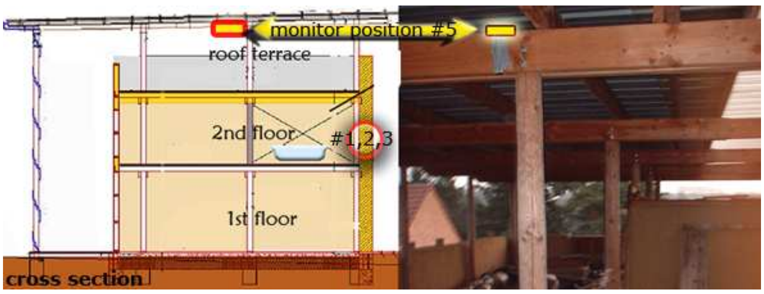


Figure 6.5: Straw bale house in Blanden, Belgium. The external monitor #5 was fixed to the top of the roof joist just under the metal roof (see **yellow arrow**) far from the internal monitors #1,2,3 (see **red circle**).

If monitor #5 measured outdoors conditions just next to the location of the internal monitors #1,2,3 (see the red circle on fig. 6.5) the calculated data would have been different. Due to its great distance from the internal monitors, monitor #5 didn't supply WUFI calculation with accurate input data. The outdoor conditions presented by monitor #5 were certainly influenced by higher values of relative humidity accumulating under the metal roof. The higher input of exterior ambient relative humidity pushed up the calculation results in position 1 (in the straw behind the exterior plaster).

This theory is supported by additional calculations. Better convergency was achieved after the subtraction of 5% of relative humidity from the input of external climate data (provided by monitor #5). The calculation got even closer to measured data with adjustment of thermal conductivity of earth plaster. Table 6.3 presents the input of thermal conductivity, $\lambda = 0.7\ \mathrm{W{\cdot}m^{-1}K^{-1}}$ as it was provided for calculation by plaster supplier. Appendix B.0.2 shows that in reality, the thermal conductivity of earth plaster might vary (0.2 to 0.7 $\mathrm{W{\cdot}m^{-1}K^{-1}}$), depending on amount of straw in the plaster, the sand/clay content ratio, etc.. This does not imply that the given material properties of the Claytec plaster manufacturer are wrong, however, the adjustment of thermal conductivity from 0.7 to 0.4 $\mathrm{W{\cdot}m^{-1}K^{-1}}$, plus subtraction of 5% relative humidity from the input of the exterior climate data results in better convergency between calculation results and monitored values (see fig. 6.6).

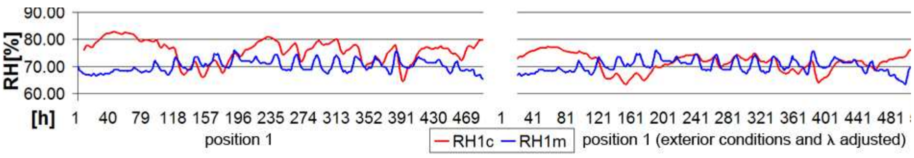


Figure 6.6: Convergency of calculation with the measured relative humidity data at position 1. The chart **on the left** shows the calculation results from fig. 6.3. The chart **on the right** gives a better convergency of measured data with the calculation that was carried out after the input of exterior climate data had been adjusted (5% of relative humidity was subtracted from the input data file). Additionally, the thermal conductivity of earth plaster was adjusted (from 0.7 to 0.4 $\mathrm{W{\cdot}m^{-1}K^{-1}}$) to give calculation results in even better agreement with measured data.

Monitor position 2

Monitor position 2 is in the middle of the bale. In general, it shows a good fit of calculated relative humidity and temperature data with the measured values. Fig. 6.7 presents the comparison of measured and calculated data over the whole period of monitoring.

At the end, calculated relative humidity departs from measured data and shows a stable increase of about 10%, while the trend is retained. The reason could again be inaccuracies in the climate input data.

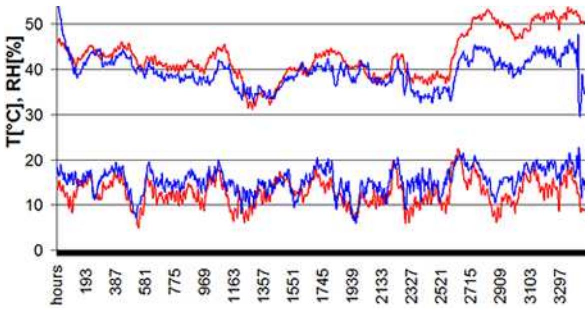
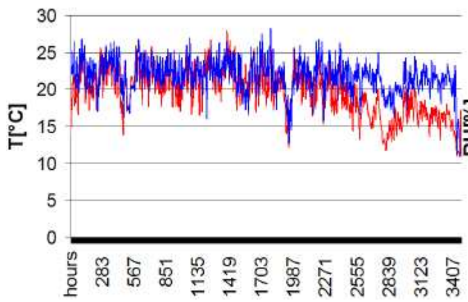


Figure 6.7: Output of WUFI (**red curves**) compared with the real measured data over the whole time of monitoring in the wall in Blanden (**blue curves**) at monitor position 2 in the middle of the straw bale. Here the calculated values of relative humidity (**upper part** of the graph) and temperature (**lower part** of the graph) agree with monitored values with satisfactory accuracy.

Monitor position 3

In the straw next to the interior plaster, position 3 is again in satisfactory agreement of calculation with monitoring.



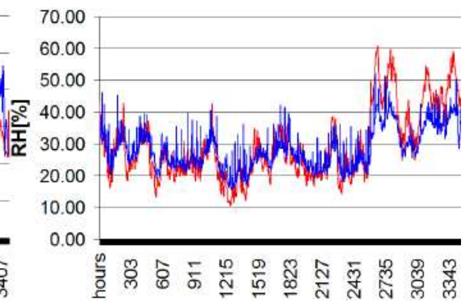


Figure 6.8: Output of WUFI (**red curves**) compared with the real measured data in the wall in Blanden (**blue curves**) at monitor position 3 in the straw next to the interior plaster. Here the calculated values of temperature (the graph **on the left**) and relative humidity (the graph **on the right**) agree with the monitored values with satisfactory accuracy.

Similarly to position 2, fig. 6.8 shows the departure of measured values from the calculated ones at the end the monitoring period. This discrepancy is most probably caused by inaccurate interior input data (see Appendix F).

6.4.4 Influence of input data on results of WUFI model

A small change in some of the input values could cause a significant difference in the calculation results, while a great alternation of another input value might be trivial in terms of moisture transfer.

Climate input data have a dominant influence on the temperature/relative humidity profile through the wall section (see Appendix I). The other factor that appears to have a great effect on calculation results is the thermal conductivity of materials within a wall assembly (see fig. 6.9).

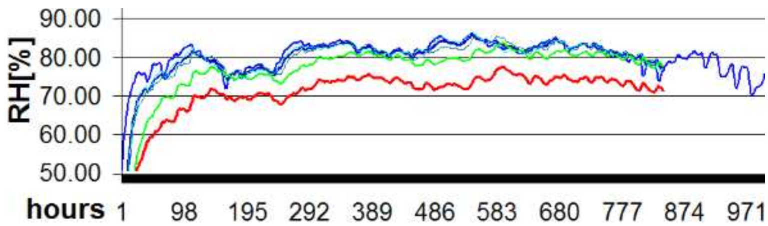


Figure 6.9: Monitor position 1 (in the straw just under the exterior plaster) over the whole monitoring time. How do particular material input data influence the results of WUFI model? The first 1000 hours of monitoring provided the specifics for this investigation. The cluster of **blue curves at the top** of the graph shows the calculation results after changing some of the material properties of the exterior plaster; in particular: porosity, specific heat capacity, density, water vapour diffusion coefficient. The major changes in those values had almost no effect on moisture performance in the wall. Improving the thermal conductivity value λ of exterior plaster from 0.7 $W{\cdot}m^{-1}K^{-1}$ to 0.1 $W{\cdot}m^{-1}K^{-1}$ (λ of straw = 0.085 $W{\cdot}m^{-1}K^{-1}$), on the other hand, reduced the relative humidity profile in this position by about 10% (see the **red curve**). Note that doubling the thickness of exterior plaster **green curve** (from 60mm to 120mm) didn't have any major significance.

Fig. 6.9 suggests that the use of a well-insulating plaster on the outside of the wall significantly lowers relative humidity values throughout the straw in a wall. The substantial changes in the rest of material data, including doubling the thickness of the plaster, didn't play a significant role in the moisture performance of the straw bale wall.

6.5 Limitations of the WUFI model

Supposedly the greatest limitation of the WUFI model is that it ignores water vapour transfer caused by air infiltration and convective air current flows (see Section 6.3.1). The comparison of the model's results against the real measured data in the straw bale wall in Blanden (see Section 6.4.3) shows reasonably good agreement, despite the fact that WUFI didn't consider air infiltration. The benchmarking proves that within a properly built basic straw bale wall assembly (plaster—straw—plaster), air infiltration as a part of overall moisture transfer plays a minor role.

The WUFI manual (2005) warns that calculation results concerned with saturated straw will be distorted, because the WUFI model fails to accurately describe the behaviour of natural fibrous material in very high relative humidity levels (90% and more).

This thesis consciously limits itself to the most frequently used and most recommended) straw bale building practice - a wall configuration of plaster—straw—plaster. The implication of the WUFI model on a more intricate wall assembly needs to be further examined.

The fact that the benchmarking ignored the effects of driving rain and solar radiation further limits the following research. Investigation in the next Chapter will not consider the effects of driving rain or sunshine on straw bale wall moisture performance.

6.6 Summary of Chapter 6

This Chapter looked at moisture transfer in great detail, documented the data used for input into the model, compared the results of the simulation with the results of the monitoring, explained the differences between monitored and modeled values and discussed the input variables that had the greatest effect on the output. Finally, it would be useful to give few recommendations regarding future benchmarking of the WUFI model:

- When benchmarking a computer hygrothermal model, it is essential to provide reliable climate input data. Ideally, the external monitors supplying a model with climate input data should be placed in close proximity to the control monitors in the wall.
- Out of all material properties, thermal resistivity influences the moisture transfer the most significantly. When benchmarking a hygrothermal model it is important to know the thermal resistivity values of all the materials in a wall accurately.

With the exception of thermal resistivity, other material properties don't play a significant role in moisture performance inside the wall. The investigation showed that when using thermally insulating plaster, the moisture performance in the straw bale wall is improved.

The benchmarking uncovered the following fact: Air infiltration seems to play a minor role in overall moisture transfer through the straw bale wall if the walls are built and plastered correctly.

The advanced theory behind moisture transfer quickly becomes very complex. Computer simulation programs like WUFI, for example, struggle to simplify the theory without losing an acceptable level of accuracy. Although quite simplified (see Appendix H.2), the WUFI model proved to be reasonably accurate for the purposes of investigation in the next Chapter.

Chapter 7

Investigation using WUFI dynamic simulation

> "... the programs are a long way from being able to deal with the intricate forms of real architecture, spiced with typical construction defects. The real usefulness of the programs is to explore general ideas about constructing fault tolerant buildings ..." (Padfield, p. 22, 2002)

The previous Chapter proved that the WUFI model can be used for basic humidity research in simple, "air convection free" straw bale wall assemblies (plaster—straw—plaster) with reasonable accuracy. By using simplified input data (without rain penetration or solar radiation), it will be possible to concentrate on the general ideas behind the moisture transfer through different straw bale wall covers without getting lost "in the intricate forms of real architecture" as Padfield (2002) puts it.

This Chapter will revisit the wet wall in Plozevet in order to give an estimation of its total drying time and also, in the next Section, it will explore the effect of various plasters on moisture transfer through straw bale walls exposed to extreme weather conditions.

7.1 Dynamic simulation in extreme climates

The advantage of the WUFI computer simulation resides in its power to analyse humidity inside a construction even after it's been standing for years in almost any conditions, anywhere in the world, without any great effort. The ability of the program to provide a researcher with 1 year moisture profiles through differently plastered straw bale walls after they've been part of occupied family houses built in Alaska or Indonesia for example, without waiting and without any traveling, is fascinating — and it is exactly what is this Section about. It will compare the viability of different basic straw bale wall assemblies in extreme northern weather with their viability in the climate of a tropical rain forest.

7.1.1 Choosing extreme exterior ambient conditions

The aim is to examine moisture in straw within a wall exposed to very humid weather. The charts on figs. 7.1 and 7.2 show weather comparison amongst possible candidates for straw bale house location in two extremes: in extremely cold and extremely hot humid climates. London and Aberdeen weather profiles were added to provide a comparison.

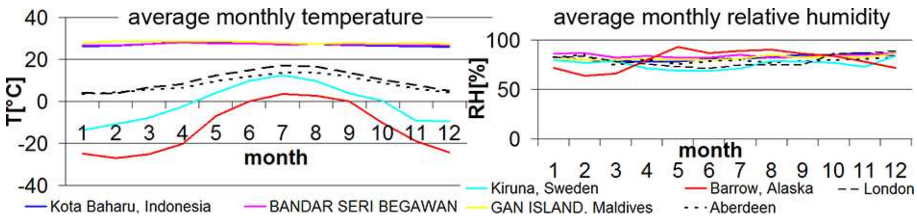


Figure 7.1: Average monthly data of relative humidity (see chart on the right) clearly show the focus of interest: humid weather. Average monthly temperature (see chart on the left) specifies two different extremes: extremely hot and extremely cold climates. A hot humid climate is represented by 3 equatorial regions: Kota Baharu in Sumatra, Indonesia; Bandar Seri Begawan in Brunei; Dar-as-Salaam and Gan Island in the Maldives. A cold humid climate has 2 representatives: Kiruna in northern Sweden and Barrow in northern Alaska. For comparison's sake, two other humid locations were added to this selection: London and Aberdeen (data from eeare, 2007).

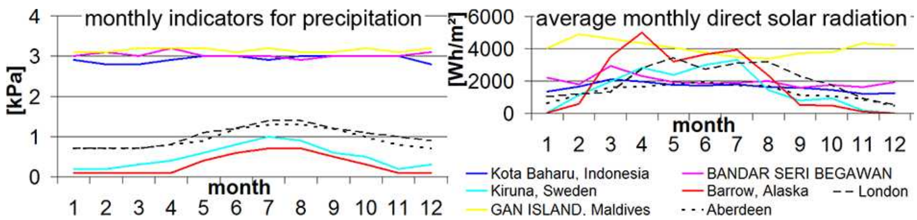


Figure 7.2: Neither rain nor solar radiation are subject of this simulation. However, it is useful in order to have a more complete picture of the locations of interest (data from eeare, 2007).

- As for a cold humid climate, Barrow in Alaska has the most extreme profile (see red curves on figs. 7.1, 7.2 and also fig. 7.3).
- According to fig. 7.1, all of the locations in hot humid climates have very similar average monthly temperatures and relative humidity data. Kota Baharu in Sumatra,Indonesia (see dark blue curve on figs. 7.1, 7.2 and

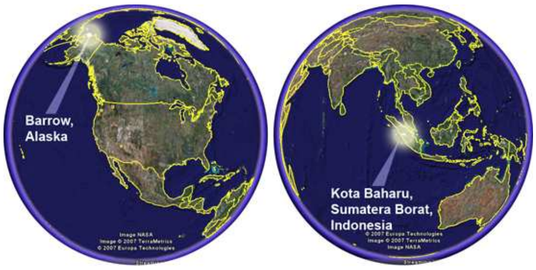


Figure 7.3: Hourly temperature and relative humidity data collected for a 1 year period in Barrow and in Kota Baharu will be used by WUFI as input for its simulation. (from Google Earth).

also fig. 7.3) was chosen for its perpetually cloudy atmosphere, suggesting minimal drying due to solar radiation (see fig. 7.2, chart on the right).

7.1.2 Choosing internal ambient conditions

One of the options that WUFI offers is to simplify indoor ambient temperature and relative humidity into sine waves that stretch over a 1 year period:

> "In some cases it is sufficient to ignore short-term fluctuations of the boundary conditions and to consider only their long-term (e.g. yearly) trend. Temperature and relative humidity may then be modeled by simple sine curves with a yearly period. These conditions are usually met by the interior climate ... WUFI generates the temperature as a sine wave with one-year period from the yearly mean value, the amplitude and the day of maximum specified by the user." (WUFI-pro Online Help, 2005)

Values specifying the shape of one year period sine waves of interior temperature and relative humidity to be used by WUFI simulation are presented by table 7.1. These values were specifically chosen because they seem to define the desirable thermal and humidity comfort of any interior space.

	T [°C]	RH [%]
mean value	21	55
amplitude	1	5
day of maximum	6/3/2007	8/16/2007

Table 7.1: Values specifying the shape of sine waves represent the input of indoor ambient conditions to be used by WUFI simulation.

7.1.3 Choosing the appropriate plaster

Plasters are excellent straw bale protection for many reasons. They are essential in protecting straw from fire, rodents and insects (e.g. Jones, 2002; King, 2006). Additionally, straw that is bonded to plaster benefits the building with amazing structural strength (see Section 4.1.5). However, not every plaster is well suited to this purpose.

Earth plaster

According to the questionnaire, straw bale builders prefer to use earth plaster on straw bales (see Section **??**).

There are many reasons why. Local earth has very low embodied energy. Earth plaster is easy to work with, easy to maintain, and it is easily reparable due to the non-chemical nature of clay bonding. Furthermore, it creates an intelligent protective system dynamically responding to presence of moisture (King, 2006). The breathability of earth plaster depends on its humidity.

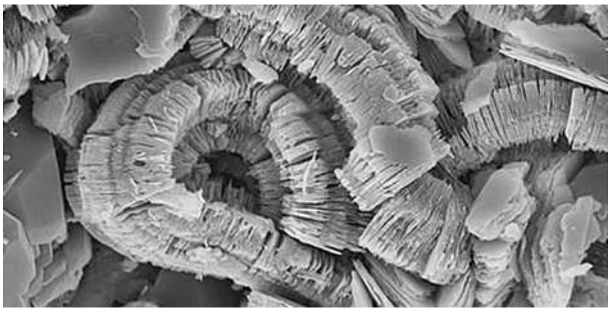


Figure 7.4: "Clays are very small components (0.002mm) formed and reformed by chemical action consisting of stacked plate crystals held in position by elektrostatic (= electromagnetic - ed. author) surface forces: restricted by their nature to microscopic size." (Warren, p. 48, 1999).

There is a strong electromagnetic bond between clay crystals and that is why it gets so hard when dry. This electromagnetic force attracts water molecules as well. They get in between the crystals through capillary action. As more and more water is bound between the crystals, pushing them apart, the clay appears to swell. The swelling reduces the pores between sand particles in the earth plaster and that is why its breathability decreases, protecting straw from moisture intrusion. The spaces between crystals can hold large amounts of water, and therefore, clay plasters have large moisture storage capacity. During drying, the breathability of earth plaster increases again, allowing the straw behind it to easily dry out (Warren, 1999).

However, clay crystals and sand particles in earth plasters are not mechanically, nor chemically interlocked with each other, so earth plasters are prone to erosion. They need to be protected from frequent rains by large overhangs, porches, or silicate - or plant oil - based paints.

Lime plaster

The use of lime plaster on straw bales has become another successful option, especially as an exterior covering in rainy climates such as those found in the UK and Ireland. It is quite durable. Jones (2002) recommends using traditional lime plaster mix made out of lime putty and well graded sharp sand in a ratio of 1/3 (see fig. 7.5).

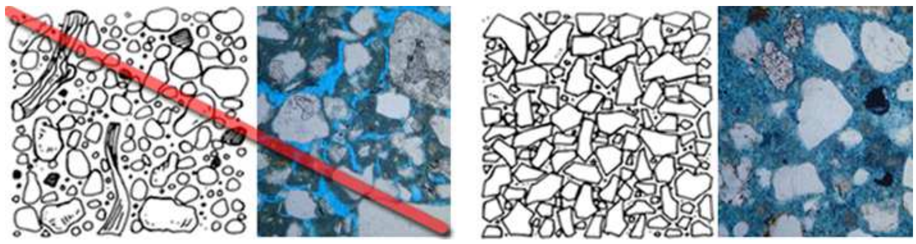


Figure 7.5: Illustrations of sand to be used (on the **right**), or not to be used (on the **left**) as a filler for lime plaster mix are paired with cross section cutaways of matured lime plaster. **Blue** shows an open pore structure. On the **left**: poorly graded and round sand with organic additives is not suitable as filler for lime plaster mixes, because it creates large pores for liquid penetration. On the **right**: well graded sharp sand with particle sizes from dust to 5mm mixed with lime putty in ratio 3/1 creates a highly vapor permeable and at the same time liquid resistant plaster. From Jones (2002) and deGruchy (2007).

Sharp sand of all different particle sizes from dust to approx. 5mm ensures that all the gaps are evenly filled up with matter. The ratio of 1 part lime to 3 parts sand provides the precise amount of lime necessary to cover the particle surfaces with a thin, continuous film, without pushing particles away from each other. In this way, lime creates a seamless, permeable fabric with a crystalline structure. There are no gaps between particles, just miniature pores that fence off the conglomerates of water molecules (liquid water), but allow single water vapour molecules to freely penetrate through the plaster.

Properly cured lime plaster (see Section 4.2.1) is not only breathable and water resistant, but also flexible and easily reparable due to its capacity to heal itself. DeGrunchy (2007) writes:

> "If a building is subject to movement, a lime mortar will move with the building. Through crystalline bridging, using the free lime content, the lime mortar will autogenously heal those fissures that occur."

Cement based plaster

In relation to moisture, cement-based plasters fail the requirements for plasters on straw bale walls and are not suitable for straw bale cover.

- Cement-based plasters are too hard and brittle to be used on soft material such as straw bales. They will crack and lead to significant infiltration problems. It is now widely accepted that plaster should be weaker than the material to which it adheres (Harrison, 2005).
- Cement-based plasters are impermeable. Water that gets into the wall via capillary action through cracks becomes trapped and can't escape.
- Cement-based plasters are very difficult to repair. Once a crack appears, it is very difficult to re-establish the bond.

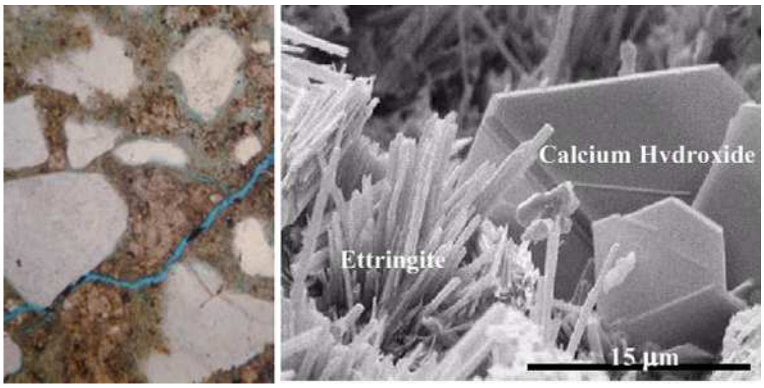


Figure 7.6: On the **left**: the cross section cutaway through cement plaster. Harrison (2005) writes: "Note the dense fabric and the greatly reduced porosity with only the presence of shrinkage cracks. The shrinkage cracks are a portal for moisture to get into the wall." — If it were lime plaster, the sun would draw moisture back out of it due to its vapour permeability (see fig. 7.5) — "However, because of this portland cement based plaster, the inevitably supersaturated wall of trapped moisture can only have rain driven much further into the building .... accelerating its deterioration." (Harrison, 2005). On the **right**: the crystals of Ettringite that form during the chemical set of cement give the cement based plaster hardness and brittleness. "Lime (calcium hydroxide - ed. author), however, has an open pore structure and a hexagonal crystal structure which allows the plates to shift between one another and yields flexibility and high vapor and liquid permeability." (DeGrunchy, 2007). From DeGrunchy (2007).

For all its disadvantages, cement somehow remains attractive to some straw bale builders, because it sets fairly quickly in comparison to lime and hence speeds up the work.

Is it possible to blend these two materials in order to gain the advantages of lime while retaining the setting properties of cement?

- When blending cement plaster with lime (more cement than lime) the permeability of plaster increases with increasing lime content, but it will never be as permeable as pure lime plaster (see Appendix B.0.2). On top of it, a high percentage of cement will always give the plaster inadequate strength for straw bale walls. It will keep cracking. Cement colloid will clog the pores in the lime and thus largely restrict proper lime carbonation. Therefore, the cracks will be never able to heal properly (Harrison, 2005).
- When blending lime with cement (more lime than cement), there is a great danger of segregation which becomes even more pronounced when using less cement (Harrison, 2005).

> "Given the possible hazards of segregation, an un-gauged lime mortar relying solely on carbonation is likely to be more resilient in the long run than one gauged with a small amount of cement....The resulting mortar will be seriously weakened, with a poorly formed pore structure leaving it very susceptible to frost damage and deterioration, even after carbonation of the non hydraulic lime (components) present has taken place." (O'Hare, 2004)

Resume

As for moisture balance (see Section 4.1.8), the basic requirements for plasters that work well with straw bales can be summarized as follows:

- must prevent liquid water from entering straw,
- must be breathable to allow drying,
- must be flexible,
- must be easy to repair.

category	earth plaster	lime plaster	cement based plaster
water resistivity	**	***	*
permeability	***	***	*
flexibility	***	***	*
possibility of repair	***	***	*
embodied energy	***	*	*

Table 7.2: As for performance of plaster in given category: * poor; ** good; *** excellent. There are only two kinds of plaster suitable for straw bale wall cover: earth and lime plaster

According to table 7.2, there are only two kinds of plaster that meet all four requirements and thus are suitable for straw bale protection:

1. earth plaster
2. lime plaster

7.1.4 Choosing appropriate wall assemblies

The previous Chapter found WUFI software reliable when simulating moisture performance in a simple wall assembly of plaster—straw—plaster. The following investigation will continue with this proven model. There is a pleasing simplicity in this formula, which seems to work best for straw bales anyway.

Assembly ESE, earth plaster — straw bale — earth plaster

This is the most desirable straw bale wall assembly. WUFI will show how well it works in extremely humid climates, in comparison to the following wall assemblies.

Assembly EdSdE, earth plaster - straw bale dipped from both sides in a clay slip - earth plaster

Tom Rijven started to use straw bales dipped in liquid clay solution (clay slip - see fig.7.7), because he believes that it improves the structural bond between earth plaster and straw. He also assumes that this method prevents condensation (see Appendix A.2). Let's see how it would work in Alaska and Indonesia.

Figure 7.7: Prior to being placed in the wall, straw bales are dipped on their exterior and interior facing sides in a water-rich clay solution (clay slip) and stored on pallets to dry a bit. Photography by Tom Rijven.

Assembly LESE, lime plaster - earth plaster — straw bale — earth plaster

A finishing coat of lime plaster is used over the scratch (body) coat of earth plaster to protect it from erosion in rainy climates by some professional builders. Unlike lime plaster, earth plaster can be applied in a thick layer, so this method offers the advantage of having flat and even surfaces on the exterior of the house (any deep grooves in the straw bale wall can be filled with a thick layer of earth), with the advantage of durability provided by a thin layer of lime plaster finish.

> "There is some risk in using dissimilar materials, as the layers may expand and contract differently in response to temperature and moisture and thus delaminate over time." (King, p.30, 2006)

However, let's assume that the lime plaster finish was properly done over a base of earth plaster and that it will prove to be a durable solution. The question is: will the thin layer of lime plaster over the earthen base influence the moisture performance of the whole wall?

Assembly LSE, lime plaster — straw bale — earth plaster

Having lime plaster outside and earth plaster in the interior of a house is a very common and preferable straw bale wall assembly used in rainy climates.

In general, the permeability of earth plaster is greater than permeability of lime plaster (see Appendix B.0.2). It is now widely accepted that having a more breathable plaster on the outside and a less breathable plaster on the inside of the house is beneficial for overall wall moisture performance in heating climates. In the tropics, however, the opposite is true. Having less permeable lime plaster on the outside of a house in Indonesia should be advantageous. How will this wall assembly, which protects straw from rainy weather, perform in the equatorial region and how it will perform in the extreme north?

Assembly LSL, lime plaster — straw — lime plaster

The final straw bale wall assembly is another common possibility for a rainy climate. As for moisture transfer, will lime plaster perform better than earth plaster?

7.1.5 Input for WUFI simulation

Wall assembly, monitor position and grid

Wall assembly ESE

Wall assembly earth plaster — straw bale — earth plaster was already used for to benchmark of the WUFI simulation and is described in Section 6.4.1 (see fig. 6.1).

Wall assembly EdSdE

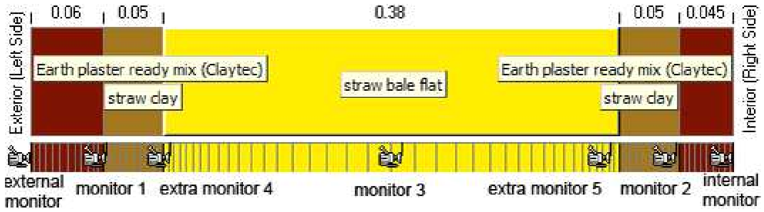


Figure 7.8: Wall assembly: earth plaster - straw bale dipped on both sides 50mm in clay slip - earth plaster. Two additional monitors (cameras) were added to this wall assembly in order to monitor conditions on the border between pure straw and straw dipped in clay slip, as well as on the border between the bale dipped in clay and earth plaster.

Wall assembly LESE

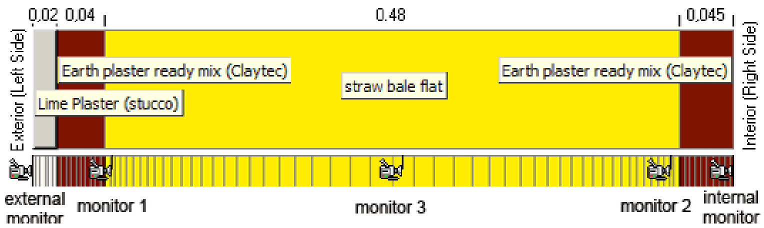


Figure 7.9: Wall assembly: lime plaster - earth plaster — straw bale — earth plaster. The scratch (body) coat of earth plaster is 40mm thick on the outside and there is 20mm of lime plaster finish coat on top of the scratch coat.

Wall assembly LSE

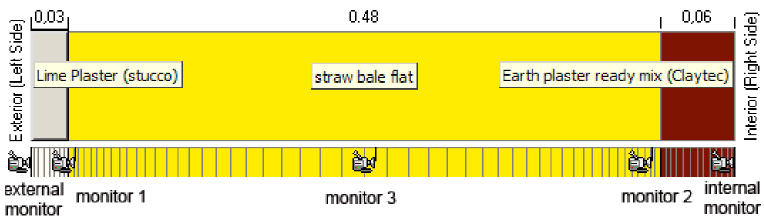


Figure 7.10: Wall assembly: lime plaster — straw bale — earth plaster. Lime plaster usually has three coats. Each coat needs to be about 10mm thick to allow for proper carbonation. The overall thickness of the lime plaster is then 30mm.

Wall assembly LSL

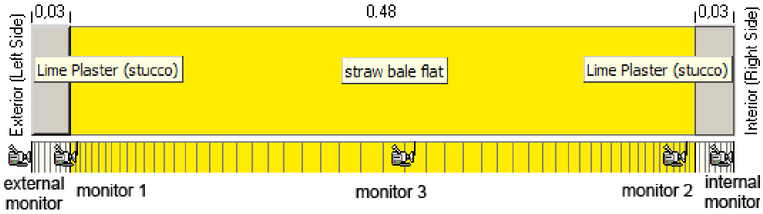


Figure 7.11: Wall assembly: lime plaster — straw bale — lime plaster.

Material properties

material characteristic	units	straw[a]	earth plaster[a]	straw & clay[b]	lime plaster[c]
basic values					
bulk density	$[kg\cdot m^{-3}]$	100	1600	400	1600
porosity	$[m^3\cdot m^{-3}]$	0.9	0.3	0.75	0.3
vapour diffusion coefficient	[-]	2	8	4.5	7
dry material:					
specific heat capacity	$[J\cdot kg^{-1}\cdot K^{-1}]$	2000	850	1175	850
thermal conductivity	$[W\cdot m^{-1}K^{-1}]$	0.085	0.7	0.12	0.7
optional parameters					
sorption isotherm		yes[d]	yes[e]	-	yes[c]
water absorption coeff.[f]	$[kg\cdot m^{-2}\cdot s^{-\frac{1}{2}}]$	-	0.068[g]	-	$1.5\cdot10^{7}$ [c]
typical built in moisture[h]	$[kg\cdot m^{-3}]$	9	1.4	1	1.4
moisture dependent:					
thermal conductivity	$[W\cdot m^{-1}K^{-1}]$	-[i]	-[i]	-[i]	0.7 - 1.7[b]
vapour diffusion coefficient	[-]	-[i]	yes[j]	-[i]	yes[b]

[a] see Section 6.4.1, table 6.3
[b] material properties of straw & clay mixture achieved after the straw bale had been dipped in a clay slip were taken from Oliva (2002)
[c] from WUFI material database
[d] (Minke, 2006)
[e] see fig. 3.5
[f] determines liquid transfer coefficients - suction and redistribution $[m^2\cdot s^{-1}]$
[g] (Straube, 2003)
[h] It is estimated from final moisture content, when running model one time with completely dry materials at the beginning.
[i] For lack of available data WUFI will not allow for it.
[j] (Andersen, 2004)

Table 7.3: Material properties required by WUFI simulation. Basic values are necessary for WUFI calculation. Optional parameters support more accurate calculation. Data taken from Appendix B.0.2, from table 5.3 if not specified otherwise.

Other input data

input data	[units]	actual value	see Appendix
time step			
	[h]	1	I.1
climate data			
exterior			
rain load	[$l\cdot m^{-2}\cdot h^{-1}$]	-[a]	I.2
solar radiation	[$W\cdot m^{-2}$]	-[a]	I.2
barometric pressure	[kPa]	101.27[b], 101.28[c]	I.2
temperature	[°C]	see Section 7.1.1	I.2.1
relative humidity	[%]	see Section 7.1.1	I.2.1
interior			
temperature	[°C]	see Section 7.1.2	I.2.2
relative humidity	[%]	see Section 7.1.2	I.2.2
surface transfer coefficients			
exterior			
vapour diffusion thickness	[m]	0	I.3.1
short wave radiation absorptivity	-	0[a]	I.3.2
long wave radiation emissivity	-	0	I.3.3
rain water absorption factor	-	0[a]	I.3.2
heat transfer	[$W\cdot m^{-2}\cdot K^{-1}$]	17	H.7.1
water vapour transfer	[$kg\cdot m^{-2}\cdot s^{-1}\cdot Pa^{-1}$]	$75\cdot10^{-9}$	H.7.1
interior			
heat transfer	[$W\cdot m^{-2}\cdot K^{-1}$]	8	H.7.1
water vapour transfer	[$kg\cdot m^{-2}\cdot s^{-1}\cdot Pa^{-1}$]	$25\cdot10^{-9}$	H.7.1
wall coponent			
orientation	-	-[d]	I.4.3
inclination	[°]	-[d]	I.4.3
height of the component	[m]	-[d]	I.4.3

[a] The wall assemblies under investigation are not exposed to rain, nor sun.
[b] Kota Baharu from eerae (2007)
[c] Barrow from eerae (2007)
[d] The data influence solar radiation and rain penetration[a].

Table 7.4: The rest of the input data required by WUFI simulation software. More detailed information is available in Appendix I.

7.1.6 WUFI calculation

During the first run of the calculation, it became clear that simulation over a 1 year period doesn't provide adequate data. According to the chart in fig. 7.12 it takes almost a year for new materials within a wall assembly to gain perfect equilibrium with the surrounding environment. At least another year of stable data is needed for further investigation.

This means that the WUFI simulation was set to run over a period of 2 years, with annual ambient conditions repeating themselves twice. The relevant results for the purpose of this investigation are the 1 year "settled" data extracted from the second half of the overall WUFI calculation (see fig. 7.12).

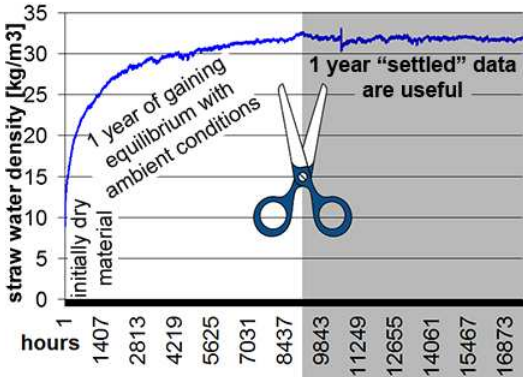


Figure 7.12: Each calculation will be performed over a 2 year period. **Blue** curve shows the calculation results of **water density (defined as how many kg of water are in 1m^3 of material**, see Section 3.5) in straw (wall assembly ESE) in the climate of Kota Baharu in Indonesia. It is apparent that for initially dry material within a wall assembly, it takes almost a year (0-8772 hours) to gain equilibrium with the ambient conditions and to settle its moisture profile. Thus the most useful results are the 1 year data extracted from the second (settled) half of the overall calculation output.

7.1.7 Summary of results

Simulated straw bale walls provide a pleasant and moderate environment inside the house, despite the extremely humid and extremely hot/cold weather. It will be interesting to compare the results of moisture transfer through all of the wall assemblies under investigation, both to each other and between the two locations.

One summer day (June 25th, 10:00)

On June 25th at 10:00, the temperature and relative humidity outside the virtual straw bale house in Alaska was 5°C and 83%. At the same time, the fictional house in Indonesia was exposed to 29°C and 88% relative humidity. These values of relative humidity and temperature, as they were monitored by virtual internal monitors in wall assemblies ESE and EdSdE (see fig. 7.13), confirm the basic difference between the two climates. A cold humid climate (blue curves on fig. 7.13) is characterized by moisture transfer from the warm side of the wall to the cold side. The wall gets gradually more humid towards the exterior, which is the usual scenario for the most of the straw bale building world . However, in a hot humid climate (red curves on fig. 7.13), relative humidity has a reversed gradient. The wall gets seriously saturated with water towards the interior of the building.

Fig. 7.13 provides an excellent opportunity to consider the moisture benefits of straw bale dip in clay slip.

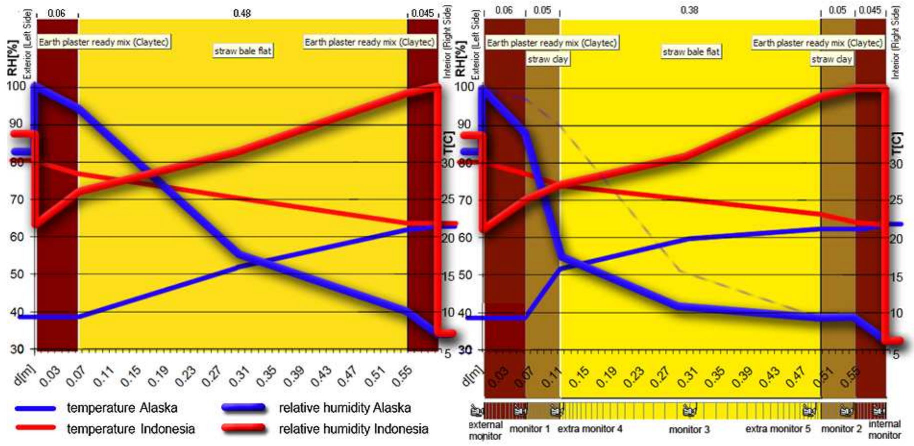


Figure 7.13: Two wall assemblies, ESE (on the **left**) and EdSdE (on the **right**) were "opened" on July 25th at 10:00 to give an instantaneous profile of relative humidity (**thick** curves) and temperature (**thinner** curves) measured in Alaska (**blue** colour) and Indonesia (**red** colour). The main difference between the two locations is that they have almost perpetually opposite gradients of temperature, which reverses the gradients of relative humidity. The wall in Alaska always has a warmer temperature on the inside of the house and a seriously humid exterior climate. The wall in Indonesia absorbs water on its interior side, because it is subjected to higher exterior temperatures throughout the year. Dipping the straw bales in clay slip seems to have a tremendous effect on relative humidity levels in straw in a cold humid climate, while in the hot humid climate the moisture profile through the dipped straw is similar to the one in the wall without a dip. The **faint thin dashed blue** line (chart on the right) shows the instantaneous relative humidity profile after the thermal conductivity of straw bale dip was altered from 0.12 $W{\cdot}m^{-1}K^{-1}$ to 0.4 $W{\cdot}m^{-1}K^{-1}$ in order to support theory of thermal conductivity being the major influence on moisture transfer through building components. *When looking at the charts above one has to keep in mind that the curves do not show a stabilized picture. They represent instantaneous measurements influenced by changing outdoors conditions.*

According to the simulation results, 50mm of straw bale dip (in final form: straw & clay mixture) to the outside of the wall in a cold humid climate has a tremendous ability to reduce the relative humidity level in straw. The overall properties of the straw & clay mixture certainly support a positive outcome but the humidity reduction seems to happen mainly because of its relatively low thermal conductivity (see table 7.7). The previous Chapter investigated the influence of input data on the results of simulation (see Section 6.4.4) and found out that thermal conductivity plays a major role in moisture transfer through materials. This is especially true for a wall with such a steep temperature gradient, like the wall exposed to weather in Alaska. The temperature gradient through the wall in Indonesia is much less pronounced, so the moisture-reducing effect of straw bale dip is negligible.

This theory was supported by another calculation, during which the thermal conductivity of straw & clay was intentionally tripled (0.12 $W{\cdot}m^{-1}K^{-1}$ was increased to 0.4 $W{\cdot}m^{-1}K^{-1}$), while the rest of the input data remained the same. The results of the adjusted simulation (see the faint thin dashed blue line in fig. 7.13, chart on the right) shows that with its thermal conductivity tripled, the dip in clay slip stops being a useful moisture buffer. In fact, the moisture influenced by straw bale dip with tripled thermal conductivity starts to behave like there wasn't any dip at all (compare with wall assembly ESE, chart on the left, fig. 7.13).

Water density

The WUFI simulation enables the monitoring of the development of water density in individual materials over the monitored time. According to WUFI-pro on line help (2007), water density is defined as: "how many kg of water are in $1m^3$ of material." (see Section 3.5).

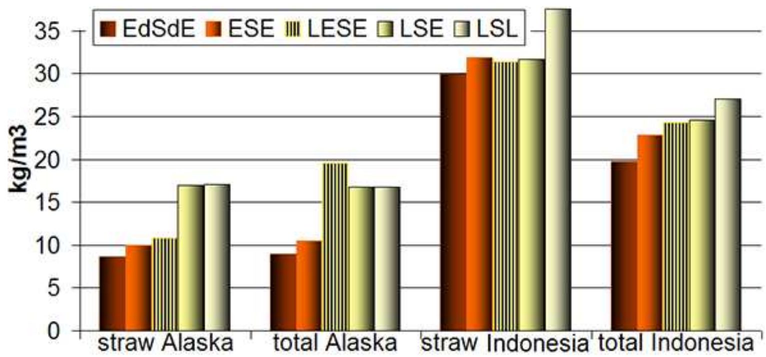


Figure 7.14: Each column represents a wall assembly. Its height shows the average weight of moisture (over a period of 1 year) that was kept within $1m^3$ of the monitored material (**straw**) or within $1m^3$ of the whole wall assembly (**total**). The **Left** part of the figure belongs to calculation results from Alaska, the **right** part gives results from Indonesia. Indonesian weather provides the straw bales with roughly twice as much moisture in comparison with the weather in Alaska. In general, earth plastered walls made with straw bales dipped in clay slip retain the least amount of moisture. Lime seems to lock more humidity inside wall assemblies than earth.

The average yearly amount of water in volume of single material or in volume of the whole wall (total water density) offers an easy and obvious comparison of overall moisture performance in all investigated wall assemblies. At first glance, fig. 7.14 shows that about twice as much moisture is retained over a year in straw bale walls in Indonesia in comparison to identical wall assemblies built in Alaska.

As for individual wall assemblies in the same climate, chart on fig. 7.14 confirms that straw bale dip works. It reduces the amount of water in straw as well as the total amount of moisture over the whole wall assembly in both regions, especially in Alaska. In a cold humid climate (in Alaska), straw is considerably dryer when there is earth plaster, in whatever form, on the outside of the wall. In cold humid weather, an application of lime plaster seems to attract more moisture to the straw. Straw in Indonesian walls has an almost constant amount of water in it when the interior plaster is earth. Wall assembly LSL, with lime on both sides, has in hot humid climate the worst moisture profile.

The whole wall assembly LESE in the Alaskan climate absorbs the greatest amount of water, according to fig. 7.14 (total Alaska). The same figure confirms that the moisture isn't retained in the straw. It is retained in the exterior plaster (see fig. 7.15).

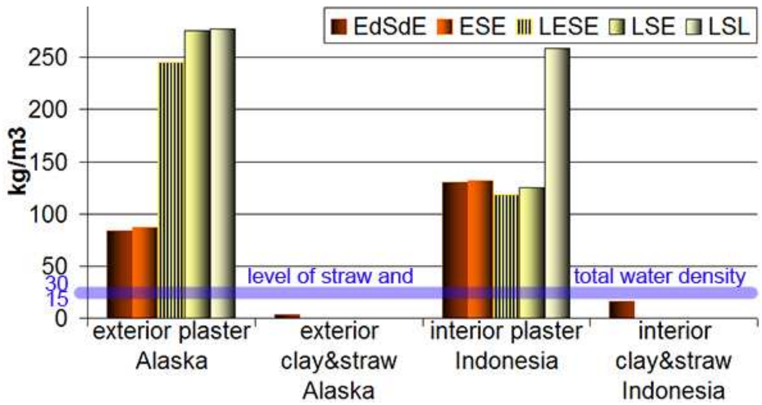


Figure 7.15: Water density in the most humid plaster, which is in Alaska the exterior plaster and in Indonesia the interior one. The blue line shows (for comparison) the level of total water density as well as the water density found in straw from fig. 7.14. It is interesting that the Alaskan exterior earth plaster in the wall assembly EdSdE has about 80 kg of water in each 1 m^3 while 1 m^3 of dip containing straw & clay **just next to it** remains very dry. It absorbs only 3kg. The dip in Indonesia behaves in a similar way. Interior earth plaster has 130 kg/m^3 and the straw & clay next to it only 16 kg/m^3.

Fig. 7.15 shows that in a cold humid climate, 20mm of lime plaster finish over 40mm of earth plaster scratch coat is a moisture catcher (as all the lime plaster finishes on straw bales seem to be). It appears that the moisture performance of walls plastered with just earth is much better.

In Indonesia, all the wall assemblies have similar interior plaster water density except the wall assembly LSL. This is the only wall assembly which has a non-earthen interior finish. Its interior lime plaster absorbs about twice as much water.

According to fig. 7.13 in the previous subsection, the exterior earth plaster of the EdSdE wall assembly in Alaska shows high levels of relative humidity, while the mixture of straw & clay (straw bale dipped in a clay slip) just next to it has a considerably reduced amount of moisture over its thickness. This fact is supported by the results presented in fig. 7.15 above. There are 80 kg of water in each 1 m^3 of exterior earth plaster in the wall assembly EdSdE simulated in Alaska while the neighbouring dip of straw & clay remains very dry. Each 1 m^3 of straw & clay mixture contains only 3 kg of moisture. A similar effect can be observed in the EdSdE wall assembly in Indonesia, where interior plaster with water density of 130 kg/m^3 is next to dipped straw bales with water density of only 16 kg/m^3.

Dynamic monitoring

Relative humidity monitors buried in the straw of virtual wall assemblies in Indonesia and Alaska collected hourly readings over a period of 1 year. The focus was on three locations. Monitor 1 gathered relative humidity data in straw just under the exterior plaster, monitor 2 was placed in the middle of the straw bale and monitor 3 was in straw very near the plaster towards the interior of the building (see figs. 7.8 - 7.11).

Alaska

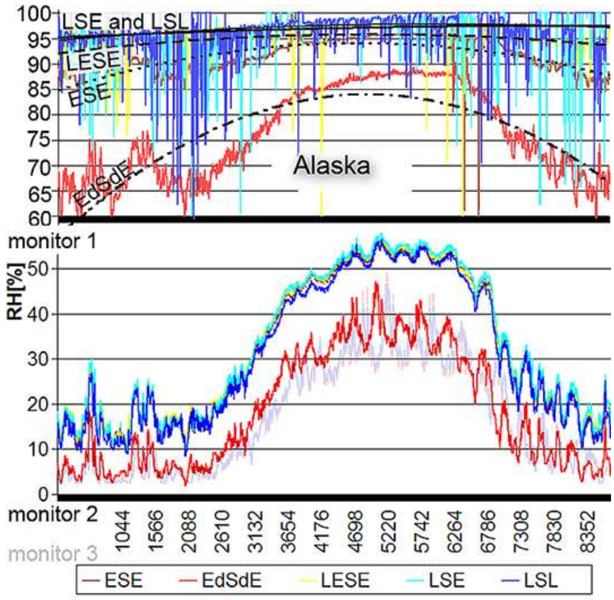


Figure 7.16: Simulation results of relative humidity development in Alaska (from January 1st to January 1st of the next year), in straw bale wall assemblies ESE, EdSdE, LESE, LSE and LSL (see figs. 7.8 - 7.11) , collected by three monitors: in straw just next to the exterior plaster (**monitor #1**), in the middle of the straw bale (**monitor #2**) and in straw just under the interior plaster (**monitor #3**). The data provided by monitor 3 are almost identical in all wall assemblies (see **faint grey** curve in the lower part of the chart). The EdSdE wall assembly in monitor position 2 gives much better data than the same position in the other wall assemblies (see **red** curve in the lower part of the chart in comparison to the **conglomerate of** coinciding **blue** curves just above it). Monitor #3 shows the advantage of the dip and also illustrates the differences between the influence of exterior earth plaster on straw with the influence of lime plaster on straw in the same location (see fig. 7.17).

Fig. 7.16 presents relative humidity data provided by 3 monitors in all wall assemblies of the Alaskan house.

The simulation in monitor locations 2 and 3 gives good results. The interior facing half of each wall assemblies dries out in winter and gets only moderately wet during summer. Both locations show coinciding relative humidity data despite different wall assemblies. The only exception is the data from monitor 2 in wall assembly EdSdE (red curve in the lower part of the chart). Relative humidity readings in the middle of a straw bale that was dipped in clay slip are significantly lower than readings in the same location in all other wall assemblies. This result was anticipated when discussing the instantaneous humidity profile (see fig. 7.13).

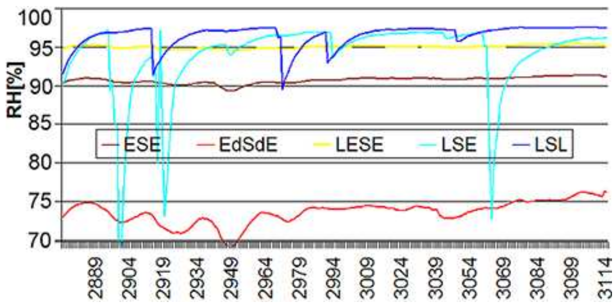


Figure 7.17: Detail of simulated data in monitor position 3 in all wall assemblies in Alaska over a randomly chosen period of 10 days. Lime plaster seems to react to weather more dynamically than clay. **Dark blue** and **light blue** curves show signs of significant drying and wetting on an almost daily basis, even though the straw under the lime plaster tends to remain wet close to saturation point for the most of the time. Straw under the earth plaster with lime plaster finish is perpetually very wet (see **yellow** line). However, WUFI-pro online help (2006) warns that simulation of very humid conditions in straw is unreliable (see the previous Chapter, Section 6.5).

The upper part of the chart shows the development of relative humidity conditions under the exterior plaster provided by monitor 1. Close observation reveals the difference between the data measured under the earth plaster and the data influenced by lime plaster. Not only are the relative humidity values under the earth plaster in wall assemblies ESE (brown curve) and EdSdE (red curve) lower than the values monitored under the lime plaster, but they are much more stable and the earth plaster tends to dry out over the winter. The drying is very significant in straw bales dipped in clay slip (red curve). The data measured under the lime plaster in wall assemblies LSL, LSE and to some extent also LESE are largely unstable and their values are consistently very high over the whole year. According to WUFI simulation, lime works with moisture more dynamically than clay. Short periods of drying under the lime plaster are followed by longer periods of serious wetting (see fig. 7.17).

Lime plaster finish on top of the earth plaster scratch (body) coat seem to have adverse effect on the straw behind it. The WUFI simulation shows that

20mm of lime plaster locks humidity into the earth plaster. It discourages drying and makes the neighbouring straw permanently wet (see the yellow line on fig. 7.17). However, let's not forget that the WUFI simulation of straw moisture behaviour is unreliable in the "grey area" of very high relative humidity levels (see the previous Chapter, Section 6.5).

Indonesia

Fig. 7.18 shows the WUFI simulation results recorded by three monitors in all wall assemblies situated in the tropical climate of Indonesia.

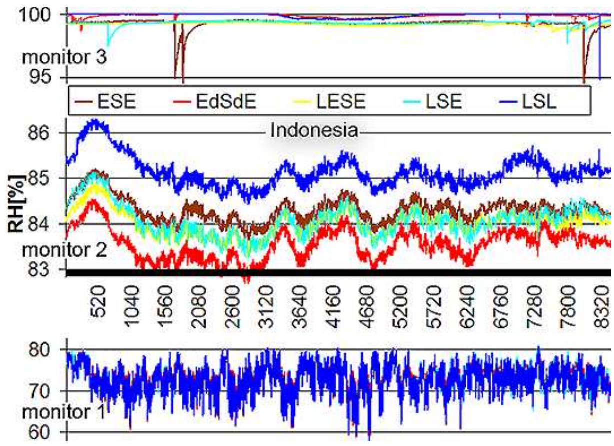


Figure 7.18: The simulation results of relative humidity development (from January 1st to January 1st of the next year) in all wall assemblies under investigation in Indonesia. Data were collected by three monitors: in straw just next to the exterior plaster (**monitor #1**), in the middle of a straw bale (**monitor #2**) and in straw just under the interior plaster (**monitor #3**). The most dynamic response to changes of ambient relative humidity is showed by the environment in straw under the exterior plaster (monitor #1). The diurnal relative humidity changes have amplitude of about 10%. Monitor 2 gives more or less steady results with the amplitude of 1% relative humidity. Variations among individual wall assemblies are within 1% of relative humidity (the chart in the middle, which exaggerates this fact due to the fine relative humidity scale). Monitor 1 provides saturated data, even though this might be unreliable (see the previous Chapter, Section 6.5). Sudden shifts towards lower values of relative humidity in this location (see the top chart, abrupt sinks in brown and light blue curves) are most probably caused by major divergences in calculation. It is unlikely that earth plaster would give those dynamic responses.

Again, the difference is apparent at first sight. In Indonesia, the straw inside a wall gets progressively more humid. There isn't any drying. There aren't great differences between individual wall assemblies. The average relative humidity in straw over the whole bale is in all cases around 85%. Monitor position 1 shows that straw under the interior plaster is perpetually saturated no matter the wall assembly.

Warm and humid straw bale house in Indonesia

The simulation input that has the greatest influence on the calculation of moisture profile through the building components are the ambient conditions (see previous Chapter, Section 6.4.4). The results of the previous calculation were based on the fact that despite very humid and hot[1] Indonesian weather, the straw bale house had an inside temperature average of 21 °C and 55% relative humidity (see table 7.5). The previous calculation proved that these somewhat unrealistic conditions (especially difficult to achieve without an air conditioning system) put a great strain on the straw in the walls.

Would the moisture performance in the straw bale wall improve with slightly adjusted and perhaps more natural and realistic interior conditions?

	previous		adjusted	
	T [°C]	RH [%]	T [°C]	RH [%]
mean value	21	55	25	60
amplitude	1	5	3	5
day of maximum	6/3/2007	8/16/2007	6/3/2007	8/16/2007

Table 7.5: Perhaps more realistic interior conditions inside the simulated straw bale house in Indonesia would put less strain on the straw inside the wall assemblies under investigation.

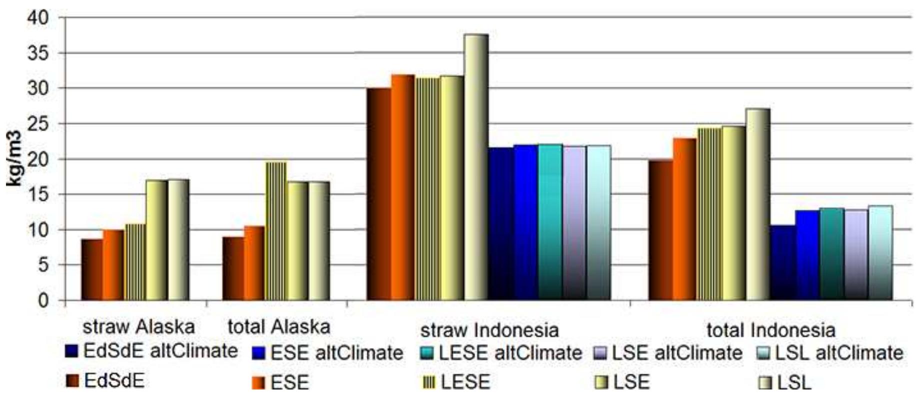


Figure 7.19: Total water density and water density in straw within all investigated wall assemblies was presented by fig. 7.14. In this chart, the same values are compared with results of the new simulation with slightly adjusted interior conditions (see table 7.5). All of the wall assemblies seem to benefit from the adjustment (see **blue** columns).

Allowing the interior of a straw bale house in Indonesia to work more dynamically with weather, to be about 4°C warmer and 5% more humid results in much dryer walls (see the blue columns on fig. 7.19). As for moisture performance in the hot humid climate, there are practically no differences among the individual wall assemblies.

[1]Kota Baharu: average yearly relative humidity = 83%, average yearly temp. = 27 °C)

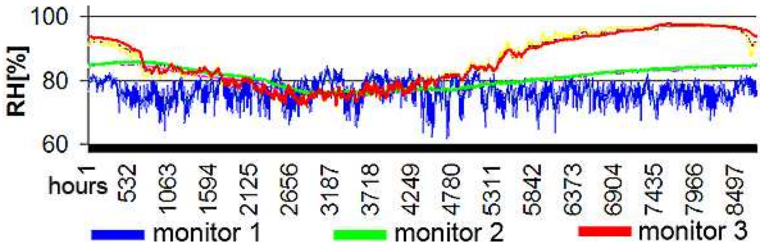


Figure 7.20: . Results of WUFI simulation over a 1 year period, from January 1st to January 1st of the next year. The charts show dynamic moisture performance in all the wall assemblies under investigation in Indonesia with adjusted interior conditions (see 7.5). In a hot humid climate, there seems to be no difference among the individual performances of different wall assemblies. The **Red** curve shows a blend of curves belonging to all wall assemblies, representing the dynamic relative humidity profile collected by monitor 3. The **Green** curve matches all wall assemblies at monitor position 2 and the **blue** curve gives the relative humidity data collected in all wall assemblies at position 1.

Fig. 7.20 further proves it. Curves belonging to dynamic relative humidity profiles of all of the investigated wall assemblies in a given monitor position blend into one thick line. During summer, the moisture profile through the wall levels out across the straw in the wall, as all monitors seem to measure about 75% relative humidity. In winter, straw towards the interior side of the wall gradually gets very wet.

7.1.8 Resume

The WUFI simulation showed that in the cold and wet climate of northern Alaska, earth plastered straw bale dipped in a clay slip is a winner. Assembly EdSdE ensures that the relative humidity in straw is always kept at a reasonable level, no matter how wet or cold the outside weather. Earth plaster on both sides of a bale without a dip is another good solution, although the values of relative humidity close to the exterior get quite high during the Alaskan summer. The simulation of lime plastered walls (assemblies LSE and LSL) shows very wet straw under it, even with lime plaster finish on a scratch (body) coat of earth plaster (wall assembly LESE). In this particular case lime plaster seems to trap moisture in earthen part of the straw bale coat, even though it doesn't seem to have any effect on moisture density across straw behind it.

According to WUFI, it looks like very wet and hot climates are problematic for straw bale construction. The simulation of an "air conditioned" interior was a potential disaster for straw in a wall, no matter what it was covered with. Considerable improvement of the water retention in straw was achieved when the temperature in the interior of the house was sometimes above 25°C, especially when the outside was more than 30°C. The adjustment of interior conditions resulted in humid walls with relative humidity across the wall almost constantly above 80%.

The simulation results weren't significantly different from one wall assembly to another. The amount of moisture in straw within a wall in hot humid weather doesn't significantly depend on a particular wall assembly. According to WUFI's results, the theory of having a less permeable surface on the outside and a more permeable on the interior of the house (wall assembly LESE and LSE) didn't prove effective in a tropical climate.

7.2 Simulation of a case study in Plozevet, Brittany, France

Section 4.2.1 analyzed the consequences of a disastrous storm that caused a lasting high humidity level (about 75%) in straw in the western wall of a straw bale house in Plozevet, Brittany, France. The research estimates drying at the very slow rate of about 1% of relative humidity per month (see fig. 4.17). It could be interesting to use WUFI to simulate this case study in order to see if it agrees with the data showing such a slow drying process. If the results of a WUFI simulation match the monitoring, WUFI can estimate how long it would actually take for this wall to dry out.

In order to obtain a successful simulation it is necessary to provide WUFI with input that would match the case study in Plozevet as closely as possible. However, the following simulation serves to give a general trend, rather than precise values, so when considering the input data, some simplification will be necessary.

7.2.1 Choosing an appropriate wall assembly to match the wall in Plozevet

The complete wall assembly in Plozevet includes exterior timber cladding with a ventilated air gap approximately 40mm in front of a lime plastered straw bale wall. The WUFI model fails to calculate moisture transfer through an air gap (see Section 6.3.1), though it proved to be quite accurate in calculating moisture profiles through the simple wall assembly plaster—straw—plaster. It is reasonable to simplify the model. Let's assume that the ventilated air gap will supply the lime plastered straw bale wall with relative humidity and temperature in accordance with the weather outside. The timber claddng and ventilated air gap will be omitted from the simulation. Further simplification will be achieved by assuming that the timber cladding shields the wall assembly from the direct influence of rain and sun. This way solar radiation and precipitation data can be omitted from the input of exterior ambient conditions.

7.2.2 Choosing ambient conditions to match those in Plozevet

External ambient conditions

External ambient conditions were obtained from eerae (2007), using the hourly temperature and relative humidity data collected for 1 year in Brest, which is approximately 60 km north of Plozevet.

Internal ambient conditions

Internal ambient conditions inside the straw bale house in Plozevet were irregularly monitored during spring and summer 2006 (see Appendix E). These data are sufficient for modeling the yearly interior conditions by sine wave with reasonable accuracy (see table 7.6).

	T [°C]	RH [%]
mean value	18	60
amplitude	3	5
day of maximum	7/25/2007	7/25/2007

Table 7.6: These interior conditions characterize sine waves of temperature and relative humidity within a yearly period. Their mean value and amplitude match the interior conditions in Plozevet with reasonable accuracy.

7.2.3 Input data

Wall assembly, monitor position and grid

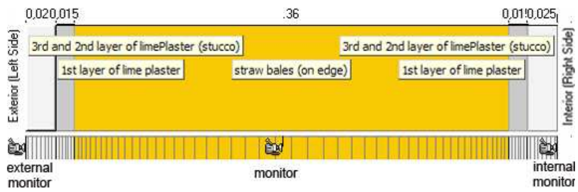


Figure 7.21: LSL wall assembly in Plozevet. The 2nd and 3rd layer of lime plaster have the same material properties as the lime stucco used for LSL, LSE and LESE wall assemblies in the previous Section. It is 25mm thick in total. The thickness of the 1st layer of lime plaster is 15mm and it will be slightly less permeable than the 2nd and the 3rd coat due to the hydraulic lime that was added to mixture (see Section 4.2.1). Straw bales in Plozevet were laid on edge, thus their thickness is 360mm. A virtual monitor was installed in the exactly same place as the datalogger that measured relative humidity and temperature in the actual wall in Plozevet — in the middle of the straw bale.

The lime plaster — straw bale on edge — lime plaster wall assembly in Plozevet was introduced in Section 4.2.1 in great detail.

Material properties

material characteristic	units	straw[a]	lime plaster 1st coat	lime plaster 2nd and 3rd coat[a]
basic values				
bulk density	$[\mathrm{kg \cdot m^{-3}}]$	100	1600	1600
porosity	$[\mathrm{m^3 \cdot m^{-3}}]$	0.9	0.3	0.3
vapour diffusion coefficient	[-]	2	10	7
dry material:				
specific heat capacity	$[\mathrm{J \cdot kg^{-1} \cdot K^{-1}}]$	2000	850	850
thermal conductivity	$[\mathrm{W \cdot m^{-1} K^{-1}}]$	0.085	0.8	0.7
optional parameters				
sorption isotherm		yes[b]	yes[c]	yes[c]
water absorption coeff.[d]	$[\mathrm{kg \cdot m^{-2} \cdot s^{-\frac{1}{2}}}]$	-	$1.5 \cdot 10^7$ [c]	$1.5 \cdot 10^7$ [c]
typical built in moisture[e]	$[\mathrm{kg \cdot m^{-3}}]$	9	1.4	1.4
moisture dependent:				
thermal conductivity	$[\mathrm{W \cdot m^{-1} K^{-1}}]$	-[f]	0.7 - 1.7[c]	0.7 - 1.7[c]
vapour diffusion coefficient	[-]	yes[g]	yes[c]	yes[c]

[a] see Section 6.4.1, table 6.3
[b] see fig. 3.5
[c] from WUFI database
[d] determines liquid transfer coefficients - suction and redistribution $[\mathrm{m^2 \cdot s^{-1}}]$
[e] It is estimated from final moisture content, when running the model once with completely dry materials at the beginning.
[f] For lack of available data WUFI will not allow for it.
[g] (Andersen, 2004)

Table 7.7: Material properties required by WUFI simulation. Basic values are necessary for WUFI calculation. Optional parameters support more accurate calculation. Data taken from Appendix B.0.2, or from table 5.3 if not specified otherwise.

Other input data

input data	[units]	actual value	see Appendix
time step			
	[h]	1	I.1
climate data			
exterior			
rain load	$[l \cdot m^{-2} \cdot h^{-1}]$	-[a]	I.2
solar radiation	$[W \cdot m^{-2}]$	-[a]	I.2
barometric pressure	[kPa]	100.01[b]	I.2
temperature	[°C]	see Section7.2.2[b]	I.2.1
relative humidity	[%]	see Section7.2.2[b]	I.2.1
interior			
temperature	[°C]	see Section7.2.2	I.2.2
relative humidity	[%]	see Section7.2.2	I.2.2
surface transfer coefficients			
exterior			
vapour diffusion thickness	[m]	0	I.3.1
short wave radiation absorptivity	-	0[a]	I.3.2
long wave radiation emissivity	-	0	I.3.3
rain water absorption factor	-	0[a]	I.3.2
heat transfer	$[W \cdot m^{-2} \cdot K^{-1}]$	17	H.7.1
water vapour transfer	$[kg \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}]$	$75 \cdot 10^{-9}$	H.7.1
interior			
heat transfer	$[W \cdot m^{-2} \cdot K^{-1}]$	8	H.7.1
water vapour transfer	$[kg \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}]$	$25 \cdot 10^{-9}$	H.7.1
wall component			
orientation	-	-[c]	I.4.3
inclination	[°]	-[c]	I.4.3
height of the component	[m]	-[c]	I.4.3

[a]The wall assembly in Plozevet is permanently covered by exterior timber cladding, therefore it isn't exposed to rain or sun.
[b]Brest from eerae (2007)
[c]The data normally influenced by solar radiation and rain penetration[a].

Table 7.8: The rest of input data required by WUFI simulation software. More detailed information is available in Appendix I.

7.2.4 Calculation by WUFI

The WUFI calculation begins with the start of monitoring in the actual wall in Plozevet: January 25th 2006 (see Section 4.2.1). The initial relative humidity over the whole wall assembly will be input in WUFI dialog at 80% across the whole assembly, which is the value that was measured by the datalogger in the middle of the wall on the first day of monitoring (see fig. 4.17). The simulated wall will be exposed to ambient conditions for three years and the results from the virtual monitor in the middle of the fictional straw bale wall in Plozevet will show the relative humidity profile and thus the rate of drying.

7.2.5 Summary of results

Indeed, WUFI confirms the slow drying process. The simulated wall might be drying at a slightly faster rate, but fig. 7.22 shows that the difference between simulation and reality is negligible.

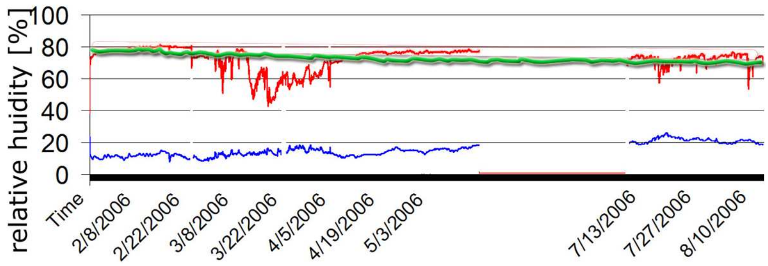


Figure 7.22: The **Red** curve gives relative humidity data collected by a datalogger that was placed in the middle of the wet straw bale wall in Plozevet 8 weeks after the damaging storm. The actual rate of drying is about 1% per month. The **Green** curve represents the results of WUFI simulation at the same location. The initial condition in WUFI dialog was set at 80% of relative humidity across the whole wall assembly. There is a very small difference in the drying rate between the relative humidity measured in the real wall and the relative humidity calculated by the model.

In order to estimate the time necessary for drying, it would be useful to run another calculation, this time starting one year earlier (January 25th, 2005), with dry straw. It would take close to one year for dry straw to gain equilibrium with the ambient conditions. After one year, however, the humidity in straw within an initially dry wall should perform in accordance with ambient conditions. This simulation is going to represent a "healthy" wall that was never subjected to an accident. It will be a matter of time for the relative humidity profile of an initially wet wall to merge with the moisture pattern for a healthy wall. The time needed for that to happen will be the drying time (see fig. 7.23).

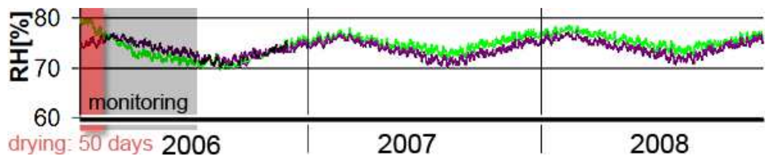


Figure 7.23: Results of two simulations run over a three year period are necessary to estimate drying time after the wall in Plozevet was wet by a disastrous storm. The **Green** curve shows the relative humidity profile in the middle of the straw bale wall in Plozevet, which had 80% relative humidity throughout at the beginning of the simulation. It represents an accident which happened December 1-2nd, 2005 (see Section 4.2.1). The **Dark purple** curve displays a relative humidity profile in a straw bale wall without any defect. It is performing naturally in accordance with local ambient conditions. The time needed for the green curve to merge with the dark purple one is the total drying time (see pink area, approx. 50 days). The gray area spreads across the time of monitoring in Plozevet (see fig. 7.22).

7.2.6 Resume

According to fig. 7.23, it took roughly 60 days (counting from the start of monitoring) for the curves to merge. Given that the damage happened on December 1-2nd, 2005, 8 weeks before the start of monitoring, straw needed altogether about 120 days for its recovery from saturation caused by driving rain.

Besides the drying time, the simulation over three years shows another surprising revelation. The average relative humidity in the middle of the lime plastered straw bale wall in Plozevet is quite high: 74% (see fig. 7.23). A higher value could be measured only in the middle of a straw bale wall built in Indonesia.

7.3 Summary of Chapter 7

Chapter 6 has shown that if wall assemblies are kept basic (plaster—straw—plaster) and "air convection free", the results of WUFI simulation agree with the monitored cases with reasonable accuracy. Simple ambient conditions, without extensive rain and solar data contribute to the transparency of calculated values, so that it is simple to trace any oddity, or disagreement in the simulated results. These basic precautions put a researcher in an excellent position to simulate other dynamic cases with confidence in the reliability of the results.

WUFI simulation assumes that the saturated straw in the western wall in Plozevet dried out about 120 days after the storm that caused the saturation. Surprisingly, the high value of relative humidity in the middle of the straw bale wall in Plozevet occurs naturally due to the humid local climate. It was anticipated that even without any moisture damage, the average relative humidity value in a lime plastered straw bale wall in Plozevet is 74%.

Besides the drying in the Plozevet wall, WUFI simulation investigated two basic scenarios: Alaska and Indonesia. In each scenario, five different wall assemblies were analyzed for their internal moisture performance over a period of two years in extremely humid weather conditions. WUFI simulation results revealed one basic difference between the two diverse locations. The type of plaster on an Indonesian straw bale wall doesn't seem to affect its moisture content at all. No matter what wall assembly, relative humidity across straw in Indonesia is always high. In Alaska, on the other hand, the characteristics of plaster influence humidity in straw significantly.

- *Earth plaster - straw bale dipped in a clay slip - earth plaster*

  Earth plastered straw bales dipped in clay slip proved to perform the best by far out of all assemblies under investigation in cold humid weather. The property that seems to enhance the excellent moisture buffering capacity of the dip (straw & clay mixture)is its good insulating characteristic (thermal conductivity). That might explain why it works so well in Alaska where there is a large temperature gradient through the wall, while it doesn't affect the humidity profile in a wall in Indonesia, where the temperature of the outside air is similar to that inside a house.

- *Earth plaster — straw bale — earth plaster*

  WUFI confirmed that this classic straw bale assembly, well-tested in buildings standing for more than 100 years in Nebraska, performs reasonably well in Alaska, despite the fact that relative humidity values in the wettest part of the straw (next to the exterior plaster) sometimes reached as much as 95% during summer months.

- *Lime plaster finish - scratch (body) coat of earth plaster — straw bale — earth plaster*

  Even though quite common in cold and humid North America, in the cold and humid climate of Alaska this wall assembly acted as a moisture catcher. According to WUFI results in Alaska, lime plaster finish seem to prevent earth plaster from drying and moisture tends to get trapped within the exterior scratch earth plaster. However, in this case the moisture level across the Alaskan straw bale wall seems to be reasonably good, except, again, for the very high humidity levels appearing in the most stressed part of the wall, just under the exterior plaster.

- *Lime plaster — straw bale — earth plaster, lime plaster — straw bale — lime plaster*

  Out of all the examined wall assemblies, lime plastered bales delivered the worst moisture performance. Straw in an Alaskan wall is often saturated under the exterior lime plaster, regardless of whether there is earth plaster or lime plaster on the interior of the wall. In the middle of the wall, there is no difference between the humidity level in straw plastered with lime, and humidity levels in the straw of the other wall assemblies under investigation.

  WUFI doesn't provide confirmation of the theory describing the benefit of having more permeable plaster on the interior side and less permeable plaster on the exterior side of straw in a hot and humid climate. The simulation of moisture in straw plastered with lime on the outside and earth on the inside of a house in Indonesia shows the same results as simulation across any other investigated wall assembly exposed to the same conditions.

  In order to gain more confidence in simulating wall assemblies containing lime plaster, the WUFI computer model should have been benchmarked using a case study with lime plastered straw bale walls.

Dynamic relative humidity profiles as results of WUFI simulation through all of the investigated wall assemblies suggest that there is no problem with building straw bale houses in northern Alaska, while it seems questionable to build them in Indonesia. The average relative humidity through straw bales in Indonesian walls, despite different wall assemblies, is about 85% and the straw just behind the interior plaster of all wall assemblies was saturated most of the time. When analyzing WUFI results displaying straw saturation one has to be careful not to draw any definite conclusions. WUFI isn't reliable in simulating very high relative humidity in straw. As regards straw bale building potential in equatorial regions, further research needs to be done to establish if straw bale construction is appropriate for these hot and humid climates.

Chapter 8

Questionnaire

So far, this thesis has looked at the causes of straw rot and the relevance of relative humidity for its determination; it has summarized the results of existing research into moisture monitoring in straw bale walls; it introduced a theory behind moisture transfer across straw bale walls and proved that WUFI computer simulation could be used for detailed investigation of moisture behaviour in different straw bale wall assemblies. The investigation by computer model brought forward the assumption that the right choice of straw protection plays an important role in successful straw bale building design.

Since there are a growing number of straw bale building professionals worldwide, and many of them have had in-depth experience with straw bale building, some of these experts were asked to share their knowledge through a questionnaire. This Chapter will introduce their expert opinions into the mixture of theory and practice presented up to this point.

8.1 Sending out the questionnaire

The questionnaire was addressed to experienced straw bale builders and architects. Its goal was to find out:

- the most common reasons for straw rot in existing straw bale walls
- the best proven prevention against moisture failure of a straw bale construction

At first, a draft of the questionnaire was reviewed by professional straw bale builder Bee Rowan of Amazon Nails, straw bale pioneer and self builder Martin Oehlmann and student of architecture Jonathan Parker. All the comments were carefully integrated into a second version, which was then sent by e-mail to 86 selected professional straw bale builders from all over the world. Two weeks later, more professional straw bale builders were approached with the questionnaire through the Global Straw Bale Network, GSBN[1]

8.2 Statistical analyzes of the questionnaire

Feedback from 27 completed questionnaires was collected and statistically processed. Even though 27 respondents is not enough to generate reliable statistical analysis, most of them have adequate experience to give this research a sufficient base. As discussed further in Section 8.2.2, 72% of respondents have participated in building more than 10 straw bale houses.

Furthermore, some of the architects, engineers, straw bale builders and straw bale building contractors who answered the questionnaire are all professionals who have decided to dedicate their careers to straw bale construction. There are people amongst them like Barbara Jones (UK), Andre de Bouter (France), Bruce King (USA), Chris Magwood (Canada) and Herbert Gruber (Austria) who have written popular books about straw bale building. Other respondents like Rikki Nitzkin (Spain), Chug (UK), Frank and Ingrid (Australia), Dirk Schramer (Germany), Martin Hammer (California), Rene Dalmeijer (Holland), Greame North (New Zealand), Jeff Ruppert and David Arkin (Colorado) are professionals who are not only constructing with straw, but also lead national straw bale building networks.

8.2.1 Profession

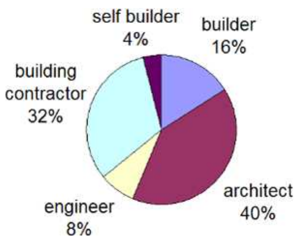


Figure 8.1: The chart shows the respondents' profession by percentage.

Fig. 8.1 shows that the majority of respondents are architects. Professional straw bale building contractors and professional straw bale builders made up another substantial part of respondents.

[1] An email discussion list composed of representatives of regional organizations and other non-affiliated key individuals involved in the general advancement of straw bale and other straw-use building materials and techniques.

8.2.2 Experience

According to fig. 8.2, 36% of respondents were involved with between 10 to 30 straw bale buildings. 28% of respondents have experience with 30 to 100 buildings. The same percentage has experience with less than 10 straw bale buildings. 2 respondents have participated in more then 100 buildings.

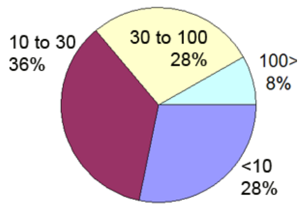


Figure 8.2: *How many straw bale buildings have you had direct involvement with designing and/or building?*

8.2.3 Favourite straw bale wall finish

Two questions concerned a favourite straw bale wall cover:

Interior finish

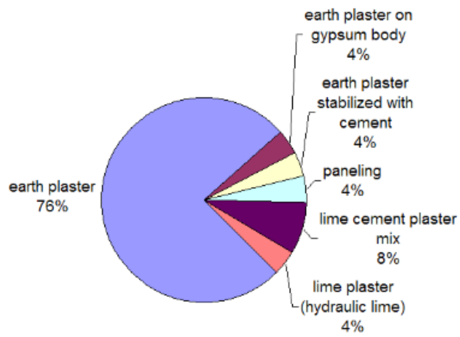


Figure 8.3: *What kind of finish do you prefer to use for the interior of a straw bale wall?*

The favourite interior straw bale wall cover is earth plaster (see fig. 8.3).

Exterior finish

The favourite exterior straw bale wall cover is again earth plaster, closely followed by lime plaster made from lime putty (see fig. 8.4).

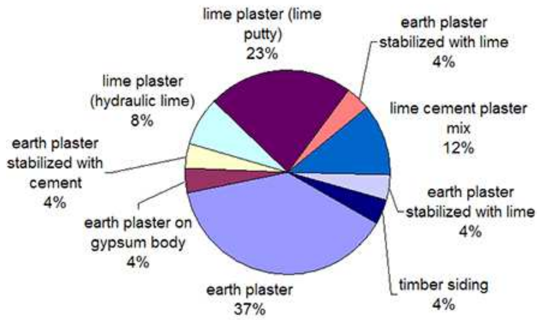


Figure 8.4: *What kind of finish do you prefer to use for the exterior of a straw bale wall?*

8.2.4 Weather resistance of exterior straw bale wall finish

Judging from the question: *What makes your exterior plaster weather resistant?* respondents don't have a universal method (see fig. 8.5).

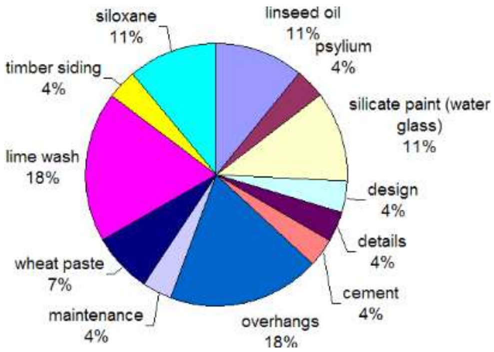


Figure 8.5: *What makes your plaster weather resistant?*

Lime wash and overhangs were the most cited options. Linseed oil, silicate based paint (water glass) and siloxane are quite popular as well.

8.2.5 Condensation in straw bale walls

According to the majority, condensation doesn't occur in the straw bale wall assemblies favored by respondents. The majority also agrees that condensation isn't a serious risk (see fig. 8.6).

Two questions were concerned with condensation:

Figure 8.6: Chart **on the left**: *With your choice of materials, do you think that condensation occurs in the straw just under the coat on the colder side of a straw bale wall?* Chart **on the right**: *Do you think that condensation is a serious risk?*

8.2.6 Causes of moisture problems in straw bale walls

Respondents were asked to write about cases of straw damage they had experienced that were related to specific moisture problems in straw bale walls. In this context, "moisture problem" signifies any problem related to straw and moisture (either directly or indirectly) that caused damage needing repair.

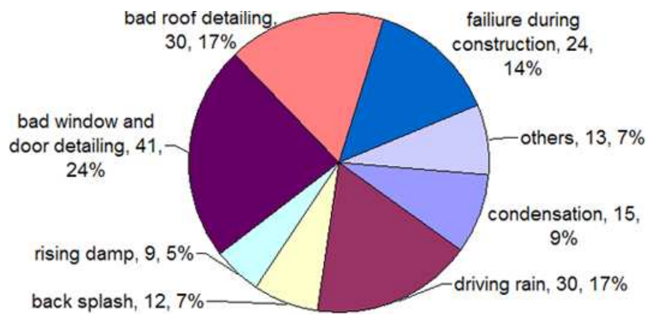


Figure 8.7: *How many straw bale buildings with a moisture problem that you think is related to* condensation; driving rain; backsplash; bad windows, door and roof detailing; failure during construction *have you encountered?*

In the course of their careers, 27 respondents encountered 174 moisture problems in total. Fig. 8.7 shows that straw moisture damage was caused by bad window and door detailing 41 times; 30 cases were related to bad roof detailing; 30 cases involved driving rain; on 24 occasions moisture failure was due to neglect during construction. According to the respondents, 15 cases of straw bale wall damage involved condensation.

8.2.7 Previously rained on straw

A bale that has been rained on becomes discoloured when it dries. Depending on the amount of rain exposure, the layer of discoloured straw penetrates the straw bale. Discolouration is caused by fungi that starts to be visible on straw stems. Straw affected in this way, even after it dries, is more vulnerable to rot when wetted again.

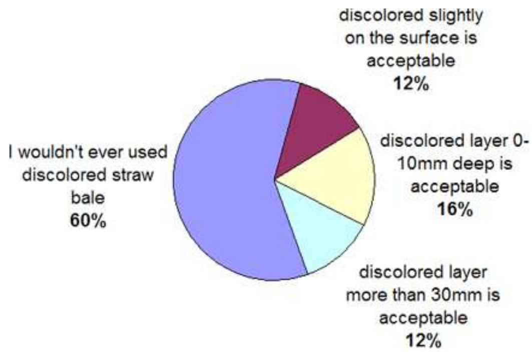


Figure 8.8: *What depth of penetration do you consider acceptable for use in straw bale construction?*

According to fig. 8.8, the majority of respondents would never use discoloured straw in straw bale construction.

8.2.8 Weeds and grass in straw

Sometimes a straw bale consists not only of pure straw but also of various weeds and grass. Weeds and grass generally contain more nutrients and for that reason, the mixture of straw, weeds and grass in bales could be more vulnerable to rot.

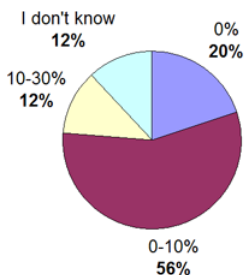


Figure 8.9: *What is the acceptable percentage of weeds mixed with straw in straw bales for use in straw bale construction?*

According to fig. 8.9 the majority of respondents consider up to 10% of weeds mixed in straw acceptable for construction.

8.2.9 Monitoring of straw moisture content

Two questions concerned moisture monitoring in straw:

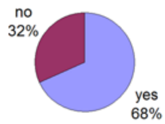


Figure 8.10: Chart **on the left**: *Do you use moisture meters?* Chart **on the right**: *Have you monitored moisture inside a straw bale wall?*

Fig. 8.10 indicates that the majority of respondents use moisture meters in order to check the moisture content of straw in bales during construction on the site. A smaller number of respondents, but still the majority, have actually monitored long term moisture development in straw bale walls.

8.2.10 Acceptable moisture content of straw

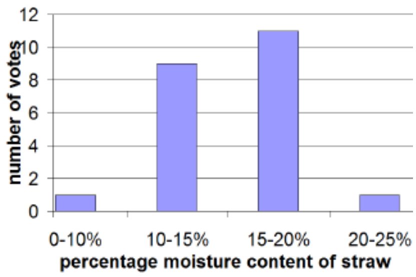


Figure 8.11: *What do you think is the acceptable moisture content of straw in inhabited straw bale buildings?* The basis of moisture content wasn't specified.

49% of respondents consider a range of moisture content between 15—20% as acceptable. For 41% of respondents, more conservative values of moisture content between 10—15% were acceptable .

8.2.11 Straw bale walls in a hot and humid climate

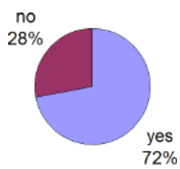


Figure 8.12: *Would you build, for a client, a straw bale construction in a hot, humid climate?*

According to fig. 8.12 the majority of respondents would take the risk of building a straw bale construction for a client in a hot and humid climate.

8.3 Quotes from completed questionnaires

Moisture stories

Within the questionnaire, respondents had a space to share any moisture stories that are funny, scary, or instructive, or to express any further recommendations. This Section presents a few quotes from this "free" space.

> "...cement plaster with lots of cracks where moisture could penetrate and get trapped, also this building was painted with oil based paints and appeared to be sweating. We measured the moisture content in some sections of the walls several years later and found readings in the bales up to 35%, this was one of the first straw bale buildings in Australia (thankfully not our project) and we believe we have come a long way since then with most people advocating natural renders and paints for straw bale walls.
>
> With the clay and lime render as well as the natural paint products we use, we seem to have very few problems with moisture here in Australia. We believe that most moisture problem incidents happen when cement plaster or oil based paints and sealers are used. Our finishes allow the walls to absorb and shed moisture, in other words the walls remain vapour permeable." (Frank & Ingrid)

•

> "A house with a roof leak happened when the owner/builder left town for 2 weeks with an unfinished roof. Many bales in the 8 bale (three string bales) high walls were saturated, with no mold. The building was wrapped in plastic and heated throughout winter. By late spring the walls were dry, still no mold, and have not had a moisture problem since." (the author wishes to be treated as anonymous)

•

> "The two houses with damage from driving rain have not been houses I built, but ones which I have been asked to comment on the problems and how to solve them. I don't know how to express strongly enough that people must not design bale buildings to achieve their desired aesthetic without considering how driving rain will hit the walls. A 24 inch overhang on a second story roof is not going to provide any protection for the lower walls! I feel bad about telling people that a fundamental design flaw is the root of their problem,

but it's true. If a client truly desires a particular appearance, then the bale walls should have a rain screen of some kind (wood siding I think is best) with an air gap of at least 1.5 inches to allow for air movement between the bale wall and the rain screen.

We often see patterns of moisture accumulation behind the exterior plaster on houses we have built. At first these scared the heck out of me! But having spent some time opening up walls in these places and testing and observing the straw, I don't feel that it is a problem. These spots occur where the straw in the wall is not as well packed, ie, where air is more free to circulate. Any moisture in this moving air condenses on the back of the plaster and soaks through as it dries out of the plaster. We most commonly see these spots when a streak of cold weather is followed by a day of much warmer temperatures. I speculate that on the continuously cold days, this moisture is transpiring into the very dry air very quickly, so doesn't accumulate in the plaster. A bit of warmer, damper weather will slow this drying and the moisture hangs out in the plaster a bit longer. The moisture meter inserted into this damp spot does not give worrying figures (usually under 15%), but the figures are higher than in the dry-appearing sections of wall. I haven't found any discoloured or deteriorated straw in these places, but don't know what another 50 years of cycling will do.

Most of this moisture is entering the wall from gaps in the interior plastering. Especially important is sealing up electrical boxes and the plaster seam with the ceiling and/or top plate. And making sure that the bales do not have voids or unstuffed areas stops moisture from accumulating in concentrated areas." (Chris Magwood)

•

"As for moisture stories, I have more than I have time to describe - come to Canada and buy my new book, "Design of Straw Bale Buildings"" (Bruce King)

•

"In 1998? when visiting the oldest straw bale building I know in California (built 1982) by Jon Hammond, which had the bales just stacked on a slab on grade, we were able to stick a bale moisture meter into the walls at their base, where we found.... air! Apparently, the bales had rotted away where they met the concrete, and the walls were being held up by the cement stucco skins." (Bob Theis)

•

"...also am concerned about snow accumulation next to bale walls where the snow melt takes place over an extended period, say over 30 days, that would keep the walls wet." (John Swearingen)

•

"Parapet roofs etc. are so high risk they should be banned." (Greame North)

Regarding the question: ***Would you build a straw bale house in a hot and humid climate?***

"Doesn't everyone? Think of your bathrooms and kitchens. What is important is to balance wetting potential with drying potential. In high humidity areas, this means the wetting potential should be zero. Maybe cladding could do this." (Chris Newton)

•

"This is a YES, with a big MAYBE attached to it. I would evaluate the entire scope of the project and determine if it would work. I wouldn't generally recommend it, but it could be done." (Jeff Ruppert)

•

"In a hot climate yes. It's humidity that I think is the problem. I think that you could build a straw bale sauna for instance and have a humid atmosphere inside, because it would pass to the outside as long as you have breathable plasters, but if you had humidity inside and outside the building, because of the climate, I think it would be risky. I can't say definitely whether it would work or not, because I've never tried it. I think it might be risky." (from an interview with Barbara Jones, see Appendix A.1)

•

"The experience is already there. The local people do build their houses with natural fibre. The truth is that the layer of fibre they use is less than 35cm thick straw bale, so they get more airation. They might also use other fibre than straw. They use fibre coming from that area, so I think it has to have its own natural protection. Maybe we should make the bales from that local fibre.

Yes. For sure I would take that job. I would take that risk." (from interview with Tom Rijven, see Appendix A.2)

8.4 Summary of results

At the end of this thesis, the summary of statistical data obtained by the questionnaire will serve as a tool for final recapitulation.

Earth plaster seems to be the favourite wall cover for both sides of straw bale walls. Lime plaster made out of lime putty is the second most popular exterior cover.

Exterior straw bale walls are most frequently protected by large overhangs and lime wash wall finish.

There seems to be a general consensus that previously rained on straw is not acceptable in straw bale construction, while a small percentage of weed and grass content in straw bales doesn't matter.

The majority of respondents use portable moisture meters to measure the immediate moisture content of straw. The acceptable level of moisture content seems to be 20-25%.

The subject of building with straw bales in a hot and humid climate provokes controversial responses . With the exception of Chris Newton, respondents lack experience. However, the majority believes that it could be done and would take the risk of building a straw bale house for a client in those specific conditions.

The most important conclusion the questionnaire provided is that moisture transfer caused by a difference between inside and outside vapor pressure, or inside and outside relative humidity and temperature isn't a threat to a straw rot inside a straw bale wall (no matter what plaster or cladding is used). The questionnaire supports the analyzes of the case studies from Chapter 4 in that the reason for straw rot in a straw bale wall is usually a concentrated leak of liquid water into a wall caused by:

bad design, lack of attention to detailing, or driving rain.

Chapter 9

Conclusion

While interest in environmentally appropriate building is increasing, and with the likelihood of environmental impact methods being imposed through legislation and regulation, now is the time for the building industry to fully acknowledge the potential of straw bale as a valuable building component.

> "Building physicists have much to offer to, and maybe to learn from, the alternative ecological enthusiasts who mix their clay with water from holy springs then tramp the mud to the accompaniment of lyrics from the high school songbook before smacking the dough up on the slowly rising wall of their new house. Practical work brings new insight and surprises." (Padfield, p.39, 2002)

Actual research, as well as a survey of theory, suggests that even with relative humidity of 78% peaking over the winter, the walls in Plozevet won't provide enough moisture for microorganisms to break them down.

Relative humidity is a satisfactory indicator of microbial growth because it is in absolute equilibrium with straw moisture content. Fluctuating relative humidity in a wall doesn't fully correspond to the amount of moisture absorbed by its materials, which will be always less than peaks of relative humidity would suggest. However, moisture isn't the only indicator of microbial life, and its influence on organic matter breakdown, as well as the influence of the other factors, is still not completely understood. However, it is clear that for the extensive decomposition of straw, microorganisms need a long term supply of liquid water, that is, an environment with relative humidity very close to 100%.

When designing and constructing straw bale buildings, it is extremely important to avoid any long-term liquid moisture occurrence within the straw bale walls.

- The most frequent source of long-lived liquid moisture within straw bale walls, and thus the most common cause of straw decomposition is:

- due to bad window and door detailing,
- related to leakage from a badly executed roof.

When building with straw bales, special attention needs to be paid to the window, door and roof details.

- Although driving rain in a cold and humid climate is a fairly common cause of high humidity levels inside straw bale walls, it is usually a relatively short-lived moisture source and the straw generally manages to dry out without any serious damage.

- Drying within a straw bale wall is possible due to the use of permeable plasters, which are able to absorb and subsequently release moisture. Earth and lime plasters are ideally suited to this objective.

- The danger of straw rot posed by condensation due to water vapour transfer caused by air infiltration and air convection can be avoided by careful infill of all the spaces between bales with loose straw and by seamless plaster execution directly on straw bales. Further improvements could be achieved by building "air convection free" load bearing walls with straw bales laid flat.

- Condensation due to water vapour diffusion through a simple straw bale wall assembly (plaster—straw—plaster) doesn't prove to be a potent enough source of moisture to cause straw decay.

- Moisture transfer in straw bale walls due to inadequate drainage can be problematic. Attention should be paid to the creation of an efficient drainage system under the bottom row of bales.

- The bottom of the wall also often suffers from rising damp. The proper approach to the base of straw bale walls needs to include either an impermeable barrier of some sort or an effective capillary break. In the case of gravel trench foundations, the trench needs to be drained in order to prevent liquid moisture accumulation directly under the walls.

- To stop moisture problems caused by rainwater backsplash, it is essential to lift the straw bale walls at least 350mm above the grade.

It is tempting to use a scientific proof and assess moisture performance in straw bale walls by mathematical model. It might be unreliable as well. Building science has gotten used to employing Glaser's model for the prediction of interstitial condensation in constructions to such an extent that the results of Glaser's model can influence major decision making. As for plastered straw bale walls, Glaser's model is misleading because it isn't accurate, and it tends to shift the main focus to condensation due to water vapour diffusion, which is rarely a problem anyway.

The WUFI computer model, on the other hand, proved to be reliable in assessing moisture performance in plastered straw bale walls as long as they have been built "naturally convection free" and are spared driving rain and sunshine. The simplified investigation by WUFI model into straw bale walls with various plasters resulted in following main findings:

- In a cold and humid climate, out of all the investigated wall assemblies, earth plastered straw bale dipped in 50mm of a clay slip (only on the sides of bales facing the plaster) ensures the driest environment for straw within a wall. The dip (a mixture of straw & clay) becomes increasingly effective as a humidity buffer the colder the outdoor climate.
- Lime plaster finish over an earth plaster scratch (body) coat in a cold and humid climate prevents the earth plaster under it from drying, even though it doesn't seem to significantly affect the moisture level in straw.
- For keeping straw moisture content in the wall low, earth plaster is superior to lime plaster in a cold and humid climate.
- In a hot and humid climate, the different wall assemblies all performed the same, no matter what kind of plaster the straw was covered with. Investigation by computer simulation of virtual straw bale houses in Indonesia reported high yearly average relative humidity of about 85% across the whole straw section, with long lasting (2 month) winter peaks of 98% in the straw next to the interior plaster.

72% of the straw bale building professionals who responded to the questionnaire wouldn't hesitate to build a straw bale house for a client in a hot and humid climate.

This thesis began with saturated straw in the western wall of a lime plastered straw bale house in Plozevet, Brittany, France. Now that the thesis is at its end, it turned out to be a successful story. One of the questions in the Preface related to this moisture damage caused by driving rain was: *Will the straw have a chance to dry before it decomposes?*

The interior of the straw bale house in Plozevet lost its rotten smell long ago. The walls dried out naturally to an adequate average moisture content of 74% relative humidity in about 120 days after the disastrous storm. The moisture damage was fixed by cladding the entire house in a ventilated timber facade, which removed the cause of any further damage. The damage could have been prevented if the lime plaster had been sufficiently carbonated at the time of the storm.

The issue of humidity in straw bale walls and how it affects the decomposition of straw within is quite important, because if we understand how to prevent straw in walls from rotting, straw bale houses will be durable. A great majority of that understanding comes from common sense. Most of the world has ancient and traditional local knowledge of how to handle organic natural materials. In effect, if you want to know how to prevent straw from rotting in your walls, look at the oldest timber houses in your area. This thesis approached the topic of moisture from a scientific point of view and based its research on current scientific knowledge and data collection. It is gratifying to see that practical knowledge based on the observation of natural houses over the centuries seems to dovetail with the results of the latest scientific understanding and analysis.

Chapter 10

Terminology needing explanation:

10.1 Chapter 1 terminology:

Parts Per Million

(PPM) A unit of concentration often used when measuring levels of pollutants in air, water, body fluids, etc. One ppm is 1 part in 1,000,000. The common unit mg/liter is equal to ppm. Four drops of ink in a 55-gallon barrel of water would produce an "ink concentration" of 1 ppm (Kimball, 1997)

10.2 Chapter 2 terminology:

Decomposition

is more or less permanent structural breakdown of a molecule into simpler molecules or atoms (Mc Graw - Hill, 2003)

Enzyme

is protein that acts as a specific and highly efficient catalyst in biochemical reactions (Singleton, Sainsbury, 2001)

Protein

is large organic molecule containing carbon, oxygen, hydrogen and nitrogen as well as small amount of other elements. (Kendrew, 1994)

Fungi

is a group of diverse and widespread unicellular or multicellular microorganisms, Fungi do not contain chlorophyll. (Singleton, Sainsbury, 2001)

Fungal hyphae

one of the filaments of mycelium (Hawksworth, 1996). It represents the active phase, while resting stages like *spores* are inactive (Gams, 1992)

Fungal mycelia

cotton like plexus of fungal hyphae - filaments (Wieland, 2004). It is a thalus of a fungus (Hawksworth, 1996).

Macrofungi

are those fungi individually visible with naked eye, e.g larger than 1mm. The remaining fungi are called *microfungi.* (Arnolds, 1992)

Saprothropic fungi, also *saprophytic*

are fungi belonging to one of the three main functional groups. Saprothropic fungi specializes in decomposition of dead organic matter.

Saprothropic microfungi, also *saprophytic*

are involved in decomposition of simple carbon compounds. Numerous species are able to break down cellulose and hemicellulose, but only few are involved in lignin decomposition.

Saprothropic macrofungi, also *saprophytic*

contributes substantially to the chemical degradation of cellulose, hemicellulose and lignin. Lignin being almost exclusively tackled by basidiomycetes, which are in majority macrofungi.

Bacteria

is a group of diverse and omnipresent single celled organisms. (Singleton, Sainsbury, 2001)

Bacterial Spore also *endospore*

Only few bacterial species produce spores: Bacillus, Clostridium, Coxiella, Desulfotomaculum, Sporolactobacillus, Sporomusa and Thermoactynomices.

Spore

are specialized propagative, tough, thick-walled cells, with impermeable outer walls, produced by bacteria, fungi, moss and ferms. (Kendrew, 1994)

Spore dormancy

is a resting state in which metabolic activity is low. There is no synthesis of new cellular material. (Singleton, Sainsbury, 2001)

Spore germination

means activation, resulting in breakage of dormancy by physical or chemical agents like heat, cold, certain chemicals (water, required nutrient) (Singleton, Sainsbury, 2001)

Viable but nonculturable state

is a state of bacteria, in which they are alive, but not capable of growing or dividing (Oliver, 2005).

Rot

is plant disease characterized by primary decay and disintegration of host tissue.

Mould

a fungus that produces a superficial growth on various kinds of damp or decaying organic matter (Wordnet, 2006).

Mycelia

is the thallus of a fungi. (Hawksworth, 1995)

Water activity

is an expression for the amount of available water in a given substrate. Water activity may be defined as 1/100th of relative humidity of air which is in equilibrium with that substrate. RH of 95% corresponds to a_w of 0.95. Most bacteria fail to grow if the water activity of the medium is below 0.92

Cell wall

of a plant provides mechanical strength, maintains cell shape, controls cell expansion, regulates transport, provides protection, functions in signalling processes, and stores food reserves. (Bidlack at al., 1992)

Primary cell wall

is formed during cell expansion. The principal components are polysaccharides - these include cellulose, hemicellulose and pectin (lignin can replace pectin at the end of the cell expansion). Within the primary cell wall, cellulose fibers are highly disorganized and are bond with hydrogen bonds.

Secondary cell wall

is formed inside the primary wall after cell expansion has ceased. Cellulose fibers in the secondary cell wall create discrete layers which have opposing patterns of deposition. Secondary cell wall becomes often lignified.

fungicides fungi killing pesticides (Wieland, 2004). Non active fungi are not affected by it, although many species are sensitive (Gams, 1992). Oomycetes - affected by benomyl, polyene antibiotics, Metaxyl and similar. Fusarium species with PCNB. Penicilium species with dichloran. Rhizoctonia solani with pencycuron (Monceren). Fungal respiration can auppressed by actidione. Streptomycin was found to be overall most convenient surpressorbacterial activity (Gams, 1992).

10.3 Chapter 3 terminology:

Hydrophobic material:

Materials like silicon, oil, etc, which repel water due to electromagnetic forces on the atomic level.

Hydrophilic material:

Material which attracts the water molecules due to electromagnetic forces on atomic level. Most building materials are hydrophilic (Straube, 2002).

Hygroscopic material:

Materials like straw, wood, earth, concrete, ceramic, cellulose, etc, that get wet in contact with humid air.

Non-hygroscopic material:

Materials like glass, plastics, metals, that remain dry in contact with moisture in the air . This means that moisture in liquid form doesn't appear in these materials until dew point conditions (Kunzel, 1995).

Adsorption:

The attraction process initiated by electromagnetic forces between material surface and the water molecules.

Absorption:

The attraction process initiated by electromagnetic forces between water surface and the water molecules.

References:

ACHARYA C., N. (1934) *LXI. STUDIES ON THE ANAEROBIC DECOMPOSITION OF PLANT MATERIALS. I. THE ANAEROBIC DECOMPOSITION OF RICE STRAW (ORYZA SATIVA).*, [Internet], From the Fermentation Department, Rothamsted Experimental Station, Harpenden, Available from: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1266647, Accessed 25/07/07.

ACHARYA C., N. (1935) *CXV. STUDIES ON THE ANAEROBIC DECOMPOSITION OF PLANT MATERIALS. II. SOME FACTORS INFLUENCING THE ANAEROBIC DECOMPOSITION OF RICE STRAW (ORYZA SATIVA).*, [Internet] From the Fermentation Department, Rothamsted Experimental Station, Harpenden, Available from: http://www.pubmedcentral.nih.gov /articlerender.fcgi?artid=1266647, Accessed 25/07/07.

Andersen, J., M., Andersen B., M., (2004) *Halmhuse, Udformning og materialeegenskaber,*[Internet] Danish Building and Urban Research, Statens Byggeforskningsinstitut, By og Byg Resultater 033 Statens, Denmark, Available from: www.dejsign.dk/cosco/by_og_byg_resultater_033.pdf , Accessed 25/07/07.

Arango, M. (1981) *Responses of Microrganisms to Tempearture*in Lange, O., L., Nobel, P.,S., Osmond, C., B., Ziegler, H. (1981) Physiological Plant Ecology 1,Springer-Verlag Berlin Heidelberg, New York, p.339.

Arnolds, E., (1992) *Macrofungal communities outside forests*, in Winterhoff, W, (ed.), *Fungi in Vegetation Science*, pp. 113-149, Kluwer Academic Publishers, Netherlands

Balderstone, S. (2005) *Built Heritage: A Major Contributor to Environmental, Social and Economic Sustainability*, [Internet] SUSTAINABILITY FORUM DISCUSSION PAPER, Available from Heritage Victoria database: http://www.heritage.vic.gov.au/pages/pdfs/sustainability.pdf, Accessed 25/07/07.

Bares, J. (2003) *Stavebni a energeticke vyuziti slamy - Prelouc 2003*, Vyzkumny ustav zemedelske techniky a EKODESKY STRAMIT s.r.o., Sbornik prednasek, Ministerstvo zemedelstvi Ceske republiky, Praha, Czech Republic

Beare, M.H., Wilson, P.E., Fraser, P.M., Butler, R.C. (2002) *Management Effects on Barley Straw Decomposition, Nitrogen Release, and Crop Production*, [Internet] Institute for Crop & Food Research, Ltd., Canterbury, Nakas and Agriculture and Science Centre, Christchurch, New Zealand, Available from: http://soil.scijournals.org/cgi/reprint/66/3/848, Accessed 25/07/07.

Bidlack, J., Malone, M., Benson, R. (1991) *Molecular Structure and Component Integration of Secondary Cell Walls in Plants*, [Internet], Department of Biology, University of Central Oklahoma, Edmond, USA, Available from: http://digital.library.okstate.edu/oas/oas_pdf/v72/p51_56.pdf, Accessed 25/07/07.

Boyle, G. (2004) *Renewable Energy, Power for Sustainable Future*, Second edition, Oxford, Oxford University in association with The Open University.

Brandon D., M., Brouder, S., Chaney, D., Hill, J., E., Scardaci, S., C., Williams, J., F. (1995) *Rice Straw Incorporation*, [Internet] Agronomy Fact Sheet Series 1995-1, Department of Agronomy and Range Science, University of California, Davis, Available from: http://www.agronomy.ucdavis.edu/uccerice/AFS/agfs0195.htm, Accessed 25/07/07.

BS 5250, (1995) *Code of practice for control of condensation in buildings*, British Standards Institution, London, UK

BS 6229, (2003) *Flat roofs with continuously supported coverings. Code of practice*, British Standards Institution, London, UK

Buis, A. (2002) *Scientists Say 'Grace' as Water-Sensing Satellites Lift Off* [Internet], NASA News Archive, Available from earth observatory: http://earthobservatory.nasa.gov/Newsroom/NasaNews/2002/200203178303.html, Accessed 25/07/07.

Calamita, G. (2005) *Aquaporins: highways for cells to recycle water with the outside world*, [Internet] Biology of the Cell 97, (351-353), Great Britain, Available from: http://www.biolcell.org/boc/097/0351/0970351.pdf, Accessed 25/07/07.

Cappaert, I., Verdonck, O., De Boodt, M. (1976) *Composting of bark from pulp mills and the use of bark compost for plant breeding*, Compost Science, 17 (4) pgs. 6-9.

CEST, (2001) *MONOCOTYLEDONS*, [Internet], Available from database of NTNU, the Pulp and Paper Group: http://www.chemeng.ntnu.no/research/paper/Online-articles/Nonwoods/Nonwood.html, Accessed 25/07/07.

Christian, J., E., Desjarlais, A., O., Stovall, T., K. (1998) *Straw Bale Wall Hot Box Test Results and Analysis*, The Thermal Performance of the Exterior Envelopes of Buildings VII, 4b103, ASHRAE learning institute, Atlanta, USA.

CIBSE (1999) *Environmental design, CIBSE, Guide A*, The Chartered Institution of Building Services Engineers, London, UK

CIBSE (2001) Reference data, CIBSE, Guide C, London, Butterworth - Heinemann, UK.

CLAYTEC (2006) *6.1 Lehmputz, Neuauflage 01.2006*, [Internet] Claytec Arbeitsblatt, Germany, Available from:http://www.claytec.com/, Accessed 25/07/07.

CLEAR (2006) *Residential Water Consumption (Per Capita)*, Available from CLEAR Network database:http://www.clear.london.ca/Drinking_Water_Residential.html, Accessed 25/07/07.

CMHC (1996) *Straw Bale Moisture Sensor Study*, [Internet] Canada Mortgage and Housing Corporation, Research & Development Highlights, Available from :http://www.cmhc-schl.gc.ca/publications/en/rh-pr/tech/00-103-E.htm, Accessed 25/07/07.

CMHC (2000) *Straw Bale House Moisture Research*, [Internet] Available from Canada Mortgage and Housing Corporation database: https://www03.cmhc-schl.gc.ca/b2c/b2c/init.do?language=en&shop=Z01EN&areaID=0000000040&productID=00000000400000000030, Accessed 25/07/07.

Cortazar, V., G., Silva, P., Acevedo, H. (2001) *EVALUATION OF A PREDICTIVE MODEL OF THE EFFECT OF TEMPERATURE AND HUMIDITY ON WHEAT STRAW DECOMPOSITION*, [Internet] Laboratorio de Relacin Suelo-Agua-Planta, Facultad de Ciencias Agronmicas, Universidad de Chile, Santiago, Available from: http://biblioteca.universia.net/html_bura/ficha/params/id/3919137.html, Accessed 25/07/07.

CWC, (2006) *FAQ Mould / Mold*, [Internet] Canadian Wood Council and Forintek Canada Corp, Available from Wood Durability database: http://www.durable-wood.com/faqs/mould.php#SPECIAL, Accessed 25/07/07.

Dalgliesh, A., Cornick, S., Maref, W., Mukhopadhyaya, P. (2005) *Hygrothermal performance of building envelopes: uses for 2D and 1D simulation*, [Internet] 10th Conference on Building Science and Technology Proceedings,

deGruchy, A. (2007) *Highlights from the interview with details about lime and cements used for mortar.*, [Internet] Chicago Tribune/Washigton Post, USA, Available from Palimeworks database: http://www.palimeworks.com/lwus/Infoall.html, Accessed 25/07/07.

Doyle, W.T. (1973) *Nonseed Plants: Form and Function*, Second Edition, Fundamentals of Botany Series, University of California, Santa Cruz, Macmillan Press Ltd, UK

Dresboll, D., B., Magid J. (2005) *Structural changes of plant residues during decomposition in a compost environment*, [Internet] Bioresource Technology, Elsevier, Available from Science Direct database from: www.sciencedirect.com, Accessed 25/07/07.

Edwards, D., Hamson, M. (1990) *Guide to mathematical modelling*, CRC Press, Florida, USA

EELS, (2005) *Nature Notes: Recycling Nutrients - The Decomposition Process*, [Internet], Available from database of EELS, Ecological & Environmental Learning Services: http://www.eelsinc.org/id41.html, Accessed 25/07/07.

eia (2005) *Energy Efficiency - 9th Graders and Up*, [Internet] Available from: http://www.eia.doe.gov/kids/energyfacts/saving/efficiency/savingenergy_secondary.html, Accessed 25/07/07.

EN 13788 (2002) *Hygrothermal performance of building components and building elements – Internal surface temperature to avoid critical surface humidity and interstitial condensation – Calculation methods*, International Organization for Standardization, Geneva, Switzerland

Fernandez, R. (2003) *Fibre reinforced soil crete blocks for the construction of low cost housing*, [Internet] Laboratory of construction materials, University of the Witwatersrand, Available from:http://idm.epfl.ch/stages/pdf/113.pdf¿, Accessed 25/07/07.

Ficker, T. (2003) *Non-isothermal steady-state diffusion within Glaser's condensation model*, [Internet] International Journal of Heat and Mass Transfer 46, Science direct, Available from: www.elsvier.com, Accessed 25/07/07.

Fogel, R. (2001) *Fun Facts About Fungi*, [Internet] edited by Patricia Rogers, Available from: http://herbarium.usu.edu/fungi/FunFacts/Decay.htm, Accessed 25/07/07.

Gams, W. (1992) *The analysis of communities of sprophytic microfungi with special reference to soil fungi*, in Winterhoff, W, (ed.), *Fungi in Vegetation Science*, pp. 113-149, Kluwer Academic Publishers, Netherlands

Glassford, J. (2004) *3.4e Straw bale*, [Internet] Australia's guide to environmentally sustainable homes, Available from: http://www.greenhouse.gov.au /yourhome/technical/fs34e.htm, Accessed 25/07/07.

Gonzales, H. (1999) *The Outer Edge: Testing Straw Bale Wall Moisture Near the Exterior Plaster*, Canadian Mortgage and Housing Corporation, Ottawa, Canada

Goodhew, S., Griffiths, R., Wooley, T. (2004) *An investigation of the moisture content in the wall of a straw-bale building*, Building and Environment, 39, pp. 1443-1451, Elsevier

Guy, B. (2004) *Early recovery: collected data can yield insight into the potential of the deconstruction market*, [Internet] The Hamer Center for Community Design Assistance at The Pennsylvania State University, Available from:http://www.findarticles.com/p/articles/mi_m0QMH/is_4_6/ai_n6150130, Accessed 25/07/07.

Hansen, J.E. (2006) *GISS Surface Temperature Analysis, Global Temperature Trends: 2005 Summation*[Internet] Goddard Institute for Space Studies, New York, USA, Available from: http://data.giss.nasa.gov/gistemp/2005/

Hansen, J.E., Sato, M. (2001) *Trends of measured climate forcing agents*, Proceedings of the National Academy of Sciences, 98, 14778-14783, New York, USA

Harrison, J., W. (2205) *Carbonating and Hydraulic Mortars - the difference is not only in the binder. Aggregates are also important.*, [Internet] TecEco Pty. Ltd., Gaia Engineering, Tasmania, Australia, Available from: http://www.gaiaengineering.net/files/conference_papers/CarbonationOfMortarsandRequirementsSand040595.pdf, Accessed 25/07/07.

Hawksworth, D.L., Kirk, P.M., Sutton, B.C., Pegler, D.N. (1995) *Ainsworth & Bisby's Dictionary of the Fungi*, Eight Edition, International Mycological Institute, CAB International, University Press, Cambridge, UK

Hoflich, G. (1977) *The effect of biocides on the microflora of soils and their degradation. II. Correlations between a changed population of micro-organisms and the degradation of straw*, [Internet] Zentralbl Bakteriol Parasitenkd Infektionskr Hyg. 132(1), Pgs. 67-74, Available from: http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&list_uids=857507&dopt=Abstract, Accessed 25/07/07.

Hopkins, W.G. (1999) *Introduction to Plant Physiology*, Second edition, John Wiley & Sons, Inc, UK

Houben, H., Guillaud, H. (1994) *Earth Construction, A comprehensive guide*, CRATerre-EAG, ITDG Publishing, SRP Exeter, UK

INTERNATIONAL PROGRAMME ON CHEMICAL SAFETY, (1993) *ENVIRONMENTAL HEALTH CRITERIA 149, CARBENDAZIM*,[Internet] World Health Organization, Available from: http://products.ihs.com/Ohsis-SEO/271300.html, Accessed 25/07/07.

ISHS (2005) *Belgium, General info*, [Internet] International Society for Horticultural Science, Horticulture Research International, Available from: http://www.hridir.org/countries/belgium/index.htm, Accessed 25/07/07.

ITCF, (2002) *Fongicides, cereales et proteagineux*, Cerealiers de France,Institute Techniques des Cereales et des Fourrages, Paris, France

Jolly, R. (2000) *Straw Bale Moisture Monitoring Report*, Canadian Mortgage and Housing Corporation, Ottawa, Canada.

Jones, B. (2002) *Building with Straw Bales, A practical guide for the UK and Ireland*, Green Books, Dartington, Devon, UK

Kaboneka, S., Nivyiza, J., C., Sibomana, L. (2002) *Effects of Nitrogen and Phosphorus Fertilizer Addition on Wheat Straw Carbon Decomposition in a Burundi Acidic Soil*, [Intermet] Universit du Burundi, Facult des Sciences Agronomiques, Bujumbura, Burundi, Available from: http://www.ciat.cgiar.org/tsbf_institute/managing_nutrient_cycles/AfNetCh10.pdf, Accessed 25/07/07.

Kargiozis, A., Kuenzel, H., Holm, A. (2002) *WUFI ORNL/IBP Hygrothermal Model*, [Internet] Available from: www.ornl.gov/ webworks/cppr/y2001/pres/111509.pdf, Accessed 25/07/07.

Kendrew, J. (1994) *The Encyclopedia of Molecular Biology*, Blackwell Science Ltd, Oxford and Northampton, UK

Kimball, J. (1997) *Kimball's Biology Pages*, [Internet] Available from: http://users.rcn.com/jkimball.ma.ultranet/BiologyPages/P/Ppm.html, Accessed 25/07/07.

King, B. (2006) *Design of Straw Bale Buildings, The State of the Art*, Green Building Press, San Rafael, California, USA

Kirby, R. (2006) *Actinomcetes and Lignin Degradation*, in Laskin, A., I., Bennet, J., W., Gadd, G., M., Sariaslani, S. *applied Microbiology, volume 58, Elsevier, USA*

Kolbert, E. (2006) Chilling, New Yorker, The style issue, March 20, Condé Nast Publications, USA

Kolbert, E. (2006) *Chilling*, New Yorker, The style issue, March 20, Conde Nast Publications, USA

Katterer, T., Reichstein, M., Andrn, O., Lomander A. (1998) *Temperature dependence of organic matter decomposition: a critical review using literature* *data analyzed with different models*, [Internet] Biol Fertil Soils (1998) 27, 258262, Springer-Verlag, Available from: http://www.springerlink.com/content/fhleah8najy1x21h/, Accessed 25/07/07.

Kudo, R.R. (1971) *Protozoology*, Fifth Edition, Second Printing, Thomas Books, Springfield, Illinois, USA

Kummer, K.F. (2004) *Understanding Nitrogen and its use in Agriculture*, [Internet] efma, European Fertilizer Manufacturers Association, Brussels, Belgium Available from: http://www.efma.org/publications/Nitrogen

Kunzel, H., M. (1995) *Simultaneous Heat and Moisture Transfer in Building Components, one- and two-dimensional calculation using simple parameters*, PhD Dissertation, Fraunhofer, IRB, Verlag, Stuttgart.

Kunzel, H., M. (2004) *Questions and Answers*, [Internet] WUFI-pro 3.3.1 (e), Online Help, Available from WUFI database: http://www.hoki.ibp.fhg.de/ibp/publikationen/konferenzbeitraege/pub1_26.pdf, Accessed 25/07/07.

LASCAR (2005) *EL-USB-2 Humidity, Temperature and Dew Point USB Data Logger*, [Internet] Available from LASCAR electronics database: http://www.lascarelectronics.com/data/pdf/EL

Liebich, J., Schäffer, A., Burauel, P. (1997) *STRUCTURAL AND FUNCTIONAL APPROACH TO STUDYING PESTICIDE SIDE-EFFECTS ON SPECIFIC SOIL FUNCTIONS*in *Environmental Toxicology and Chemistry*, Volume 22, Issue: 4, Pgs: 784-790, 1552-8618

Lindow, S.E. (2005) *Investigation of Communication of Bacteria on Plant Surfaces*, Plant & Microbial Biology.

Lindow, S.E., Brandl, M.T. (2003) *Microbiology of the Phyllosphere*, [Internet] Applied and Environmental Microbiology, 69(4): 1874-1883, American Society for Microbiology, Available from:http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=154815, Accessed 25/07/07.

Lynch, J.M. (2000) *Agricultural practices and biodiversity.*, [Internet] School of Biomedical and Life Sciences, University of Surrey, Guildford, UK, Available from: http://webdomino1.oecd.org/comnet/agr/soil_ero_bio.nsf/viewHtml/index/$FILE/Lynch8sep.PDF, Accessed 25/07/07.

MacMath, R. (2000) *CARBON DIOXIDE INTENSITY RATIOS: A Method of Evaluating the Upstream Global Warming Impact of Long-Life Building Materials*,[Internet] Available from: http://www.cmpbs.org/publications/T1.2-AD4.5-Up_Gbl_wrm.pdf, Accessed 25/07/07.

Magid, J., Luxhoi, J., Lyshede, O., B. (2004) *Decomposition of plant residues at low temperatures separates turnover of nitrogen and energy rich tissue components in time*, [Internet] Plant and Soil 258, Kluwer Academic Publishers, Available from: http://www.springerlink.com/content/k3530j34198p3870/, Accessed 25/07/07.

Magwood, C. (2004) *Straw Bale Building, On the Cusp of the Mainstream*, [Internet] home power 101, june & july, Available from homepower database: http://www.homepower.com/files/HP101_14.pdf, Accessed 25/07/07.

Massey, F., P., Ennos, A., R., Hartley, S., E. (2006) *Silica in grasses as a defence against insect herbivores: contrasting effects on folivores and a phloem feeder - Abstract*, Journal of Animal Ecology 75, 595603 doi: 10.1111/j.1365-2656.2006.01082.x.

McGraw - Hill, (2003) *McGraw - Hill Dictionnary of Scientific and Technical Therms*, Sixth Edition, McGraw - Hill Companies, Inc., USA

Meteo (2005) *Meteo-Mayenne*, [Internet] Weather Archive, Available from: http://gagcbrfree.fr/

Meteofrance (2005) *Climate, France, Finistere*, [Internet] Available from meteofrance database: http://www.meteofrance.com/FR/climat/dpt_tempsdumois.jsp?LIEUID=DEPT29, Accessed 25/07/07.

Minke, G. (2006) *Building with Earth: Design and Technology of a Sustainable Architecture*, Birkhauser, Germany

Mustin, M. (1987) *Le compost, Gestion de la matiere organique*, Editions Francois DUBUSC, 35, rue Mathurin Regnier, 75015 Paris, France

Newport Partners, (2004) *BUILDING MOISTURE AND DURABILITY; PAST, PRESENT AND FUTURE WORK*[Internet] Prepared for: U.S. Department of Housing and Urban Development Washington, D.C. Office of Policy Development and Research, USA, Available from: http://www.toolbase.org/PDF/CaseStudies/BuildingMoistureandDurability.pdf, Accessed 25/07/07.

Nielsen, K., F. (2002) *Mould growth on building materials*, [Ineternet] By og Byg, Statens Byggeforskningsinstitut, Denmark, Available from: http://www.sbi.dk/download/pdf/phd_kfn.pdf, Accessed 25/07/07.

O'Hare, G. (2004) *Lime Mortars and Renders: The Merits of Adding Cement*, [Internet] Gaia Engineering, Tasmania, Australia, Available from: http://www.gaiaengineering.net/files/conference_papers/CarbonationOfMortarsandRequirementsSand040595.pdf, Accessed 25/07/07.

Oliva, J., P. (2002) *L'isolation ecologique*, terre vivante, Mens, France

Oliver, J.D. (2005) *The Viable but Nonculturable State in Bacteria*, [Internet] The Journal of Microbiology, p.93-100, Vol. 43, special issue (No. S), The Microbiological Society of Korea, Available from: www.msk.or.kr/jsp/downloadPDF1.jsp?fileName=p%5B1%5D.93-100.pdf, Accessed 25/07/07.

Orskov, E.R. (2002) *Consistency of differences in nutritive value of straw from different varieties in different seasons*, [Internet] The Rowett Research Institute, Bucksburn, Aberdeen, Scotland, Available from: http://www.fao.org/Wairdocs/ILRI/x5495E/x5495e0a.htm, Accessed 25/07/07.

Padfield, T. (1998) *THE ROLE OF ABSORBENT BUILDING MATERIALS IN MODERATING CHANGES OF RELATIVE HUMIDITY*, [Internet], Ph.D. thesis, The Technical University of Denmark, Department of Structural Engineering and Materials,Available from: www.padfield.org/tim/cfys/, Accessed February 12th, 2005

Padfield, T. (2002) *THE WINDOW IN CONTEXT: THE INTERPLAY BETWEEN BUILDING COMPONENTS*, [Internet], Available from: http://www.padfield.org/tim/cfys/wproj/wproj_tp_ver9.pdf, Accessed February 12th, 2005.

Padfield, T. (2005) *How to keep for a while what you want to keep for ever*, lecture notes for museology course at Denmark's Library School [Internet], Available from: www.padfield.org/tim/cfys/, Accessed February 12th, 2005.

Perry, R.H., Green, D.W., (1997) *Perry's Chemical Engineers' Handbook*, Seventh edition, McGraw-Hill, USA

Peuhkuri, R. (2003) *Moisture Dynamics in Building Envelopes*, [Internet] Ph.D. Thesis, Report R-071, Department of Civil Engineering, Technical University of Denmark, Available from: http://www4.byg.dtu.dk/cv-www/rhp/publications/PeuhkuriPhDThesis_web.pdf, Accessed 25/07/07.

Peuhkuri, R., Rode, C., Hansen, K., K. (2004) *Response of insulation materials on non-isothermal moisture transport: Final results*, [Internet] Department of Civil Engineering, Technical University of Denmark, Available from: http://www.byv.kth.se/avd/byte/reykjavik/pdf/art_163.pdf, Accessed 25/07/07.

Peuhkuri, R., Rode, C., Padfield, T., Hansen, K., K., Hedegaard, L. (2003) *Moisture distribution in absorbent insulation*, [Internet] Dnamarsk Tekniske Universitet, Sagsrapport, BYGDTU SR-03-11, Available from: http://www4.byg.dtu.dk/cv-www/rhp/publications.htm, Accessed January 17th, 2005.

Piepkorn, M. (2000) *Moisture and Straw-Bale Walls*, [Internet] The Last Straw, bonus unpublished article, Available from: http://www.thelaststraw.org/bonus-articles/strawter.htm, Accessed January 17th, 2005.

Platts, B. (1997) *Pilot Study of Moisture Control in Stuccoed Straw Bale Walls*, [Internet] Canadian Mortgage and Housing Corporation, Ottawa, Canada, Available from: http://www.cmhc-schl.gc.ca/cmhc.html, Accessed 25/07/07.

Platts, B., (1998) *A Threat To Strawbale Housing*, [Internet] The Last Straw, Issue #22, 1998, Available from http://www.thelaststraw.org/backissues/articles/22_07.html, Accessed January 17th, 2005.

Price, L., Worell, E., Khrushch, M. (1999) *Sector Trends and Driving Forces of Global Energy Use and Greenhouse Gas Emissions: Focus in Industry and Buildings*, [Internet] Energy Analysis Department, Environmental Energy Technologies Division, Ernest Orlando Lawrence Berkeley National Laboratory, University of California, USA, Available from: http://ies.lbl.gov/iespubs/43746.pdf, Accessed 25/07/07.

Ribeiro, R.J.M.C. (2000) *Nutritive value of treated straw*,ESTAAO ZOOTECNICA NACIONAL, SANTAREM, PORTUGAL, [Internet], Available from: http://ressources.ciheam.org/om/pdf/b06/95605269.pdf, Accessed 25/07/07.

Richard, T. (1996) *The Effect of Lignin on Biodegradability*, [Internet], Available from Cornell Composting database, Science & Engineering: http://compost.css.cornell.edu/calc/lignin.html, Accessed 25/07/07.

Rohrer, J.D., Heimlich, J.E., (1998) *Comparative Decomposition Rates for Shredded Newsprint, Straw, and Sawdust*, Ohio State University Fact Sheet, Community Development, CDFS-124-98, Ackerman, Ohio, USA, [Internet], Available from: http://ohioline.osu.edu/cd-fact/0124.html, Accessed February 28, 2006.

Salzman, W., R. (2004) *The Melting Curve for Water; Vapor Pressure*, [Internet] Available from Salzmanindex: http://www.chem.arizona.edu/ salzmanr/480a/480ants/watvp/watvp.html, Accessed 25/07/07.

Sanders, C. (2005) *New Models for Interstitial Condensation*, [Internet] Presentation, BRE Scotland, Available from: projects.bre.co.uk/moisture/Moisture.ppt, Accessed 25/07/07.

Schmidt, (2001) *IBP Software / WUFI / Basics*, [Internet] Available from: http://www.hoki.ibp.fraunhofer.de/wufi/wufi_frame_e.html, Accessed 25/07/07.

Sedlbauer, K., Krus, M., Zillig, W., Künzel, H., M. (2001) *Mold Growth Prediction by Computational Simulation.*, [Internet] ASHRAE-Conference IAQ, San Francisco, Available from: http://www.hoki.ibp.fraunhofer.de/ibp/publikationen /konferenzbeitraege/pub1_32.pdf, Accessed 25/07/07.

Singleton, P., Sainsbury, D. (1978) *Dictionary of Microbiology*, A Wiley-Interscience Publication, John Wiley & sons, Sainsbury, UK

Smith, D. (2006) *Strawbale Info:*, [Internet] Available from DSAA database: http://www.dsaarch.com/SB

Still, D (1997) *Testing Straw Bale Construction in the Soggy Northwest*, [Internet] Available from Aprovecho database: www.aprovecho.net/at/projects/ strawbale.htm, Accessed 25/07/07.

Still, D (1999) *Our Strawbale Dorm: 2 Years Later*, [Internet] Available from Aprovecho database: www.aprovecho.net/at/projects/strawbale.htm, Accessed 25/07/07.

Still, D (2003) *Our Strawbale Dorm: 6 Years Later*, [Internet] Available from Aprovecho database: www.aprovecho.net/at/projects/strawbale.htm, Accessed 25/07/07.

Straube, J. (2003) *Moisture Properties of Plaster and Stucco for Strawbale Buildings*, [Internet] EBNet, Available from:www.ecobuildnetwork.org/ pdfs/Straube_Moisture_Tests.pdf, Accessed 25/07/07.

Straube, J., Burnett, E., (2001) *Review of Modeling Methods for Building Enclosure Design*, [Internet] University Waterloo, Canada, Available from: http://www.civil.uwaterloo.ca/beg/CE708/HAM

Straube, J., F. (2002) *Moisture, Materials & Buildings, HPAC Engineering*, [Internet] April, pp.37-46, Available from: www.ecobuildnetwork.org/pdfs/
Straube
textunderscore Moisture
textunderscore Tests.pdf , Accessed October 12th, 2005.

Straube, J., King, B. (2006) *Moisture Basics and Straw-bale Moisture Basics*, The Last Straw, Issue #53, The Green Prairie Foundation for Sustainability, GPFS, Lincoln, USA

Straube, J., Schumacher, C. (2003) *Comparison of Modeled and Monitored Performance of a Wall Insulation Retrofit in a Solid Masonry Building*, report for Canada Mortgage and Housing Corporation, Research Highlights, Technical Series 03-111, Ontario, Canada

Straube, J., Schumacher, C. (2003) *Monitoring the Hygrothermal Performance of Strawbale Walls*, [Internet] Balnced Solutions, University of Waterloo, Canada, Available from EBNet database: http://www.ecobuildnetwork.org/pdfs /Winery_Monitoring.pdf, Accessed 25/07/07.

Studemund-Halevy, M. (1994) *Tips and Hindweise*, Merian, Bretagne, C 4701 E, July 94, Nurenberg, Germany

Summers, M.D., Blunk S.L., Jenkins B.M., (2003) *How Straw Decomposes*, [Internet] EBNet Straw Bale Test Program, DRAFT 12/8/2003, Available from ecobuildnetwork Database: http://www.ecobuildnetwork.org/pdfs/How
textunderscore Straw
textunderscore Decomposes.pdf, Accessed January 17th, 2005

Swearingen, J. (2005) *Moisture Barriers in Straw-bale Construction*, [Internet] Available from Skillful Means database: http://www.cc-w.co.uk/Documents /Swearingham-moisture1.pdf, Accessed January 17th, 2005

Tariku, F., Kumaran, M., K. (2006) *Hygrothermal modeling of aerated concrete wall and comparison with field experiment*, [Internet] International Building Physics Conference, Montreal, QC., August 27, 2006, pp. 321-328, Canada, Available from: http://irc.nrc-cnrc.gc.ca, Accessed January 17th, 2005

Thompson, M. (2000) *Relative Humidity and Psychometric Chart*, in Msc architecture: Advanced Environmental and Energy Studies, Unit A2 Oct. 04, Center for Alternative Technology, Machynleth, UEL, p.91.

Time, B., Uvsløkk, S. (2003) *Intercomparison on measurement of water vapour permeance*, Prosjektrpport 339, Norges byggforskningstitutt, Blindern, Norway

Tuller M., Or, D., Dudley, L.,M. (1999) *Liquid retention and interfacial configurations in angular pores*, [Internet] WATER RESOURCES RESEARCH, VOL. 35, NO. 7, PAGES 19491964, Available from: soils.ag.uidaho.edu/Tuller/ Markus_Tuller/Publications_pdf/1999WR900098.pdf, Accessed 25/07/07.

Tywoniak, J., Kulhanek, F. (1995) *Stavebni fyzika 20, Stavebni tepelna technika - Pomucka pro cviceni*, Ceske vysoke uceni technicke, Fakulta stavebni, Vydavatelstvi CVUT, Praha, Czech Republic

Vinha, J., Mikkil, A., Valovirta, I., Lindberg, R. (2002) *Water Vapour Resistance as a Function of Humidity*, Building Physics - 6th Nordic Symposium, Session 12: Hygrothermal Properties of Materials, Norway.

Wahr, J. (2006) *Antarctic ice sheet losing mass, says University of Colorado study*[Internet] University of Colorado at Boulder, Available from Eurek Alert database: http://www.eurekalert.org/pub_releases/2006-03/uoca-ais022806.php, Accessed January 17th, 2005.

Wanek, C. (1998) *Straw-Bale Buildings You Can Visit*, The Last Straw, A Nat Works Production, Issue #23, New Mexico, USA

Warren, J. (1999) *Conservation of Earth Structures*, Butterworth Heinemann, Oxford, UK

Washington University, 2005 *Compost Fundamentals, Compost Needs*, [Internet] Washington State University, Whatcom County Extension Available fromhttp://whatcom.wsu.edu/ag/compost/fundamentals/needs_carbon_nitrogen.htm, Accessed 25/07/07.

Wieland, H. (2004) *Mikrobielle Empfindlichkeit von Bau-Strohballen*, [Internet] Fachverband Strohballenbau, Deutschland, Available from fasba database: http://www.downloads.fasba.de/3mikrobiell_72dpi.pdf, Accessed 25/07/07.

Wihan, J. (2005) *Is it necessary to build airtight and to use heat recovery in order toachieve the energy efficiency of passive-enrgy building standard?*, [Internet] UEL/CAT Msc AEES, Student essay, Machynlleth, UK

Wilhelm, G. (2004) *The Realities of CO2: Seeing through the Smog of Rhetoric and Politics*, [Internet] Conservation Design Forum, Available from: http://www.cdfinc.com/CDF_Resources/Realities

Wimmer, R., Hohensinner, H., Drack, M. (2004) *S-HOUSE SUSTAINABLE BUILDING DEMONSTRATED BY A PASSIVE HOUSE MADE OF RENEWABLE RESOURCES*, [Internet] GrAT - Center for Appropriate Technology at the Vienna University of Technology, Vienna, Austria, Available from GrAT database: http://www.strawbalebuilding.ca/documents.shtml, Accessed 25/07/07.

Wimmer, R., Hohensinner, H., Janisch, L., Drack, M. (2001) *Wandsysteme aus nachwachsenden Rohstoffen*, [Internet] Haus der Zukunft, Gruppe Angepasste Technologie an der TU Wien, Available from Baubiology database: http://www.grat.at/Publikationen/Wandaufbau_aus_NWR.pdf, Accessed 25/07/07.

WUFI (2005) *WUFI pro 4.0 Online-Help*, Microsoft Windows Help, IBP, feature of WUFI pro 4.0 software

Yang, C.H., Crowley D.E., Borneman, J., Keen, N.T. (2001) *Microbial phyllosphere populations are more complex than previously realized*, [Internet] Proceedings of the National Academy of Sciences of the United States of America, The National Academy of Sciences, Available from Pub Med Central database: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=31148, Accessed 25/07/07.

Bibliography:

EEA (2005) *The European Environment, State and Outlook 2005*, [Internet] EEA, Copenhagen,

CMHC (1997) *Pilot Study of Moisture Control in Stuccoed Straw Bale Walls*, [Internet] Available from Canada Mortgage and Housing Corporation database:

Fugler, D., Starube, J. (2000) *Moisture Properties of Plaster and Stucco for Straw bale Buildings*, [Internet] Available from Canada Mortgage and Housing Corporation database:

Fugler, D. (1997) *Straw Bale Moisture Sensor Study*, [Internet] Available from Canada Mortgage and Housing Corporation database:

Appendix A

Interviews

A.1 Interview with Barbara Jones of Amazon Nails at Ecobuild 2006 in London.

April 2006

On how many straw bale buildings have you participated so far?

Probably over a hundred.

Since...?

Since 1994.

How many times have you encountered moisture problems in straw bale walls?

Very, very rarely. There's two I can think of. No, three.

What was it about?

Two of them were because they were left unplastered and open to the weather and they went through quite severe wind and rain during winter. Some of the straw wasn't protected enough and got very wet right through the center of the bale.

Where was it?

It was in northern Scotland and the other was in Ireland.

Was the cause driving rain or moisture that leaked through the top of the wall?

One of them happened because the roofers didn't put tarpaulins over the top of the roof and rain got into the top of the wall and went down through the center. That one also had a problem from rain hitting the wall on the southwest side. And those bales got very wet right at the bottom just on top of the foundation.

The other one was also a driving rain on unplastered wall.

Those two cases were unplastered straw bales. What about the third one?

The third one was a design failure, I think. It was plastered, but architect had designed very wide window sills covered in lead and they collected a lot of rain. Wind funeled it off the edge, so it was like house pipe that went on to part of the wall and that got very wet. We had really great success repairing that.

Did you repair those previous cases as well?

Yes. They all were repaired successfully.

Even though they all were loadbearing structures? People promoting post and beam,with straw as infill, often stress the fact that infill is much more easily repaired.

When it's loadbearing it is absolutely easy to replace the straw, because you've got a wall plate around the top that acts as a lintel so you don't have to prop anything. You can take out whole sections of straw and replace them. We've done that. In fact there is another building,

there are four buildings that I know of. They got very wet through a lack of proper care and attention. And we've repaired them successfully by taking out sections. Sometimes we've taken out sections about 300mm wide. From the wall plate down to the base plate. And we've repaired it from bottom upwards with fresh straw.

Flakes of fresh straw?

Yes. With one of them, the one in Ireland, we advised the owner to drill holes in the wall. Holes about 50mm in diameter, and to leave them with newspaper inside, because the newspaper draws water from the wall. One of the qualities of straw is that it gets wet very quickly, but it also gets dry very quickly and if you make the hole through the whole wall as long as it isn't raining on it, it will dry out very quickly. And you can do that all over the wall if you want. It doesn't effect the structure.

How many times have you seen mold growing on a plastered straw bale wall, when the building was occupied?

Never.

What is your favourite straw bale wall cover?

Always, either lime or clay.

Exterior?

For the exterior, lime and for the interior lime or clay.

What kind of lime do you use?

Almost exclusively fat lime—lime putty. We sometimes use hydraulic lime if it's little bit late in the season, but we would never use lime beyond the end of August.

Would you mix lime putty and hydraulic lime together?

No there is no point in doing that as far as I'm concerned.

Why?

Because it is still hydraulic, so you might as well use hydraulic. If you mix lime putty with hydraulic you'v got hydraulic.

Is it weaker?

Well it is debatable. People have different theories about whether it is really weaker or not weaker, or what it does.

When would you apply your plaster so that it has time to carbonate enough for protection of straw through the winter?

We always say that all the plaster coats on the outside have to be completed by the end of August. Otherwise you risk the frost damage from lack of carbonation, because lime won't carbonate if the temperature drops below 10°C and if the temperature is not much above 10°C it will carbonate much, much more slowly. So, you just don't have protection against the weather and than the rain can penetrate through the plaster.

I heard that carbonation is a very slow process anyway, 2mm per month. How much time then is enough to protect the straw? Does the plaster need to be fully carbonated?

Not fully carbonated. No, some of the buildings in England that were built 400 years ago are still not fully carbonated. (Barbara laughs) It's a slow process, but it takes about three months in good conditions for it to carbonate enough to provide a weather resistant coating.

What about interior plaster?

Well, it is not the same. Very often the interior plaster takes longer to carbonate if the house isn't inhabited, because it is cold inside and it doesn't have any ventilation, or not enough ventilation. So it can actually stay soft longer on the inside than it does on the outside. And that is a big problem if you are plastering during the winter. I mean, plastering is a seasonal process and it is not sensible to try to do it over the winter months.

Would you rather use clay than lime in interiors?

There are reasons for and against. Clay is wonderful tactile material like lime is and is not toxic. It is much better to use that with people that want to put their hands into the mix and to do sculptural work. And for many, many application clay is just the best to use, but it is not as durable as lime. For instance schools need something more durable than clay on the parts of walls that might get knocked or banged, or where cleaning equipment might rub up against it. In those cases it might be more sensible to use lime, than clay, but clay has real beauty to it that you just can't match.

There is a lot of debate about breathability and how it is important in straw bale walls. To maintain a more breathable cover of the straw bales inside rather than outside seems to be beneficial. It is suppose to prevent condensation. Would you believe in those theories and are you threatened by condensation?

Not at all. I don't think the condensation in a wall is actually an issue at all. I think it is a myth. It is like a myth that you can't built houses out of straw.

Would you use discoloured straw bale that was rained on?

No. I would always be really careful about my choice of bales. If they've been wet and they've dried out and they've been out in the elements, they're much more likely to decay, than if they're straight off the field and they've been kept dry. And it's not worth messing about with if you're a building new house. I think you need to have bales that have never been wet.

What about content of weeds, hey, grases in straw?

I'm not sure. I don't know about that. I think you sort of make a practical assessment when you are looking at the bale. You can see very clearly if it's got a lots of something else in it or not and I would generally not use it if it has a lots of material in it that could compost. Not that it would compost. It might never. It's just if you've got a choice of bales than I would go for absolute best you can get.

Do you use moisture meter?

Never. I think moisture meters should only be used by people who absolutely know what they are doing, otherwise all that happens is that you get scared.

Have you ever monitored moisture inside a wall?

Not in any formal way. No. We've done it by sticking the things into straw before it's been plastered and things like that, but I've never done the moisture. I'd like to do some, but we've never had an opportunity.

Would you build a straw bale house in a hot and humid climate?

In hot climate yes. It's humidity, that I think, its the problem. I think that you could build a straw bale sauna for instance and have it humid atmosphere inside, because it would pass to the outside as long as you have a breathable plasters, but if you had a humidity inside and outside the building, because of the climate, I think it would be risky. I can't say definitely weather it would work or not, because I've never tried it. I think it might be risky.

Thank you very much.

There was still a bit of time, so Barbara had the opportunity to give her expertise on a sample of lime plaster from Plozevet:

Barbara:

I wouldn't say I'm an expert really on analyzing lime. Is this what happened to it?

(Barbara crumbles the plaster in her hand)

> *Yes.*

In the rain?

> *Crumbles.*

Yes. It looks like it is not carbonated.

> *That is what happened. Martin (the owner) plastered in September and it didn't carbonate.*

That is what it looks like. Was it just on the weather side or was it all over?

> *More or less all over. And the wind is so bad that driving rain penetrated the whole building all the way through.*

Yes.

> *Now the owner has to make timber cladding all around it. He is convinced that you can't make a plaster that would withstand conditions in Plozevet. I thought, he had probably never seen your lime plasters before. They are like sealed skin. Do you think that the lime plaster you are applying would withstand such driving rain by the Atlantic ocean?*

Well, I don't know, I started recommending people to put a weather screen at some point to give it some protection.

> *What do you mean by weather screen?*

Either trees, or until the trees grow a natural screen of some sort. A fence that prevents all wind.

A.2 Interview with Tom Rijven of Habitat Vegetal on the way to Brittany

October 2005

On how many straw bale buildings have you participated so far?

I think between 50 and 60?

Do you keep any notes about it?

Well my notes are more special, because I do actually two parts in construction. The first is putting up the wall and the second is a clay plaster. So my interest is a follow up of the construction and clay plaster. I take notes of what kind of earth I have on the spot and then I do tests, so I know what kind of clay is in there for the next step.

If we are talking about humidity, I have moisture meter and I'm measuring moisture content in a straw bales already when farmer brings them. I need to check if there isn't too much humidity inside. I do the second check when I put on the clay, namely the first layer of clay plaster, the body coat. When the body coat dries out, it changes the colour on the outside, but you don't actually know exactly what is happening inside. So I put the moisture meter in. It has 25cm long sensor, so I can stick it to the inside of the bale and if I take it out slowly, I can see almost exactly when the bale starts to get more humid, because of the wet plaster.

What is still acceptable value of moisture content for you?

I agree to 25%. That is for me not a problem for straw bale. The transport of humidity is going on all the time there and the percentage is changing. If it is more than 25% or even 30% for longer period of time, and I'm talking about between two weeks and a month, then I'm asking myself what is going on? Because if it was just drying it would take less time. So there should be another reason why it stays humid.

How many times have you encountered straw bale rot in a wall?

Actually one time I had a rot so that part of a building was lost, almost. And that was because of the wall cover failure. The roof wasn't still there. Normally, I cover top of the wall with plastic, so it actually can stay without roof, so that the rain can't get inside the bales. In this case the carpenter took off my protection and than he put it back poorly. When the rain came, water gathered in one place and from there it followed the wooden column, came under the water protection and then it was in the center of the wall, so that the water from all that large plastic came to one spot. This happened during two weeks when I wasn't on the site.

Two weeks was enough to make the straw completely rotten?

Yes. That was actually what happened.

I had already a body coat on, so I made holes in the body coat. Later on in the season, when the roof was there already, I was heating inside of the building to 50°C with a special heating machine for one week. It didn't work, because I think that body coat in a way is blocking the drying process and the bales then rot.

Did you heat the wall inside?

No, I heated the building inside. Because the walls were already there I could heat one spot of the wall very very well.

Where did you make the holes?

On the inside and the outside as well. Finally what I had to do was that I took off the body coat from the inside. I took out—not the bale, because the bale wasn't existing anymore—I took out a black mess. But because the way I construct, I have a light wooden structure in the wall, the roof was still holding despite missing straw. And also I had still a body coat on the outside. It was already dry and standing intact by itself as a skin. I filled the large hole with a dry straw again. Then I put on the face of the fresh straw a panel and then I plastered from the inside on top of that panel. Now you don't see anymore a difference.

Was that the only time you had encountered a straw rot?

On this level yes. There is another experience with a building that we have built in the winter, so it wasn't the best time. The straw bales that my apprentice had put in the wall were grey. I came to measure a humidity and it was more than my scale could give. It was more than 45%. Normally I think this is lost. There was nothing I could do to save the straw. This was a center for experimenting, so it wasn't for a private person, and we decided to leave it there to see if it will spontaneously dry out. It had no body coat. It just had a French dip (3 to 6cm thick layer of clay slip applied by dipping a side of a bale in bathtub filled with a clay slip). I came two months later and it wasn't still a hot season, it was early in spring and I measured moisture content. It came down to 30%. It dried out very well already, so I was thinking if I wait another two months it will be in my limits. Luckily the body coat was not there to block the drying process. This was for me an example that straw bale has a great capacity of getting out the humidity, if there isn't body coat or even final coat on top.

I just remembered another example. In one building, there was a roof construction on, but not covered with tiles yet. It was a very bad weather, one of those big storms in France. Many roofs were gone, you know. Finally we had traced down the leakage that came to the very bottom of the wall. Those bales were gone. The only solution was to take them out. It was another system. It was loadbearing, but if only the small section is damaged you can get the straw out.

You have probably seen a lot of occupied straw bale buildings from the inside. How many times have you seen mold growing on straw bale wall (in occupied building)?

I have seen mold growing, but that wasn't straw bale, it was claystraw (wet mixture of straw and clay, where straw makes substantial part of the mix. It is usually poured into form work and then compacted). This was my first building. Claystraw in the formwork can dry out in about three months, because there is a wet straw even in the middle of the wall. It is also dipped in clay.

It takes three months for claystraw to dry out in high summer season. If you are late in the season, it can not dry anymore. That is what I saw. I was in the winter time there. The outside of the wall had dried out. I'm talking about 30cm thick wall. I had to install the electricity lines, so I took drill machine and drilled may be 6 or 7cm of solid stuff, which was all right and then, there was nothing and then again came the wall skin on the other side of the wall. I had drilled on several places. I thought: what's going on? So I opened the wall and inside was nothing, it was gone, it was air, or it was all wet. It was mush. The wall was made in September, which was too late in the season. Because the two sides of the wall were intact skins, and because of the wooden frame structure, the wall stayed as it is, with advantage of insulation created by air layer. We were lucky.

What kind of finish do you prefer to use for the interior of your straw bale projects?

Actually when you are looking at the both sides of the wall, you want to have the less permeable cover on straw to the inside. In general I'm working with the clay plaster, so I'm using on the inside the clay plaster anyway for a good indoor climate. This means that to the outside you need to have at least also a clay plaster and not the lime. I'm convinced that it doesn't matter if you make lime plaster only on the part of your house, for example if you lime plaster the western wall exposed to the heaviest wind and rain, to give the house extra protection. I think that the rest of the house provides enough surface to breath.

Let's talk about the inside now. Do you use any special ingredients, or trick for the interior earth plaster?

For outside clay plaster I do water proofing with the fixative, with a product that I spray on the wall. Actually the spraying gives water protection, but it is also closing free passage for humidity, that is for sure. So actually I do need to do this also inside to get the equal permeability, even though I don't need any water protection there. I do this only sometimes and not for the whole interior surface. I'm still thinking that if you are looking at the whole house that the part of its surface can take less transpiration than the majority of surface area.

You do French dip in clay slip on both sides. Interior as well as exterior side of the bale. Why do you do this?

It is for the construction purpose. Your straw bales get immediately stabilized this way. If you put them into the wall and on top of each bale you fix a lintel (lath 30mm x 30mm), every straw bale is stabilized. The surface is also stabilized. When dipping is still wet and straw bale is fixed in the wall I put a board, some kind of plywood, on the wall surface and hammer surface flat to get further compression in this direction. Structurally, this is important to me, because the wall gets well stabilized and the bales are becoming leveled by tapping on board.

And they get attached to each other.

Yes. And there is another advantage. The clay slip is not on top of the bales surface, but inside a bale. This means that my glue is inside the straw. When I do on top of this a body coat, the connection between the body coat and this part of clay slip and straw mixture is more logical, more natural, because it is already the same thing, you know? It is very logical to do that.

How many centimeters do you dip?

Dip is between 3 and 5 cm.

And by dipping, clay slip goes all the way in. It doesn't stay on the surface?

It is in. By using all the other methods, it stays on top. People tell me that they have very strong spraying machines. I don't believe them, because the straw is closing itself under the pressure of sprayed plaster. If you put a force on the straw it bends in and there is another straw and another to block the passage inside.

Intermezzo: *Playing with straw*

I have so many ideas, you know. I just want to play in winter. To play with round bales, big jumbo bales, this and that. So much to experiment.

In a way I like the building process, because at first you don't know the building. After one, two weeks you start to get ideas, you see what is possible, but you are not paid for that, so you need to do something extra. For example we do the research on the weekend and we find another colour of earth. That is because you are there and you see what is possible. This is exactly a process that I appreciate, because every house is then different. In every house we did this year, we used something extra but different way. That is fun, you know.

With building for a client there are too many things that you have to think about, but we need to do more research, not only building for clients and not only in a small scale, but also real buildings. There we could show what are the possibilities of a straw bale. We don't know. We think we know, but we don't know. You are researching humidity, someone else is researching fire-protection, but I want to experiment how far I can tip the wall on the angel before it collapses, or something like that. We don't know how much weight can round bale carry, we haven't done research on that. There is a lot, a lot, a lot.

To make a research on building, you need a free contract, so may be not a house, but some other building, where you are going to be really free to do anything you want. May be if it takes a year. Than you will have a building as a standard for straw bales. You can say "O.K., this is a beauty" or "So, this is the quality of straw bale!". Something that you can not do with anything else, because this is what only straw bale can do. Then the architects can say "Hmm, these are not African cabins, that you are making. No, this is real architecture, this is another approach." The ecological architecture doesn't need to be rigid. I'm not talking about the sun orientation e.t.c. These are technical things. I'm talking about the material. It is not an infill, it is just not a brick. No. Straw bale is something else. As an architect, you can put juice into your design. Straw bale is flexible. You can put it on edge, but next to it in single row you can alternate the directions for example, so you can do in the building alternating widths of the wall. That is also what I'd like to explore.

Do you think that there is a condensation happening in the straw bale wall, especially on the cold inner surface of exterior plaster in the winter?

Yes.

Do you think that this is a serious risk?

Well, there is a relation between risk and the time the condensate stays in the wall. In the moment the sun hits the plaster, condensation dries very fast. Here I wouldn't be worried.

Would you worry about the wall with northern exposure in winter?

There is in my opinion also a difference between a plaster, adhering just to the bale surface and plaster that gradually merges with straw. In the middle of the bale there is a straw and then slowly the clay comes in, so condensation is gradual. There is more density in body coat and then even more density in finish layer. So there is the whole process going on in there. It isn't abrupt change.

Like glass for example.

Yes. That is for sure. Also I think that cement for example creates such an abrupt environment. Or you need to dip your bales in cement, so that you have

3cm dip where there is a mixture of air straw and cement. The condensation will be different than the condensation would be on the pure cement stucco.

This is just my imagination saying that the part of the risk of the condensation is taken by the concentration of the clay, where the clay comes in contact with the straw. But still I think, the condensation happens.

A bale that had been previously wetted by rain, becomes discoloured. Would you put discoloured bale in the wall?

I put them in, if they are dry. What had happened before doesn't matter. I had built with bales damaged by moisture from one side, because I took them directly from the ground, where they had been laying for several months. When I placed them into the wall they were dry. When it is dry, it is dry. Once the straw bale is moisturized the way that the fungus is visible, then the fungus grows easier the next time the bale gets wet again, because the straw is more vulnerable. When straw bales stay dry enough the fungus is not a problem. I'm convinced about that. I wouldn't use discoloured straw bales for the whole construction, but few are acceptable.

Would you built with a bale that has a lot of grass in it?

Especially in biological straw, you can see from which part of the field a bale comes from. At the edge of the field, there are many other plants, for example the plants with needles. This is one of the reasons why I don't like too much working with biological straw. I'm working with bare hands, you know. People have their own reasons to use biological straw, but me as an constructor, it isn't my first choice.

How often have you worked with biological straw?

At least 50% of building straw in France is biological, because people who choose to have straw bale building, they are often looking for the biological alternative.

Biological straw is different, isn't it?

Yes, Can be. First of all there are other plants in it, so the work isn't so pleasant and second of all, if I dip a biological bale, its straw is more protected so that my dip in clay slip doesn't attach to it so well.

Why is that?

Because biological straw is protected by silica, which is a natural coating. When it is still on the field, the straw is protected from humidity. In the moment I want to dip it in clay slip it is also protected. So I recommend to let biological straw bales weather in the sun for one or two months. The sun arrays break down this protection on the bale surface. This is just a little detail. There is a difference.

Would you build for a client straw bale building in hot and humid climate?

In tropics, there is a period before a monsoon comes, when the humidity level is constantly almost 100%. I have seen what this can do. It isn't rain, but humidity is everywhere. You can't escape anymore. I had my clothes hanging on line with maximum aireation and they were damp for very long time, so I lost it. Another example, I was on a bicycle and I had a saddle from natural leather, but in this climate few weeks before a monsoon the saddle started to rot. If it continued for few months I would have lost it. I was really impressed by the amount of the humidity and what it can do with materials.

I'm not 100% sure. The experience is already there. The local people do build their houses with natural fibre. The truth is, that the layer of fibre they use is less than 35cm thick straw bale, so they get more airation. They might also use other fibre than straw. They use fibre coming from that area, so I think it has to have its own natural protection. May be we should make the bales from that local fibre.

So would you take that job?

Yes. For sure I would take that job. I would take that risk.

Before I start with any building I do research in the area to see how the local people build traditionally with fibre.

At the end of our interview, would you have any interesting moisture story for me?

There is the most beautiful straw bale building I'v ever seen near Prededome, centre of France, known for it's rough climate. It is humid there and everything. Cold. It is an exceptional building. It has unplastered straw bales. Are they humid? Are they rotten? No, not at all. The colour has faded out, but anyway, the owner said, when it rains and later on - the wind comes, it is not the sun, it is the wind that dries it out. And it is dry.

For how long has been this house standing in there?

For 12 years without plaster. It is still there.

Is there a plaster inside?

There is a lime plaster on the inside.

Who built it?

The guy himself. He build it only with a quarter of the page from book "Shelter". It is the most simple house I'v seen in straw bales and the most charming. Very light roof. He prevented the roof from blowing away by hanging the ropes over the roof and on both sides of the rope he tied the rock. Only two ropes. That was it.

Is it loadbearing?

Yes. On top of the wall there is a round wood, log. He didn't fix it to the wall and on top of that he put his roof.

It must have been one of the first houses in France.

You know, we don't know. Nowadays there are in France at least 500 straw bale houses. At least! Because everywhere where I come, and I build in a lot of different regions, people tell me: "Yes, there is somebody who has built in straw bales already." Everywhere. You don't know. The known structures are often the ones that have been build officially with an architect, or people who are looking for publicity. Cabins, sheds e.t.c—we don't know.

Thank you very much.

A.3 Interview with Martin Oehlmann in his and his wife's straw bale house in Plozevet—Brittany, France.

House still under construction, October 2005 (few weeks before the great storm that soaked the walls all the way through)

On how many straw bale projects have you participated so far?

I think during last ten years about 4 each year? I just don't know.

What kind of plaster have you chosen to protect the exterior of your straw bale walls?

Here, because the house is in a very rough climate by the Atlantic ocean I'v chosen lime plaster. The lime had been used traditionally in this location. It is a product that you can buy in every building store. You can't buy clay plaster here, by the way.

What makes your plaster weather resistant?

First of all there are three layers of lime plaster. The last finish is very much rubbed in and smoothed out by trowel, so that it is almost like a tadallact finish, which is absolutely moisture resistant.

Lets look at your plaster in detail layer by layer. Exterior and interior. How was it made?

I was at first informed a bit about lime plaster in general, because there are different qualities available. I went to different supplier. I also talked to Pascal[1], who did a lot of lime plastering on straw bales here in Brittany. It is good to use the materials that he has direct experience with, because there are different products, which may vary in quality. Even though we have European standards, like NHL2 for example, there are differences in quality within these limes. I was listening to other opinions as well. Someone who used rather ruff sand, sort of stony for the first layer to build it up roughly and then get into the smaller sizes of sand in next layers ending up with fine plaster on the surface. I didn't do that. I applied the first layer of lime plaster made out 50% of hydraulic lime and 50% of air lime (hydrated lime - ed. author). 1 part of lime mixture like this and 3 parts of sand.

How did you apply this layer?

[1]Pascal Thepaut is Europe's first pioneer of straw bale construction.

Partly with a spray machine and partly by hand, because with the spray we didn't have very good experience and even the hose was not long enough to get all the way to the north side.

Have you used netting as well?

We used netting on all walls and it was very good.

For the inside and for the outside?

The same think. The same materials, the same way of application are on either side of a wall.

We've chosen netting because the "I" beams in the walls are surfacing in the same level as the straw bales and the "I" beams need to be covered. We actually applied some scotch tape directly on to the beams before plaster application to prevent cracking. In case the wood is working, the scotch won't be connected with the lime plaster as well as wood would be. (After the winter with many driving rain conditions the wood of "I" beams started to rot under the scotch tape. This we learned when we opened the soaking wet plaster - ed. author) Afterwards we covered the whole wall with netting. It is black plastic netting 15mm by 15mm. It appeared to be very nice to work with.

Did you staple the netting on the wood?

Yes. The netting gave a very nice key.

How did you apply the first layer, when plastering by hand? Have you rubbed it in?

We had many people, volunteers who have worked on that. There were even some professionals who knew how to throw plaster on the wall. It went into the wall with some power, it went very well. It is a good method. Somebody used the board, instead of throwing plaster with a trowel.

How thick is the first layer?

Well, it is about 10mm. Somewhere few millimeters more, but not much.

What about the second layer?

Like a first layer, only that the lime isn't mixed with hydraulic lime. There is just air lime (hydrated lime ed. author) in the second layer. Proportion lime to sand is again 1 to 3. We used the same sand with 0.4mm grade. It is a red sand and we've used it for all the three layers. First I though I'll use the fine sand for the finishing layer, but the local professional warned me that the cracking might be more obvious in fine and smooth surface. We had cracking anyway. The first layer was cracking and the second layer as well. In the first layer we had cracking just around the "I"beams despite the scotch tape and netting. Around the doors and windows I wanted to put over cracks even much finer plastic mesh. Green mesh. Local professional said: "Don't do that". This was a man who worked with lime plaster before. "Just add some cement" He mixed the cement to plaster on the board in his hand and applied the mix over the cracks. Now we have the light spots on plaster around the windows and doors in places where the cement was added into it.

Is the second layer 10mm thick as well?

Yes. Sometimes it is little bit thicker because the surface was uneven. We put the bales on edge and they were impossible to shave.

The last layer.

The last layer is the finishing. We also had few cracks in it. I was a bit concern. Because of the wind and sun the plaster dried out in places so quickly, that it cracked. The air lime needs shading and slow dying process. It is also possible that it cracked in places where we applied the render too thick. We applied the third layer also by hand and then we massaged it into he wall with wooden plank.

Do you mean trowel?

Not with a trowel. Just with a plank. We got this way a really smooth surface and stiffness. If you do that, the surface is getting more solid under that plank. After few days some cracks appeared so I went around and rubbed the cracks in. This is the way to close it, because the drying process has been slow. It is still wet now. Just the surface is little bit dry, but under it—it is not dry, because of the air lime.

Are you going to limewash the walls as a final weather protection?

Yes. Also because of aesthetic reasons.

How many layers of limewash?

In the inside just one and in the outside three, four layers. One layer each year.

Thank you very much

Standing with Martin Oehlmann by the window in the straw bale house under the construction in Plozevet. There is a stormy weather outside and rain in large quantities hits te window. The stormy Atlantic ocean is in close distance.

October 2005 (few weeks before the great storm that soaked the walls all the way through)

Martin

Look at the waves over there (pointing at the ocean behind the window).

We have a lot of driving rain here.

Yes it is just coming over. The horizontal rain.

Do you think the lime plaster will withstand this?

Well, we will see. I hope so. I think so. This is the best test. I mean all the overhangs will do anything in this sort of rain. Yes, but I'm quite confident I will put one limewash on and this will continue for few years. So this will be perfect.

A.4 Interview with Simon Ayres of Lime green products ltd. and Bee Rowan of Amazon Nails at Ecobuild 2006 in London.

Friday

Simon was supervising the spraying of one of his products, hydraulic lime ready mix, on the walls of straw bale lecture theater built by Amazon Nails as a contemporary structure and demonstration project for the event.

How do you make lime breathable?

Lime is breathable. Different limes are differently breathable. The breathable is down to not just the lime, is down to aggregates, the mix composition a lots of things.

I heard that in medieval times people added blood into the mix to make it more breathable.

In our ready mixes we add different stuff that does that sort of thing. So the soap agent will make tiny bubbles, there is a tallow or things like that.

What kind of sand do you use in your ready mixes?

It varies. In this particular product (referring to ready mix that has been sprayed on straw bale walls in front of us) there is a silica sand, some lime stone and special aggregate which is recycled, which is only small percentage in this one, but in other renders we have up to 60% recycled aggregate. It makes it lighter and more thermally efficient as well.

Sitting with Bee Rowan of Amazon Nails and Simon Ayres over the sample of lime plaster from Plozevet at Ecobuild 2006 in London.

Saturday

There are two Plozevet samples in front of us. One that was taken from the wooden post ("I" beam), the other sample was taken from the major part of the wall.

> "the sand is local red sand ca. 3-4 mm. 1. layer: 1/2 airienne (Decochaux)= St. Astier + 1/2 hydraulique = Boehm natural NHL5 5 (ca. 1O-20 mm; 2. layer: 1 St. Astier airienne (Decochaux)20 mm; 3. layer same as 2. ca. 3-5 mm working in with a taloche = plank. Same inside outside." (M.Oehlmann, 2006)

How is the sand in this sample?

(Simon is crumbling sample of lime plaster from Plozevet in his hand.)
French sands are in general better than our sands, for use with lime. The grading; how well washed they are.

The sand that was used in Plozevet is nice sand. Clean.

I don't know why they have sands which are good for use with lime.

Bee:
(Also crumbling bit of plaster.)
Sharp, well graded

Simon:
Yeah. They use it with artificial hydraulic lime. In this country we have in general finer, stogier less well washed sands. So I don't think the sand is a problem in this case.

> *Let's say, they applied the lime, it's a nice weather. They wait until its hard, they apply another layer and another one. For how many days has to weather sustain after that above 8° C, in order to make plaster withstand the frost and the kind of weather common in Brittany? Is it even possible for the lime to withstand this kind of weather?*

Brittany is pretty tough.

It is very tough.

I know because, similar render we've used on there (pointing at straw bale lecture theater at ECOBUILT 2006), very similar is sold in France. Everywhere in France it's two coats, or just one coat, in Brittany it is three coats. And that's like industrial render, modified type of render. It has got water preservative. It is like a formulated product with a water repelents in it, with air drainers that sort of thing. It's called monocouche. And in Brittany they say especially on west facing gables you put the third coat.

West facing. That's it.

So is it possible for lime plaster in general to withstand this kind of weather?

Yes. We sell it in places like Scotland, Western Wales...

Do you think that it stops the driving rain from penetrating the wall? I experienced that rain there. It was enormous storm.

Bee:

In North Yorkshire, we would never use this (pointing at the sample of plaster from Plozevet on the table). We use non hydraulic lime that has a chance to fully carbonate. It's amazing. In Clow Back, because of the wide windowsill, the nonstop wind is driving rain against the same spot on the wall the whole winter and Bill Chaytor (the owner of Childerns farm in Clow Back—one of the projects of Amazon Nails - ed. author) was incredibly worried. He had Barbara (Jones) come up to take the lime off, frightened that straw will be ruined. So they took off the lime and behind it the straw was bone dry. And that, in our experience, is how lime works, that is how it works in Scotland. If it is carbonated, certainly non hydraulic lime, the ability to take that moisture in and release it, while protecting what is behind it, it's remarkable. It fails when it doesn't carbonate.

Simon:

Yeah. The carbonation needs right humidity, right temperature above 8°C. Average carbonation is about 2mm per month.

Bee:

It's a long time.

Simon:

So if someone did that in September (pointing at the sample from Plozevet) and the whole thing was nonhydraulic lime or air lime or hydrated lime what ever, That thick (50—60mm) in Brittany, in order to protect it, till spring in right conditions, really. It is going to carbonate for a long time.

Bee:

If it is exposed place they need to look after it.

Simon:

Or they have to start in spring.

What about pollution? I heard that pollution causes degradation of lime. What about pollution in the rain, or in the air?

Simon:

Anything acidic will dissolve it, but there is no gypsum in lime, unlike in cement. Portugees hydraulic lime has got 3-4% gypsum in it. Which is as much as you find in cement. That is going to be affected by solfex, may be water born, or from the ground from wherever. But in general limes have better resistance than cement. Look at Roman structures. Once they'v carbonated as Bee says, they're normally pretty good for long time. They get better over time.

Do you put any kind of water resistant material into your mixtures?

In our renders we do. In some. We put it into a natural render, as we describe a natural render. In a lime putty we don't. In hydraulic lime mix there might be included generally tallow or sterate. Commercially it is sterate, but it's tallow.

For instance Cardiff castle. They were having a lot of problems actually over the last few years. They spent five years try to repaint it and they had failures. Originally they had specified product which contained tallow. They had wall paintings inside of tower, very hard rock, some sort of granite or something. Highest point in Cardiff roughly. A lot of wind driven rain off the Irish sea, Atlantic. Very important wall paintings inside and they got water penetration. They spent a lots of time and money researching on this. Initially they specified something with small amount of sterate or tallow in it. Unfortunately the contractor thought he could skip that part. They did all sorts of other stuff. It failed and they got water penetration, so they are gone back to drawing board and start it again. They have to redo their work with a bit of tallow in.

It can repel water, because water will run off something in droplet form. But with the wind as you say, the lime is generally more porous which allows it to breathe, but if you've got high pressure, the wind blowing in, it will get in if you're not careful. It can make a significant difference.

Some people add lime wash, some people don't. We don't put limewash, we say put another couple of coats on. But in some of the renders we do, we put it in.

Bee:

How would you include it's porosity and in the same time it would be water resistant?

Simon:

(Having the sample from from Plozevet in his hand)

Compare to sort of UK aggregate, this is going to be more porous, because it is better graded, low fines. If you imagine, on sides of motorways they use a low fines concrete sometimes against the curb. Water comes right through it. That runs off from the road. It is just course aggregate. In the same way you'd the same thing with this, but you would have the great trouble in trying to get the stuff on the wall, because it will reduce workability. But you can add couple of things into it, that will give you back some sort of stodge, if you like, or body to the mortar. What the fines do, they give you body to the mix. So if you imagine, you have course bits and fine bits. To make something more porous you take some of the fines out. People in this country love using a dry screened sand. Dry screened sand hasn't been washed. It is full of clay and silt. Makes very quick ice cream mix. It is very dense nonbreathable mix because of that clay and silt in there. If you have got some clay or silt in it, it is not porous. But this is more porous (referring to sample of render from Plozevet). It doesn't have that bottom end if you like. That end makes it very workable and creamy. So you can remove that, you can add a cellulose. For instance we had a cellulose back in and starch and they give you sort of body to it.

Does it also prevent cracking, because with the cellulose you add fiber into it?

Getting a sand absolutely right prevents cracking. I'd be surprised if there is a lot of shrinkage in that type of sand. (refering to sample from Plozevet). The other thing is, that lime is always more breathable than sand. In general. If you use lime putty 1:2, the researchers say that it is more breathable than 1:3. But it depends. It depends on sand, depends on the clay content. I know companies that sell 1:3 mix for plastering, but their sand may have more fines in it or something like that. In general we use very well washed sand in proportion 1:2. It makes it more porous, carbonates more quickly. I'v been seeing jobs quite well known in Wales, that used A sands A lime that was actually hydraulic lime and it wasn't going off. What happened? They basically left very tight surface over the render. Not really like that (pointing at the sample from Plozevet) and the sand was full of clay. They sort of floated all the clay up to the surface. The clay was forming sort of film over the render. It was taking long time to go off. That is another thing to watch out. Clay is really quite bad. Potentially quite bad. Some people are mixing it in...

You wouldn't recommend it?

It's knowing is there. For instance if you're mixing hydraulic lime and air lime, if you know that it is going to work, if you know how it performs and you've done it lots of times, then you know for instance that in September you don't want to be doing it. It is the same with clay, If you know the mix has clay in it, it is going to shrink a bit and that sort of thing. We know people they've had huge problems with that in a past. Clay is a binder and it's quite cheap for people to include sand as an aggregate which has clay already in it, because it saves on the expensive bit, which is lime or cement. If you know it is in there, you can be aware.

You wouldn't probably finish it smooth so that clay comes out...

Precisely. You might put on thinner coats, you might do all sorts of stuff. It is safer not to do it, but it gets quite complex to be honest. Lime is very difficult product to get right, because you are trying to use something as soft as possible, but soft and breathable. So as soft and as breathable as possible in harsh environment. Cement is quite easy. It just goes off and goes rock hard. With lime it is quite thin line you're threading and there is a lot of ways which can go wrong.

Thank you both very much.

Appendix B

Tables

	1960	1971	1975	1980	1985	1990	1995	AAGR 1960-1990	AAGR 1971-1990	AAGR 1990-1995
Industrial Sector										
Industrialized Countries	622	932	911	970	859	887	852	1.2%	-0.3%	-0.8%
Economies in Transition		404	474	570	585	602	445		2.1%	-5.9%
Developing Cos. in Asia-Pacific		223	287	384	483	632	859		5.6%	6.3%
Rest of World		126	158	209	218	199	214		2.4%	1.4%
World		1684	1830	2133	2145	2319	2370		1.7%	0.4%
Buildings Sector										
Industrialized Countries	434	790	836	886	887	915	958	2.5%	0.8%	0.9%
Residential	323	522	543	549	537	539	560	1.7%	0.2%	0.8%
Commercial	111	268	293	336	350	377	398	4.2%	1.8%	1.1%
Economies in Transition		229	280	341	355	350	307		2.3%	-2.6%
Residential		155	200	248	266	258	244		2.7%	-1.1%
Commercial		74	80	94	89	92	62		1.2%	-7.5%
Developing Cos. in Asia-Pacific		67	88	131	179	232	292		6.7%	4.7%
Residential		57	75	110	145	180	210		6.2%	3.1%
Commercial		10	14	21	33	51	81		9.0%	9.7%
Rest of World		80	97	126	157	171	200		4.1%	3.1%
Residential		62	77	102	128	136	157		4.2%	2.9%
Commercial		17	20	24	29	35	42		3.8%	3.6%
World		1166	1302	1484	1578	1668	1756		1.9%	1.0%
Residential		797	895	1009	1076	1113	1172		1.8%	1.0%
Commercial		369	408	476	502	555	584		2.2%	1.0%
Transport Sector										
Industrialized Countries	287	494	554	612	636	743	816	3.2%	2.2%	1.9%
Economies in Transition		65	75	77	83	87	67		1.6%	-5.0%
Developing Cos. in Asia-Pacific		51	54	69	87	122	173		4.7%	7.3%
Rest of World		65	87	116	131	139	170		4.1%	4.1%
World		676	770	874	937	1091	1227		2.6%	2.4%
Agriculture Sector										
Industrialized Countries	22	35	33	38	45	48	51	2.7%	1.7%	1.3%
Economies in Transition		43	52	69	85	93	73		4.1%	-4.7%
Developing Cos. in Asia-Pacific		17	23	36	38	51	68		5.9%	6.0%
Rest of World		10	14	19	21	23	31		4.6%	5.9%
World		105	122	162	189	215	223		3.8%	0.8%
All Sectors										
Industrialized Countries	1365	2252	2334	2506	2426	2593	2678	2.2%	0.7%	0.6%
Economies in Transition		741	880	1057	1108	1131	892		2.3%	-4.6%
Developing Cos. in Asia-Pacific		358	453	620	787	1036	1392		5.8%	6.1%
Rest of World		281	356	470	528	533	615		3.4%	2.9%
World		3632	4024	4653	4848	5293	5577		2.0%	1.0%

Figure B.1: Carbon Dioxide Emissions by Sector for Industrialized Countries and Selected EIT, DC-AP, and ROW Countries (MtC). (Price et al., 1999)

Ingredient	Lig %	Cellulose %	Hemicellulose %	Nitrogen %	Ash %	C/N ratio	Leaf/stem ratio
Straw						48-150	
Barley	11	48	21	0.688	7	86	1.01
Oats	14	33	23	0.704	8	48-98	0.55
Rice	12.5	32.1	24.0	--	17.5	79	3.24
Rye						82	
	2	28	11	1.376	10		
	3.6	16.2	26	--	5.8		
Wheat						100-150	0.73
	14	40	31	0.576	8		
	18.0	30.5	28.4	--	11.0		
	18	34	27.6	--	1.3		
Paper Products							
Brown cardboard	12	72	--	--	1.7	563	
Christian Science Monitor	21	60	--	--	0.4		
Manchester Guardian	3	59	--	--	30		
Newsprint	20.9	--	--	0.816	--	398-852	
Playboy	9	51	--	--	24		
Solka floc (cellulose)	5	84	--	--	0.3		
Washington Post	26	55	--	--	0.4		
Wood							
Soft wods						212-1313	
Hard woods						451-819	
Aspen	15.5	50.8	28.7	--	0.2		
Balsam Fir	28	42.7	24.4	--	0.2		
Beech	12.7	27.7	21.1	1.44	--		
Birch	19.5	38.8	37.3	--	0.3		
Birch	19.5	40.0	39.0	--	0.3		
Pine	27.8	44.0	26.0	--	0.4		
Pine	27.8	42	23.5	--	0.4		
Red maple	23	39	33	--	0.2		
Spruce	28.6	42	26.5	--	0.4		
Spruce	28.6	43.0	27.0	--	0.4		
Sugar maple	8.49	14.1	9.95	0.97	--		
Yellow birch	12	17.3	13.2	1.42	--		
Hay						15-32	
Alfalfa, mature	14.4	29.6	14	2.24	7	18	
Alfalfa, weathered	15	30	13	1.6	8		
Brome, mature	8	37	26	0.928	8		
Wheatgrass crest., Hay	6	30	29	1.44	9	9-25	
Others							
Bamboo	20.1	--	19.6	--	3.3		
Cornstalk	11	33.5	32.6	--	1	12	
Cotton	15	42	12	--	--		
Hemp	5.3	74	20	--	--		
Reed Canary grass	5.3	28	16.5	--	--		
Miscanthus x ogiformis @ vegetative stage	13.3	42	27	--	3.2	63	
Ingredient	Lig %	Cellulose %	Hemicellulose %	Nitrogen %	Ash %	C\N ratio	

Figure B.2: Table of composition of different organic materials. Sources: Van Soest, Peter J. 1994. Nutritional ecology of the ruminant. Cornell University Press, Ithaca, New York. 476 pp. Ladisch, M. R., K. W. Lin, M. Voloch, and G. T. Tsao. 1983. Process considerations in the enzymatic hydrolysis of biomass. Enzyme and Microb. Technol. 5(2):81-160. Lynch, J. M. 1987. Lignocellulolysis in Composts. In: Compost: Production, Quality and Use (M. De Bertoldi, M. P. Ferranti, P. L.'Hermite, and F. Zucconi, ed.). Elsevier Applied Science, New York. 853 pp. Nodvin, S. C. 1983. Effects of distrubance on decomposition processes and on sulfur cycling in the northern hardwood forest. Ph.D. Thesis, Cornell University. Chandler, J. A. , Jewell, W. J., Gossett, J. M., Van Soest, P. J., and Robertson, J. B. 1980. Predicting Methane Fermentation. Biotechnology and Bioengineering Symp. No.10., John Wiley and Sons, Inc. pp. 93-107.

Treatment	% Decomposition	% Increase
Straw + 120 kg N ha^{-1}	48.10 ± 1.53	+ 155.9
Straw + 80 kg N ha^{-1}	45.40 ± 2.28	+ 141.5
Straw + 40 kg N ha^{-1}	34.11 ± 1.47	+ 81.4
Straw + 0 kg N ha^{-1}	18.80 ± 2.41	–

Figure B.3: Percent wheat straw decomposition as affected by N fertilizer rates. Table shows that N application hastened straw decomposition. When compared to straw alone, addition of 40 kg N ha-1 doubled the decomposition rate, while application of higher N rates (80 and 120 kg N ha^{-1}) tripled it. (Kaboneka et al., 2002

Treatment	% Decomposition	% Increase
Straw + 52.8 kg P ha^{-1}	58.6 ± 0.2^{a*}	+ 173.8
Straw + 35.2 kg P ha^{-1}	51.0 ± 3.3^{b}	+ 138.3
Straw + 17.6 kg P ha^{-1}	40.4 ± 0.6^{c}	+ 88.8
Straw + 0 kg P ha^{-1}	21.4 ± 3.4^{d}	–

Figure B.4: Percent wheat straw decomposition as affected by P fertilizer rates. It can be observed that P addition brought about higher percent straw decomposition when compared to N fertilizer addition. When compared to straw alone, addition of 17.6 kg P ha^{-1} doubled the decomposition rate, while application of 35.2 and 52.8 kg P ha^{-1} tripled and quadrupled it, (Kaboneka et al., 2002

B.0.1 Monitors accuracy

The accuracy of dataloggers claimed by the manufacturer (Lascar, 2005) is given in table B.1.

datalogger component	accuracy
temperature sensor	plusminus 0.1 K
relative humidity sensor[a]	plusminus 1.5 %

[a]calibrated sensors

Table B.1: Accuracy of dataloggers claimed by manufacturer (Lascar, 2005)

B.0.2 Tables of material properties

1	material	consists of	density	porosit	heat capacit	thermal cond	compr. strengt	appil. water abs	vapour perm.	vapour resist	vapour diff.	source
2			kg/m^3	m^3/m^3	J/kg*K	W/m*K	MPa	kg/m^2*h^0.5	kg/Pa*m*s	GN*s/kg*m	coef.	
3							N/mm^2		kg*m/N*s	MN*s/g*m	-	
4												
5	earth plaster (high clay content)	Clay = 28%, Silt = 34%, Sand = 38%	_						2.69E-11	37.15	7	Minke 2005
6												
7	earth plaster (high silt content)	Clay = 12%, Silt = 78%, Sand = 14%	_						3.14E-11	31.85	6	Minke 2005
8												
9	earth plaster (high sand content)	Clay = 15%, Silt = 29%, Sand = 56%	_						2.58E-11	38.75	7.3	Minke 2005
10												
11	earth render (high clay content)								2.36E-11	42.46	8	Minke 2005
12												
13	earth plaster (high silt content)								1.94E-11	51.49	9.7	Minke 2005
14												
15	earth plaster							0.152				Minke 2005
16												
17	earth plaster w/ paint	paint: 1*lime/8*casein						0.0117				Minke 2005
18												
19	earth plaster w/ paint	paint: siloxane (BS15 Wacker)						0.0017				Minke 2005
20												
21	earth plaster - 1		1531					0.075	3.01E-11	33.22	6.26	Straube, 2004
22												
23	earth plaster - 2		1769					0.068	4.57E-11	21.88	4.12	Straube, 2004
24												
25	earth plaster - 3		1844					0.067	4.01E-11	24.94	4.70	Straube, 2004
26												
27	earth plaster mix	with 100% sodium silicate	1643					0.061	5.21E-11	19.19	3.62	Minke 2005
28												
29	earth plaster mix w/ paint	with 1*lime pl/3*earth p, paint: 3 x limewash	1419					0.046	3.4E-11	29.41	5.54	Minke 2005

	material	consists of	density	porosit	heat capacity	thermal cond	compr. strengt	capil. water abs	vapour perm.	vapour resist	vapour diff.	source
			kg/m^3	m^3/m^3	J/kg*K	W/m*K	MPa	kg/m^2*h^0.5	kg/Pa*m*s	GN*s/kg*m	coef.	
31	earth plaster mix	with 50% sodium silicate	1698					0.052	4.18E-11	23.92	4.51	Minke, 2005
32												
33	earth plaster w/ paint	paint: 5 x limewash	1408					0.047	4.08E-11	24.51	4.62	Minke, 2005
34												
35	earth plaster mix	with 2% raw linseed oil	1643					0.066	3.23E-11	30.96	5.83	Straube, 2004
36												
37	earth plaster w/ paint	paint: interior - clay stabilized with wheat	1666					0.087	4.45E-11	22.47	4.23	Straube, 2004
38												
39	earth - lime plaster	with 10% lime	1621					0.106	4.17E-11	23.98	4.52	Straube, 2004
40												
41	earth - lime plaster	with 50% lime	1741					0.092	4.04E-11	24.75	4.66	Straube, 2004
42												
43	earth - lime plaster mix	cow dunk/ earth/ lime = 12/47/3/20						0.092	2.35E-11	42.55	8.02	Minke, 2005
44												
45	earth plaster - ready mix	sand + earth				0.83	1		1.88E-11	53.08	10.00	Baumit, 2005
46												
47	loam - earth - mortar	clay/sand/cut straw					2- 3	0.25	2.69E-11	37.15	7.00	Reichel, 2004
48												
49	loam - earth - mortar	clay/light adhesive/cut straw					0.1 - 1	0.25	2.69E-11	37.15	7.00	Reichel, 2004
50												
51	strawclay		1250					0.052	4.13E-11	24.21	4.56	Minke, 2005
52												
53	strawclay		950						6.20E-11	16.13	3.04	Minke, 2005
54												
55	strawclay		750						6.41E-11	15.60	2.94	Minke, 2005
56												
57	strawclay		450					0.04	8.27E-11	12.09	2.28	Minke, 2005
58												

	material	consists of	density	porosit	heat capacity	thermal cond	ompr. strengt	appil. water abs	vapour perm	apour resist	vapour diff.	source
			kg/m^3	m^3/m^3	J/kg*K	W/m*K	MPa	kg/m^2*h^0.5	kg/Pa*m*s	GN*s/kg*m	coef.	
59	strawclay		1200			0.47						Oliva, 2002
60												
61	strawclay		1000			0.35						Oliva, 2002
62												
63	strawclay		800			0.25						Oliva, 2002
64												
65	strawclay		600			0.17						Oliva, 2002
66												
67	strawclay		400			0.12						Oliva, 2002
68												
69	strawclay		300			0.1						Oliva, 2002
70												
71												
72												
73	lime plaster								1.78E-11	56.26	10.60	Minke, 2005
74												
75	lime - casein plaster mix	10*lime/1*casein							1.52E-11	65.82	12.40	Minke, 2005
76												
77	lime - linseed oil plaster mix	20*lime/1*linseed oil							1.22E-11	81.97	14.40	Minke, 2005
78												
79	trass-lime plaster	eminently hydraulic lime plaster							2.36E-11	42.46	8.00	Minke, 2005
80												
81	slaked lime plaster	lime putty	1400			0.7			1.88E-11	53.08	10.00	Oliva, 2002
82												
83	'hydraulic lime plaster		1800			0.87			7.85E-12	127.39	24.00	Oliva, 2002
84												
85	lime - cement render								7.72E-12	129.51	24.40	Minke, 2005
86												

	material	consists of	density	porosit	heat capacit	hermal cond	ompr. strengt	appil. water abs	vapour perm.	vapour resist	vapour diff.	source
			kg/m^3	m^3/m^3	J/kg*K	W/m*K	MPa	kg/m^2*h^0.5	kg/Pa*m*s	GN*s/kg*m	coef.	
87	lime stucco		1600	0.3	850	0.7			2.69E-11	37.15	7.00	WUFI
88												
89	lime plaster for demineralization		1600	0.33	850	0.7			1.67E-11	63.69	12.00	WUFI
90												
91	hydraulic lime mortar - course		1830	0.27	850	0.7			9.42E-12	106.16	20.00	WUFI
92												
93	hydraulic lime mortar - fine		1700	0.35	850	0.8			1.29E-11	77.49	14.60	WUFI
94												
95	lime based plaster		1600 - 1800							45 - 205		CIBSE, 1999
96												
97	lime plaster	1*type S slaked lime/3*sand							1.89E-11	52.91	9.97	Straube, 2000
98												
99	lime plaster	1*quick lime/3*sand							1.47E-11	68.03	12.82	Straube, 2000
100												
101	lime plaster	1*quick lime/3*sand	1748					0.164	3.01E-11	33.22	6.26	Straube, 2004
102												
103	lime plaster - ready mix	hydraulic roman lime/ sand				0.83	2.5		1.45E-11	69.00	13.00	Baumit, 2005
104												
105	lime plaster		1600		840	0.7			3.14E-11	31.85	6.00	Tywoniak,1995
106												
107	non-hydraulic lime plaster	non-hydraulic lime, putty/ sand						0.033	9.42E-12	106.16	20.00	Reichel, 2004
108												
109	hydraulic lime plaster	hydraulic lime putty/sand					1	0.033	9.42E-12	106.16	20.00	Reichel, 2004
110												
111	plaster with eminently hydraulic lime	hydraulic lime/ sand					2.5	0.016	7.54E-12	132.70	25.00	Reichel, 2004
112												
113												
114												

	material	consists of	density	porosit	heat capacit	hermal cond	ompr. strengt	appil. water abs	vapour perm	apour resist	vapour dif.	source
			kg/m^3	m^3/m^3	J/kg*K	W/m*K	MPa	kg/m^2*h^0.5	kg/Pa*m*s	GN*s/kg*m	coef.	
115	cement -lime plaster		2000		840	0.86			9.92E-12	100.85	19.00	Tywoniak,1995
116												
117	cement -lime plaster	1*lime/1*cement/6*sand	1912					0.083	1.9E-11	52.63	9.92	Straube, 2004
118												
119	cement -lime plaster	1*l/1*c/6*sand						0.0917	1.03E-11	97.09	18.29	Straube, 2000
120												
121	cement -lime plaster w/ coating	1*l/1*c/6*sand + linseed oil						0.0665	8.0E-12	125.00	23.55	Straube, 2000
122												
123	cement -lime plaster w/ coating	1*l/1*c/6*sand + elastomeric						0.0146	7.93E-12	126.10	23.76	Straube, 2000
124												
125	cement -lime plaster w/ coating	1*l/1*c/6*sand + siloxane						0.006	8.3E-12	120.48	22.70	Straube, 2000
126												
127	cement -lime plaster w/ coating	1*l/1*c/6*sand + calcium stearate						0.0934	4.30E-12	232.56	43.81	Straube, 2000
128												
129	cement -lime plaster w/ paint	1*l/1*c/6*sand + latex paint						0.0197	7.4E-12	135.14	25.46	Straube, 2000
130												
131	cement -lime plaster w/ paint	1*l/1*c/6*sand + oil paint						0.014	1.6E-12	625.00	117.75	Straube, 2000
132												
133	cement -lime plaster		1900	0.24	850	0.8		0.0917	9.92E-12	100.85	19.00	WUFI
134												
135	cement -lime mortar		1900					0.0917	9.92E-12	100.85	19.00	Kunzel
136												
137												
138												
139	cement plaster	cement/ sand					10	0.0083	3.77E-12	265.39	50.00	Reichel, 2004
140												
141	cement stucco	1*c/3*sand						0.0378	1.7E-12	588.24	110.82	Straube, 2000
142												

	material	consists of	density	porosit	heat capacity	thermal cond	compr. strengt	capill. water abs	vapour perm	vapour resist	vapour diff.	source
			kg/m^3	m^3/m^3	J/kg*K	W/m*K	MPa	kg/m^2*h^0.5	kg/Pa*m*s	GN*s/kg*m	coef.	
143	cement stucco w/ coating	1*c/3*sand + elastomeric						0.0085	1.7E-12	588.24	110.82	Straube, 2000
144												
145	cement stucco w/ coating	1*c/3*sand + siloxane						0.0004	1.50E-12	632.01	119.24	Straube, 2000
146												
147	portland (masonary) cement plaster	1*c/0.2*lime/3*sand	1997					0.059	1.37E-11	72.99	13.75	Straube, 2004
148												
149	cement based plaster		1900 - 2000							75-205		CIBSE, 1999
150												
151	cement plaster		2000	0.3	850	1.2		0.0917	7.54E-12	132.70	25.00	WUFI
152												
153												
154												
155	lime gypsum plaster	lime putty or hydraulic lime + a.g and pl. of P.						0.12	2.69E-11	37.15	7.00	Reichel, 2004
156		/ sand										
157	gypsum lime plaster	lime putty or hydraulic lime + a.g and pl. of P.					2		2.69E-11	37.15	7.00	Reichel, 2004
158		/ sand										
159	gypsum sand plaster	anhydrous gypsum and plaster of Paris					2	0.16	1.88E-11	53.08	10.00	Reichel, 2004
160												
161	gypsum plaster	anhydrous gypsum and plaster of Paris/ sand					2	0.16	1.05E-11	95.54	18.00	Reichel, 2004
162												
163	gypsum based plaster									30 - 60		CIBSE, 1999
164												
165	gypsum plaster	no additives	1200			0.35			1.88E-11	53.08	10.00	Oliva,2002
166												
167	gypsum plaster		1721	0.305	850	0.2			1.45E-11	69.00	13.00	WUFI
168												
169	gypsum plaster (interior)		850	0.56	850	0.2			2.27E-11	44.06	8.30	WUFI
170												

	material	consists of	density	porosity	heat capacity	thermal cond.	compr. strength	capil. water abs.	vapour perm.	vapour resist.	vapour diff.	source
			kg/m^3	m^3/m^3	J/kg*K	W/m*K	MPa	kg/m^2*h^0.5	kg/Pa*m*s	GN*s/kg*m	coef.	
173	anhydrite plaster	natural gypsum w/ argillaceous limestone, marl,					2					Reichel, 2004
174		iron oxide/ sand										
175	anhydrite lime plaster	as above/ lime putty or hydraulic lime					2					Reichel, 2004
176												
177												
178												
179	lightweight plaster	perlite	250 - 300		850	0.095			1.88E-11	53.08	10.00	Tywoniak,1995
180												
181	lightweight plaster	perlite w/ PPS granulate	120		1000	0.046			1.88E-11	53.08	10.00	Tywoniak,1995
182												
183	LAVAPERL plaster	perlite + hydraulic binder	270 - 300			0.08			3.77E-11	26.54	5.00	Tywoniak,1995
184												
185	LAVAPERL plaster	perlite + hydraulic binder	350 - 400			0.1			3.77E-11	26.54	5.00	Tywoniak,1995
186												
187	TERFIX	cement, lime binder + aggregate	280		920	0.06						Tywoniak,1995
188												
189	BAUMIT THERMO	perlite + hydraulic binder	1000		850	0.13	1.5		2.36E-11	42.46	8.00	Tywoniak,1995
190												
191	perlite plaster	1m^3 perlite/200kg water/200kg portland cem.	340			0.09	0.8 - 1					Allepo, 2005
192		1m^3 perlite/450kg water/300kg portland cem.	540			0.13	2.5 - 3					
193												
194	vermaculite + perlite gypsum plaster	0.03m^3 (v+p)/45kg gypsum - scratch coat	711			0.1						Schundler, 2005
195		0.09m^3 (v+p)/45kg gypsum - brown coat	629			0.13						
196		0.03m^3 (v+p)/45kg gypsum - finish coat										
197												
198	perlite cement palster	43kg portland c./23kg lime S/0.17m^3 perlite/2k	750				6.9					Schundler, 2005
199		glass fibres										
200												

	material	consists of	density	porosit	heat capacit	thermal cond	ompr. strengt	appil. water abs	vapour perm.	vapour resist	vapour diff.	source
			kg/m^3	m^3/m^3	J/kg*K	W/m*K	MPa	kg/m^2*h^0.5	kg/Pa*m*s	GN*s/kg*m	coef.	
202	synthetic resin plaster	alkali resistant, polymer resin/ organic and mineral						0.0017	1.88E-12	530.79	100.00	Reichel, 2004
203		aggregate										
204												
205												
206	straw bale wal	perpendicular	75			0.052						Straube, 2004*
207		perpendicular	92			0.056						Straube, 2004*
208												
209		parallel	75			0.057						Straube, 2004*
210		parallel	89			0.06						Straube, 2004*
211		high density	587			1.1						
212												
213	vertical (on edge) - dry straw bales				2000	0.045			7.54E-11	13.27	2.50	Minke, 2005*
214	horizontal (flat) - dry straw bales				2000	0.06			7.54E-11	13.27	2.50	Minke, 2005*
215												
216	estimation based on other fiber mat	from							5.00E-11	2.00E+10	3.77	Straube, 2004
217		to							1.00E-10	1.00E+10	1.88	Straube, 2004
218												
219	straw bale wal including lime plaster	test sample: 360mm incl. plaster and studs	110			0.095						Capron, 2002
220												
221			100.8		2000	0.045			7.54E-11	13.27	2.50	Wimmer, 2001
222												
223	wheat straw	test sample: 410mm, rel. humidity = 8.4%	133			0.045 (0.057^)						Wimmer, 2001*
224												
225	rye straw	'test sample: 410mm, rel. humidity = 8.4%	133			0.045 (0.057^)						Wimmer, 2001*
226												
227	wheat straw	'test sample: 570mm, rel. humidity = 8.4%	133			0.06 (0.072^)						Wimmer, 2001*
228												
229	wheat straw	'test sample: 460mm, rel. humidity = 4-5%	83			0.054 (0.065^)						Wimmer, 2001*

	material	consists of	density	porosit	heat capacity	thermal cond	compr. strengt	cappil. water abs	vapour perm.	vapour resist	vapour diff.	source
			kg/m^3	m^3/m^3	J/kg*K	W/m*K	MPa	kg/m^2*h^0.5	kg/Pa*m*s	GN*s/kg*m	coef.	
231	straw bale wall includng plaster	460mm				0.065						Wimmer, 2001**
232												
233	wheat straw	test sample: 126mm, dry	90			0.037 (0.0443*)						Wimmer, 2001
234												
235	wheat straw	test sample: 113mm, dry	100			0.034 (0.0408*)						Wimmer, 2001
236												
237	wheat straw	test sample: 106mm, dry	110			0.038 (0.0456*)						Wimmer, 2001
238												
239	wheat straw including paper coating	test sample: 60mm - ecopanneaux	398			0.113						
240												
241	straw	paralel to heat flow	75			0.057						Andersen, 2004
242		perpendicular to heat flow	75			0.056						Andersen, 2004
243												
244		paralel to heat flow	90			0.056						Andersen, 2004
245		perpendicular to heat flow	90			0.06						Andersen, 2004
246												
247	straw bale wall	365 + 26 mm earth plaster on both sides				0.085						Andersen, 2004
248												
249		*thermal conductivity of dry material + added 20% - estimated for "realistic" material water content - according to EU norm										
250												
251	solid clay brick		1600						1.98E-11	50.42	9.5	Kunze, 1995
252												
253	unfired clay brick 295x140x90mm	10-20% clay, 80-90% silt, sand, gravel - 1%RH	2000				3		1.1E-11	90.91	17.13	Hansen, 2002
254	(controlled additives in mixture)	dtto - 98%RH					4.5		1.6E-11	62.50	11.78	
255												
256	unfired clay brick 298x150x94mm	10-20% clay, 80-90% silt, sand, gravel - 1%RH	2100				7.5		8.0E-12	125.00	23.55	Hansen, 2002
257	(without additives - raw earth)	dtto - 98%RH					5		1.5E-11	66.67	12.56	
258												

	material	consists of	density	porosity	heat capacity	thermal cond.	compr. strength	capil. water abs	vapour perm.	vapour resist	vapour diif.	source
			kg/m^3	m^3/m^3	J/kg*K	W/m*K	MPa	kg/m^2*h^0.5	kg/Pa*m*s	GN*s/kg*m	coef.	
259	OTHER INSULATION											
260												
261	glass wool								1.7E-10	5.88	1.11	Peuhkuri, 2003
262												
263	rock wool								1.83E-10	5.46	1.03	Peuhkuri, 2003
264												
265	cellular corcrete								2.4E-11	41.67	7.85	Peuhkuri, 2003
266												
267	cellulose								1.1E-10	9.09	1.71	Peuhkuri, 2003
268												
269	wool		19						1.9E-10	5.26	0.99	Peuhkuri, 2003
270												
271	flax								1.5E-10	6.67	1.26	Peuhkuri, 2003
272												
273	perlite								1.03E-10	9.71	1.83	Peuhkuri, 2003

278	**References :**
279	Allepo (2005) Perlite, construction application [Internet], Available from <http://www.perliteco.com/consturction_application.html> [AccessedJuly 19th, 2005]
280	Baumit (2005) Welcome to Baumit website [Internet], Available from <http://www.baumit.com/en/main1/index.shtml> [AccessedJuly 19th, 2005]
281	Capron, M., A. (2002) Construction de deux maisons d'habitation dans un contexte experimental, structure bois et fibres vegetales, Montholier Jura, rapport d'etape. Novembre 2002
282	CIBSE (1999) Environmental design, Guide A, London, The Yale Press Ltd
283	Hansen(2005) Unfired clay bricks - moisture properties and compressive strength [Internet], Available from <http://www.ivt.ntnu.no/bat/bm/buildphys/proceedings/74_Hansen.pdf> [Accessed: July 19th, 2005]
284	Minke G., Mahlke F., (2005) Building with Straw, Design and Technology of a Sustainable Architecture, Basel, Birkhauser - Publishers for Architecture, *research by Wimmer (2001)
285	Peuhkuri, R., Rode, C., Padfield, T., Hansen, K., K., Hedegaard, L. (2003) Moisture distribution in absorbent insulation, Danmarks Tekniske Universitet, BYG, [Internet] Available from <http://
286	Reichel, A., Hochberg, A., Kopke, C. (2004), Plaster, Render, Paint and Coatings, Details, Products, Case studies, Baden-Baden, Birkhauser, Edition Detail
287	Oliva J., P. (2001) L'isolation ecologique, conception materiaux, mise en oeuvre, Mens, terre vivante
288	Schundler (2005) Product / Construction guide, fibre reinforced plaster [Internet], Available from <http://www.schundler.com> [Accessed: July 19th, 2005]
289	Straube, J. (2004) Moisture Properties of Plaster and Stucco for Strawbale Buildings, [Internet] Balanced Solutions, Canada, Available from EBNet Database: <www.ecobuildnetwork.org/pdfs/Straube_Moisture_Tests.pdf > [Accessed Janu
290	Tywoniak J., Kulhanek F. (1995) Stavebni fyzika 20, Stavebni tepelna technika, Pomucka pro cviceni, CVUT Praha, Vydavatelstvi CVUT
291	Wimmer R., (2001) Haus der Zukunft, Wirtschaftsbezogene Grundlagenforschung, Studie im Auftrag des Bundesministeriums für Verkehr Innovation und Technologie, Wien, GrAT asbn, *research by McCabe, Joseph: Thermal Resistivity of
292	WUFI 3.3 Pro.IBP Moisture design tool for architects and engineers, Material database, Institute Bauphysic, *Institute for Building Physics Holzkirchen, **North american educational database, ***University of Technology Vienna

B.0.3 Summary of case study investigation

ho us e #	locatio	heatin	year built	preci pita tion [mm]	T [C]	expo sure	overhan	ext cove	int cover	vent bath/ kitch	misc.	pos tion #	pos. spec	orien tation	height above ground	interio	misc.	straw cond tion	min RH [%]	T [C]	date	max RH [%]	T [C]	date	com ment
	Rob Jolly (2000)																								
1	Alberta	wood	1992	374	2	0	1st f >	cem	cem	no/n	ground	1	mid	N	300			100	22	11	April	86	17	July	
	Canad.	rad					>S,W 2m				moisture		ext	N	300		crack	0	48	3	Jun-Oc	98	17	Dec.	dr. rain, snow
		floor					2nd f>				vicking	2	mid	N	2200			100	23	9	Jan	80	21	Aug	snow
							no				through	3	mid	N	300	bath			29	#	Mar	97	14	Aug	snow
											plaster		ext	N	300	bath			8°	#	Dec M	17°	14	Jul Oct	
												4	mid	S	2200	living		100	33	1	Jan	60	16	July	
												5	mid	W	1st f.	pantry		100	33	1	Jan	68	18	Aug	
												6	ext	N	1st f.	garag	crack	100				98		Apr Jun	
												7	ext	W	150			100	6°		Dec M	8°		Sep Oct	
2	Alberta	air	1995	374	2	0	1st f>	cem	cem	3bat	suspende	1	mid	N	2200		ex leak		27	9	Jan	53	19	Jul	
							1m SEW	tyvek	latex	only	wooden		ext						58	#	Jun	96	#	Jul	dr. rain, tyvek > water vapour from dr rain
							2nd f>			y/y	floor	2	mid	E	2900				29	11	Feb	64	#	Aug	
							1m				1m above	3	mid	S	2230		ex leak		36	#	Ap	76	#	Jul	
											ground		ext					100	63	#	Jul	96	19	Ap	(ex leak or condensation) drying from 96% to 60% (100% porch protection)
												4	mid	S	2nd f.	bath			26	2	Jan	61	19	Jul	
3	Alberta		1996				NS 1.75r	cem	cem	y/y	perimeter	1	mid	S	1500				21	#	Mar	57	#	Jul	protected overhang +Tyvek - suspect only to RH atmospheric conditions. Big solar loading he
							EW 1.25r	Tyve	build.		radiant		ext		350				25	#	May	69	#	Jul	
								only	paper		floor	2	mid	N	1300				33	6	Jan	64	17	Jul	ext greatly affected by atmospheric RH (Tyvek)
		wood		570	2	70		1st f.			loops		ext		1300				47	5	Nov	77	#	Jul	Comp. 1ext and 2ext brings effect of solar drying S side, while RH peaks are not so different
		rad									under	3	ext	N	500				29	#	Feb	77	16	Jul	effect of radiant heating loops. No significant T gradient mid-int> RH almost identical (Tyvek)
		floor									bales		mid						19	#	Jan	61	16	Jul	
													int						20	#	Jan	64	17	Jul	comparison 3mid with 2mid, 3mid lower RH due to loop heating although much lower position.
												4	ext	N	2nd f.		during		33	#	Mar	77	19	Aug	
													mid				building		38	9	Nov	70	18	Aug	summer unplastered straw, just Tyvek out. Swings RH, 4ext 90% due to amb. RH, winter drying -
													int						48	#	Jul	90	0	Feb	summer plastering> peak ext, mid int 80%> drying autumn
												5	ext	W	low		after		42	8	Nov	88	19	Jul	
													ext		low		rain		7°			9°			
													ext		high		storm		47	#	Nov	97	#	Aug	It may be reasonable to assume that when comparing moisture contents to RH levels in field -
													ext		high				7°			9°			situations, the lowest diurnal RH reading will be reflective of the appropriate moisture content.
																									comparison 2ext and 3ext. Tyvek doesn't inhibit drying. Tyvek permanent peaks-
4	Alberta	radian	1996	450	4	90	0.6m	cem	cem	y/y	bales on	1	mid	S	300	living			18	#	May	62	19	Jul	, drying wetting 70-30% , without more steady RH 50-80%
		floor				in depression					edge 14"	2	mid	NW		bath			26	7	Jan	64	19	Jul	
						chinook						3	mid	W		bath			26	#	Jan	60	#	Jul	
						drying					overhang	4	mid	NW		kitch	under outd		21	#	Mar	64	19	Jul	ext mid very close readings, lack of vapour gradient
											600		ext						20	#	Mar	42	15	Jun	
												5	mid	NW	near				22	#	Feb	49	18	Jun	highest mid at the North wall, but low.
												6	ext	N	300	office			6°		all year	6°			
												7	ext	NW	400	bath			6°		winter	8°		summer	
												8	ext	S	400	bath			6°		winter	8°		summer	

house #	location	heating	year built	precipitation [mm]	T [C]	exposure	overhang	ext cover	int cover	vent bath/kitch	misc.	position #	pos. spec	orientation	height above ground	interior	misc.	stray condition	min RH [%]	T [C]	date	max RH [%]	T [C]	date	comment
5	Alberta	wood	1997	950	10	coas	0.5m	cem	no		high at RH	1		E	1200				8°		Jul	12°		Aug,Sep	
						E&N						2		S	1350		dr rain		8°		Oct	14°		Jan	
						80						3		W	1200		trees		8°		Aug	14°		all year	
						W coast						4		N	1200		trees		8°		Oct	14°		Jul-Aug	North wall - no driving rain. The high RH due to high atmospheric humidity and no drying.
														N	1200				85	#	Jul	98	13	Jul-Aug,Jan	
6	Alberta	rad flo	1991	484	4	0	2m>	cem	cem	y/n	one story	1	ext	NE	300		dr rain		42		winter	54		Jun	very steady
						in a	>W,NW	+ply	+glue		windy				400		snow		6°		Ap, Oc	8°		summer	
						valle	0.3m>	wood				2			300		dr rain		6°		Dec	8°		summer	
							>S,E,NE	vent?									snow								
							SW	no				3		E	150	bed	u/wind		6°		winter	8°		Jun	
												4		S	300	liv	b/splash		6°		summ	7°		winter	
																	roof drain								
												5		W	150	din	water		33		May	64		Jul	
																	flowers								
7	Alberta	rad	1997	412	3	0	0.6m>	cem	cem	y/y		1		W	300	den			6°		winter	8°		Jun	
		floor					>E,W												40		Mar	75		Jun	
							1.75m>					2		NW	300	den			6°		winter	10°		Jun	
							>N,S					3		S	300	bed			6°		all year	7°		Jun	
												4		SE	400	bed			7°		winter	9°		Jun	
												5		NE	400	bed			6°		winter	8°		Sep	
8	Alberta	rad	1998	412	3	80	0.6m>	con	con		E 3 cours	1		E	below				12°		May,Ja	14°		summer	
		floor					>N,S				ext tar pap	2		E	100				8°		Jan	14°		Aug	
							0.3m>				below gra	3		S	200				6°		Jan	10°		Jun	
							>E,W				S no dam	4		N	2nd f.				81	9	May	98	#	Jun	
											proof on	5		E	-1000		snow	dam	14°			14°		all year	
											courtwood														
											snow melt														
											inside														
9	Alberta	rad	1998	450	2	0	1m>	cem	earth	y/y	suspende	1		N	1000	bed			44	1	Nov	55	7	Apr	
		floor					>N,W				floor								6°		Feb,M	8°		summer, autumn	
							0.65m>				1st course	2		E	1500		above tar p		6°		Feb,M	10°		May	
							>E				tar paper				1000		under		6°		winter	11°		Apr	
							1.5m>					3		W	1500	laundry			6°		aut,win	8°		Nov,Dec	
							>S																		

house #	location	heating	year built	precipitation [mm]	T [C]	exposure	overhang	ext cover	int cover	vent bath/kitch	misc.	position #	pos. spec	orientation	height above ground	interior	misc.	straw condition	min RH [%]	T [C]	date	max RH [%]	T [C]	date	comment
Habib Gionzales (1999)																									
1	BC	rad floor		1016		80		stuc	loft>		lakefront>	1	ext	S	2nd f.	loft	no int plast		9°		Sep,Oc	14°		April	
									>no		>Swall	2	ext	W	2nd f.	loft	no int plast		10°		winter	11°		summer	
								brow	brown			3	ext	E	1st f.	kitch			9°		Sep	12°		April	
								coat	coat		by lake	4	ext	N	1st f.	bed			7°		Sep	9°		summer	
												5	ext	N	2nd f.	loft	no int plast		6°		Sep,No	8°		summer	
											2.9m snow														
												Tint								#	May,Jun		#	Jul	
												Tout								1	Dec		21	summer	
												Rhin							37		Apr		#	Jul	
												Rhout							43		Apr	98		winter	
2	BC	in floo	1996	1016		80					2 story	1	ext	S		kitch	no vent, tig		6°		winter	8°		summer	
		hydronics									+shop>	2	ext	N		bath			8°		Aug	11°		Dec,Mar	
											>heated	3	ext	W		bed			8°		May	12°		Aug	
												4	ext	S		laundr	no vent, tig		9°		Oct	11°		Jun,Aug	
											69m lake	5	ext	N		shop			6°		Sep	9°		Mar,Apr	
											2.9m sno	Tint								#	Apr		#	May	
												Tout								3	Dec,Feb		#	Aug	
												Rhin							40		Apr	50		Jul	
												Rout							38		May	80-96		winter	
3	BC	wood		desert		50-10					barn	1	ext	N	1st f.	kitch			6°		winter	9°		Mar,Apr	
		stove									open plan	2	ext	NW		living1			6°		winter	10°		Feb	Feb - Apr drying of int. brown coat stucco - plastering. Ext. brown coat in May - dry weather -
											11 bales>	3	ext	SE		living2			6°		winter	14°		Feb	drying no effect.
											>high +	4	ext	SW		bath			6°		winter	10°		Feb	
											gable 17														
												Tint								#	Nov,Dec		#	Aug	
											850m a/s	Tout								#	Nov		#	Aug	
												Rhin							35		Feb				
4	BC	wood									840m a/s	1	ext	NW	1st f.	bed1			8°		Sep	12°		Feb,Ma	no internal doors
		stove										2	ext	NW	1st f.	living	backsplash		8°	#	Oct-De	14°		Feb	
												3	ext	NE	1st f.	bath			8°	11	Jun	11°		Jul	
		hydronic										4	ext	NE	1st f.	bed2			8°	11	Oct,Ju	14°		Feb	
		floor										5	ext	SE	1st f.	bed3			8°	11	winter	11°		Mar,Jul	
												Tint								#	May		#	Mar,Jul	
												Tout								1	Nov		19	Jul	
												Rhin							34		Apr	47		Jan	
												Rhout							27		Mar	85		Jun	

ho us e #	locatio	heatin	year built	preci pita tion [mm]	T [C]	expo sure	overhar	ext cove	int cover	vent bath/ kitch	misc.	pos tion #	pos. spec	orien tatio	height above ground	interic	misc.	strav conc tion	min RH [%]	T [C]	date	max RH [%]	T [C]	date	com ment
5	BC	wood	1998			80	0.6m				load beari	1	ext	W					8°		Aug,Se	12°		Apr	
		stove										2	ext	N			leak.		14°		year	18°		Apr	
		XXXX										3	ext	E					10°		autum	12°		winter	
		unheated										Tint								3	Mar,Dec		#	May	
												Tout								2	Dec		#	May	
												Rhin							30		May	94		Mar	
												Rhout							35		Oct	94		Feb	
	Goodhew et al. (2004)																								
1	Dartm	un-	1999			N,E>	0.3m	lime	lime		suspende	B	in	W	400				17''		winter	19''		summer	
		heated				>70		base	base		timber	D	ext	W	400				17''		Jan-Ap	19''		Jul-Feb	Int ext similar readings. Lack of T and RH gradient
						trees		rend	render		floor	E	ext	S	400			degr	22''		Jan-Ap	25''		Jul-Feb	S-wall the most exposed to rain, sample of damp straw owen dried - MC 27%
											400mm>	F	int	S	400				15''		Jan-Ap	17''		Jul,Nov	Int S-wall dryer than int W-wall, moisture transfer ext - int very slow
											above gr.	G	mid	S	2900				11''		Aug,O	15''		Jan,Feb	
												H	int	E	400				14''		Jan,Fe	15''		Feb-	Int ext similar readings. Lack of T and RH gradient
												I	ext	E	400				12''		Jul-No	17''		Apr	
												Rhint							75		Jun-Au	100		Dec-Apr	
												Rhout							80		Aug,O	100		Dec,Jan,Feb-Apr	
	Straube Schummacher (2003)																								
	Califor	unhea	###	dry		100	large>	earth	earth		rain	RH out							13		Jun	100		year	great diurnal fluctuations
		except		arid			>1.6m??				christmas	T out								#	Feb		#	Jul	
		barrel									>south	rain												Nov	storm in November, rain at christmas
		room									wind														
		conditioning										1	ext	N	midwa	utility			38	#	Jun	72	5	Dec	
		15C,									a lot of sun		int						48	#	year	58	#	year	diurnal fluctuations - steady
		80%RH									all year	2	ext	N	low	rm			35	#	Jul	80	10	Mar	
													int						48	#	year	55	#	year	
												3	ext		middle				48	#	Oct	77	8	Jul,Mar	
													mid						50		Oct	68		Mar	
													int						46		Oct	64		Mar	
												4	ext		up				20		Oct	77		May	
												5	ext	W	low	bath			25		Sep	70		Jun	
													int						40		Jul	55		May	
												6	ext		mid				25		Oct	72		Mar	
													mid						45		Oct	62		May	comp. mid and int > spring summer lower int, autumn winter higher int than mid.
													int						43		Mar	55		May	
												7	ext		up				28		Oct	70		Mar,May	

heatin	year built	preci pita tion [mm]	T [C]	expo sure	overhar	ext cove	int cover	vent bath/ kitch	misc.	pos tion #	pos. spec	orien tatior	height above ground	interic	misc.	strat cond tion	min RH [%]	T [C]	date	max RH [%]	T [C]	date	com ment
										8	ext	SW	mid	rm	entrance		9		Oct	100		Nov	
											int						35		Apr	64		Jan	
										9	ext	int	mid	bath-rm			45		year	50		year	ext follows mid as for no RH gradient across two rms.
											imid						45		year	50		year	
										10	ext	int	mid	barell-rm			52		spr-sui	74		winter	
											mid						63		spr-sui	70		winter	
											int						75		winter	79		May	
										11	ext	S	low	barrel	dr. rain		15		Dec	100		Dec	
											mid						40		Nov,D	74		Feb	
											int						58		Dec	75		spring,summer,autumn	
										12	ext		mid		rain christm		25		Nov	100		Dec,Jan	
											mid						52		year	55		year	unnaturaly stabil
											int						70		winter	84		rest year	
										13	ext		up				39		Sep	85		Dec	constant, slow growth RH Sep-Dec
											mid						65		Oct	75		Mar	sinus curve
											int						70		Dec	85		Jul	sinus curve
										14	ext	E	low	barrel			30		Oct	86		Dec-Jan	
											mid						48		Nov	70		Feb	sinus curve
										15	ext		mid				33		Oct	83		Jan	sinus curve
											int						57		Nov	75		rest year	
										16	ext		up				30		Sep	98		Mar	sinus curve
											mid						54		Oct	72		Feb	sinus curve
											int						48		Nov	70		rest year	
										17	ext	E	mid	barrel			38		Oct	75		Jan	
											mid						52		Dec	62		rest year	
											int						48		Dec	65		rest year	

Appendix C

Illustrations

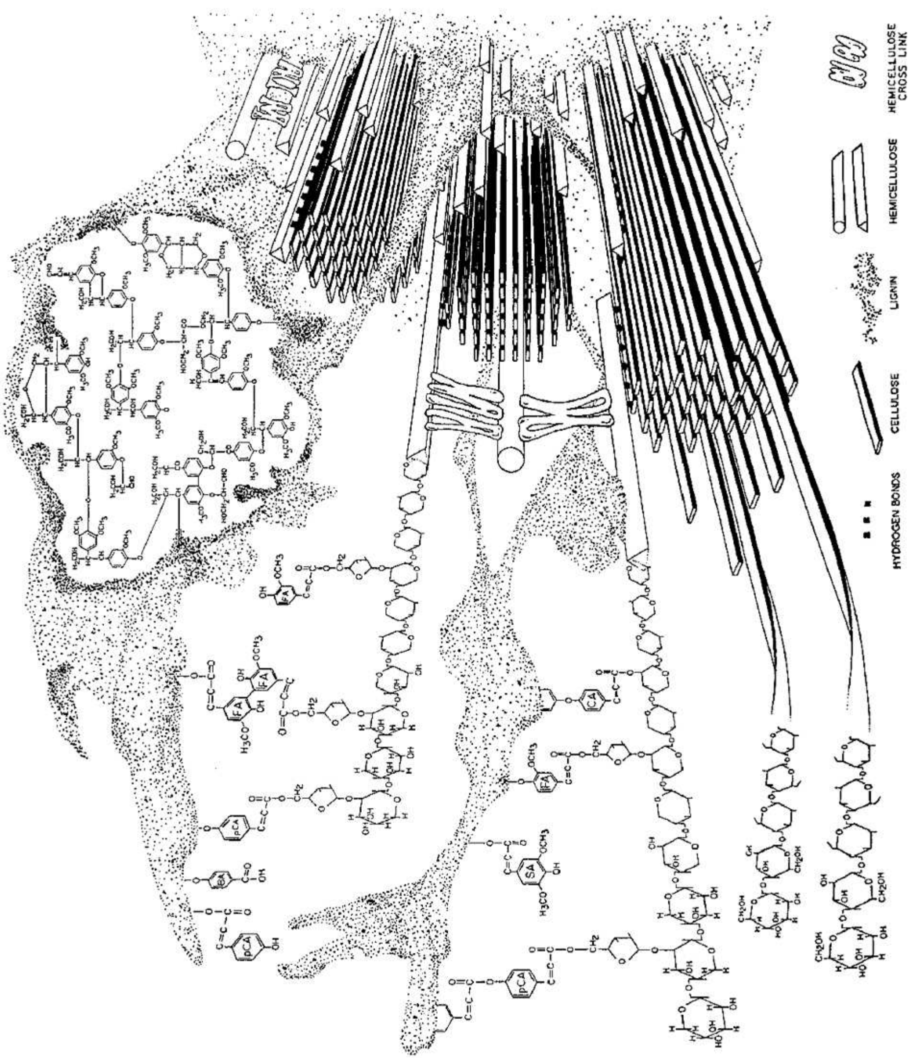


Figure C.1: *Secondary cell* wall structure. Components arearranged so that the cellulose microfibrils and hemicllulic chains are embedded in lignin. Specific linkages and components of non-core lignin are shown for a generalized grass *secondary cell wall*. Non-core lignin components include p-coumaric, ferulic, p-hydroxybenzoic, sinapic and cinnamic acids

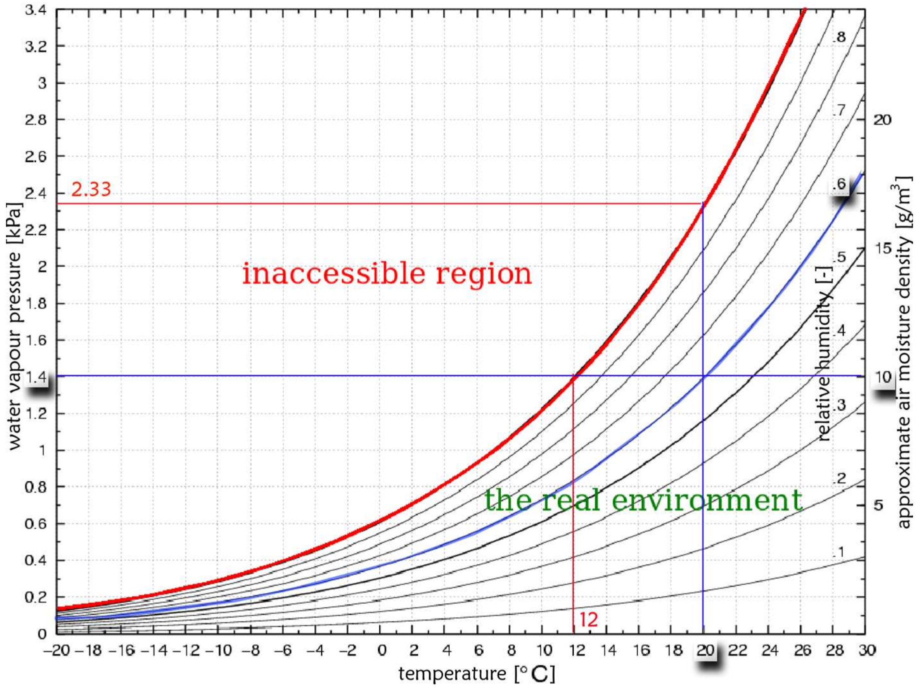


Figure C.2: Simplified psychrometric chart (Padfield, 2005). Example of how to use it: At 20°C and 10 g·m^{-3} water vapour concentration in the air, this water vapour exerts pressure of 1.4 kPa on the walls of an enclosure. Vapour pressure of 1.4 kPa at 20°C corresponds to 0.6 (or 60%) **relative humidity**. If the air in the enclosure cools down suddenly (the concentration of vapour pressure in the enclosure remains constant), there is a point at about 12°C, when the air can't sustain the vapour concentration any more and water starts to condense. 12°C is referred to as **saturation temperature** for vapour pressure of 1.4 kPa. Similarly, if temperature remains constant and water vapour concentration suddenly increases, the water will condense at vapour concentration with corresponding pressure of about 2.33 kPa, which is the **saturation water vapour pressure** for 20 degrees°C.

Appendix D

Calibration of moisture meters

The relative humidity above surface of a solution is less than above the surface of a pure water, which is always 100%. It's value depends on the nature of the solution. This physical phenomenon was explained in the section 3.8. The relative humidity above solution of table salt (sodium chloride) is at room temperature 75.7% (Padfield, 2005).

All dataloggers and thermo/hygrometers used in this thesis were calibrated by measuring the relative humidity above the surface of saturated table salt solution. The dry salt was spread in 3mm thick layer along the bottom of a plastic container. The water was mixed into the crystals of table salt until the mixture reached a muddy texture. The dataloggers and hygro/thermo meters were placed above the solution on perforated tray within the container and the container was hermetically sealed. After about 30 minutes the container was opened and the measured data were compared with known value of 75.7% relative humidity.

Appendix E

Additional monitoring; Plozevet

Monitor #2 (outdoors)

The data from 30 March 2006 till 18 May 2006 and from 1 June 2006 till 9 July 2006 are missing.

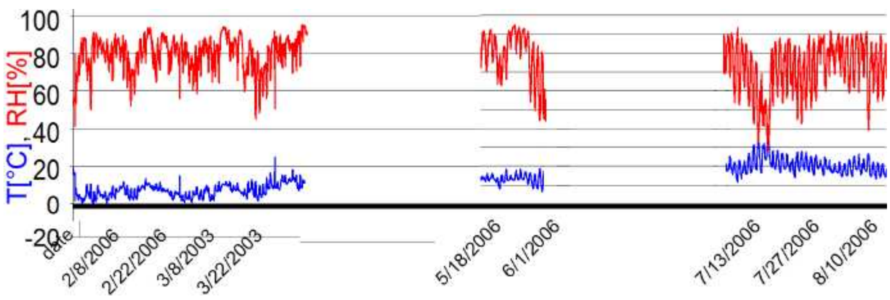


Figure E.1: Relative humidity and temperature data from datalogger #1.

Average relative humidity during first three months of datalogging was 79.7% (see fig. E.1). Average temperature was 7°C. Wet weather is typical in this area especially in late autumn, winter and early spring. Sustained humid climate certainly challenges the straw in walls of this house. However, in addition to high relative humidity, here in Plozevet, the exterior walls have to deal with severe storms.

Monitor #3 (indoors)

During the first 3 weeks of monitoring in January and February 2006 (see fig. E.2 on the left), relative humidity hovered around value of 50% with amplitude

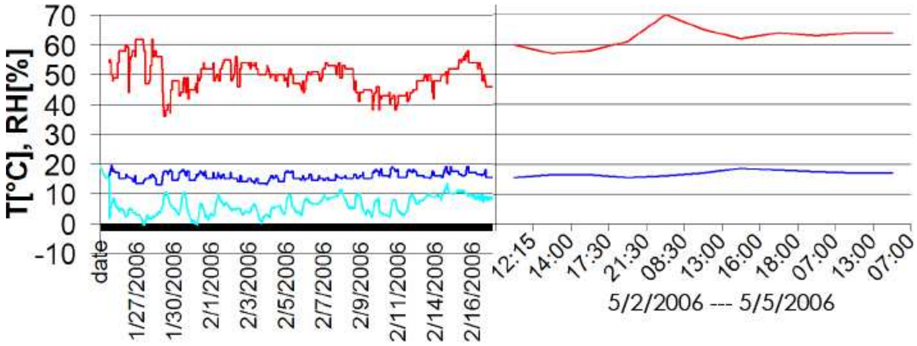


Figure E.2: Data from hygro/thermometer #3 show the conditions in the interior of the building. **Red** colour indicates interior relative humidity, **blue** colour — interior temperature. **On the left** are data collected during the first 3 weeks of datalogging. **On the right**, there are 4 days of monitoring done in May 2006. **Light blue** colour shows outdoors temperature measured by outside datalogger, monitor #1. The outdoors data from May are missing.

of about 10%. Temperature inside remained more or less stable. It's average value during monitoring was 15.7°C. During this time the house was still under the construction and the room had been serving as a workshop. It had been regularly heated in evenings by wood stove. The relatively stable temperature was despite short heating periods achieved by houses superinsulated walls and by large thermal mass in its floor and ceiling (Oehlmann, 2005). To relatively high temperature of 15.7°C (average temperature outside was 6.3 °C) also contributed extensive passive solar gain.

The final works in this room stopped in April. Second monitoring during 4 days in May shows conditions inside finished room (see fig. E.2 on the right). Clean and glossy environment in finalized living room contributed to increase of relative humidity. The average relative humidity is 62%, which is 12% higher than in February, when the interior relative humidity was presumably buffered by a large amount of saw dust and stored wood.

Appendix F

Adjustment of interior input data from monitor #4; Blanden

Before running the simulation by WUFI, the interior input data from monitor #4 had to be adjusted.

Fig. 4.23 (see Section 4.2.2) shows that the datalogger (monitor #4) was placed just under the ceiling in the interior of the bathroom. The internal monitors #1,2,3 were on the other hand buried in the wall approximately 1.3m above the floor level. This difference in hight of monitor positions made a difference in readings. For the most accurate simulation output, WUFI requires ambient relative humidity and temperature input data collected as close to the location of internal monitors as possible. Thanks to the stratification[1] of relative humidity and temperature, the monitor #4 under the ceiling (approximately 2.6m above the floor) measured unfortunately different values in comparison to the values that appeared 1.3m above the floor level and thus provided inadequate input.

The additional measuring was performed year later, in January 2007, by the house keeper. It provided the differential analysis of relative humidity and temperature data measured just under the ceiling (in the position of former monitor #4) with values measured next to the place where the internal monitors #1,2,3 had been buried. It was observed that monitor #4 under the ceiling read more or less constantly higher temperature of about 6 C° and lower relative humidity of about 9% in comparison with the location next to the place of former internal monitors #1,2,3—1.3m above the floor level.

[1] horizontal redistribution within an enclosed space

Appendix G

Calculations

G.0.4 Blanden - design conditions; Calculation of evaporation

Table G.1 summarizes the indoor and outdoor design conditions used in calculation of evaporation.

conditions	T [°C]	RH [%]	$\Longrightarrow$	vapour pressure[a] [Pa]
outside	18	65	$\Longrightarrow$	1340
inside	15	85	$\Longrightarrow$	1440

[a]From CIBSE (2001) Guide C

Table G.1: Outdoor and indoor design conditions to be used in the calculation of evaporation.

Following calculation of evaporation is identical to calculation of interstitial condensation build up, bearing in mind that contact area 3, between outside plaster and straw, is saturated with water.

contact area or connecting line	location of connecting line	temperature t_j [°C]	vapour pressure p_{vj} [Pa]	saturation vapour pressure[a] p_{svj} [Pa]	saturation
subconstruction a)					
1 outside	—	18	1340	2063	no
2	surface/plaster	17.94	1340	2058	no
3	(fixed point)	17.9	2053	2053	**yes**
subconstruction b)					
3	(fixed point)	17.9	2053	2053	**yes**
4	straw/plaster	15.06	1607	1696	no
5	plaster/surface	15.03	1440	1700	no
6 inside	—	15	1440	1704	no

[a]From Appendix C.2, or from CIBSE (2001) Guide C - vapour pressure adequate to corresponding temperature and 100% RH.

Table G.2: Results of calculation of evaporation based on design conditions. External, bathroom, wall in Blanden was divided into two subconstructions by saturated region in the area of winter condensation.

a)

1340 Pa — $\boxed{0}$ — $\boxed{3.186}$ — 2053 Pa

b)

2053 Pa — $\boxed{6.38}$ — $\boxed{2.39}$ — $\boxed{0}$ — 1440 Pa

The amount of evaporation in both subconstructions can be again determined from equation H.2:

$$q_{e_a} = \frac{2053 - 1340}{3.186 * 10^9} =$$
$$= 224 * 10^{-9}\ kg \cdot m^{-2} \cdot s^{-1}$$

$$q_{e_b} = \frac{1440 - 2053}{(6.38 + 2.39) * 10^9} =$$
$$= -69.9 * 10^{-9}\ kg \cdot m^{-2} \cdot s^{-1}$$

And analogous to condensation rate, the rate of evaporation q_e is the difference between q_{e_b} and q_{e_a}:

$$q_e = q_{e_b} - q_{e_a} =$$
$$= (-69.9 - 224) * 10^{-9} = -293.9 * 10^{-9}\ kg \cdot m^{-2} \cdot s^{-1} =$$
$$= -1\ \ g \cdot m^{-2} \cdot h^{-1}$$

G.0.5 Blanden - real data; Calculation of interstitial condensation occurance in straw bale wall

Input data, based on real conditions

Outside and inside real conditions

Table G.3 summarizes outdoor and indoor real conditions to be used in the model.

conditions to be used in model	T [°C]	RH [%]	$\Longrightarrow$	vapour pressure[a] [Pa]
outside	2	83	$\Longrightarrow$	589
inside	22	21	$\Longrightarrow$	565

[a]From CIBSE (2001) Guide C

Table G.3: Outdoor and indoor real conditions to be used in the calculation by Galser's model.

Prediction (see previous Section) estimated water vapour flow from interior towards outside, however, in reality the water vapour gradient of 589 - 565 = 24 Pa will drive the water vapour the opposite direction (from outside towards interior), because higher water vapour pressure occurs as a matter of fact in exterior.

Wall assembly

The section through the wall assembly and all it's material characteristics remain the same as in calculation of prediction (see previous Section, fig. 5.2)

Calculation

The calculation follows the routine described in detail by previous Section:

2°C — $\boxed{0.12}$ — $\boxed{0.072}$ — $\boxed{5.65}$ — $\boxed{0.054}$ — $\boxed{0.06}$ — 22°C

589 Pa — $\boxed{0}$ — $\boxed{3.186}$ — $\boxed{6.38}$ — $\boxed{2.39}$ — $\boxed{0}$ — 565 Pa

contact area or connecting line	location of connecting line	temperature t_j [°C]	vapour pressure p_{vj} [Pa]	saturation vapour pressure[a] p_{svj} [Pa]	condensation
outside	—	2	589	706	no
1	surface/plaster	2.40	589	726	no
2	plaster/straw	2.64	582	740	no
3	straw/plaster	21.62	570	2581	no
4	plaster/surface	21.80	565	2611	no
inside	—	22	565	2643	no

[a]From Appendix C.2, or from CIBSE (2001) Guide C - vapour pressure adequate to corresponding temperature and 100% RH.

Table G.4: External, bathroom, wall in Blanden. Results of calculation based on real conditions.

Appendix H

Principles of WUFI model; Advanced moisture transfer theory

WUFI means "Wärme-und Feuchtetransport instationär" (Transient Heat and Moisture Transport) and it was developed as a computer model in spring 2000 through a collaboration between Oak Ridge National Laboratory in USA and the Fraunhofer Institute of Building Physics in Germany (Newport Partners, 2004). The WUFI model's main advantage is, as one of the program's designers Künzel (p.4, 1995) says, that it works with "relatively simple moisture transport and storage functions largely derived from standard material parameters." It takes into consideration local climate influences such as driving rain, solar radiation and frost (see table 6.2 and Appendix H). The results of WUFI simulation can be displayed either in an animated form that shows changes over time, or in time charts, or in data files which are ready for further analysis.

Discussion about principles of WUFI mathematical model will help to uncover complicated theory behind moisture transfer in straw bale walls.

H.1 Moisture storage

The sorption isotherm is all WUFI needs to know in order to determine ability of hygroscopic material to store the moisture. Sorption isotherm represents connection between material's moisture content and the ambient conditions, namely relative humidity surrounding the material (see Section 3.7).

As material gets increasingly more wet, the sorption isotherm can be divided into three moisture regions, with specific moisture storage characteristics (Künzel, 1995, see fig. H.1).

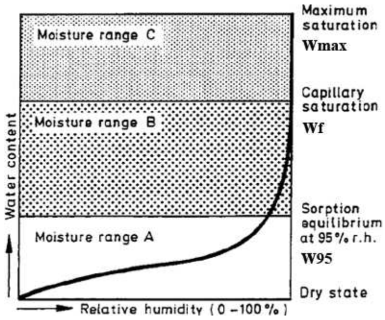


Figure H.1: Schematic sorption isotherm showing moisture storage function of hygroscopic material. From Künzel (1995).

H.1.1 Moisture region A

Moisture region A is called hygroscopic region. It corresponds to range 0—95% of relative humidity and includes the material's moisture content attained by water vapour sorption. It is characterized by hygroscopic equilibria between moisture content and ambient relative humidity. The sorption isotherm in this region is known for most hygroscopic building materials as it is easily determined in laboratory conditions. Straw has its sorption isotherm in the hygroscopic region well defined (see Section 3.7, fig. 3.5).

H.1.2 Moisture region B

In case the material gets into contact with liquid water it reaches the moisture region B, called capillary water region. Liquid water fills up all the pores until equilibrium is reached at point of free water saturation w_f, corresponding to 100% of relative humidity. The sorption isotherm in this region must be determined by special pressure plate apparatus in a laboratory and thus it might be a problem to find the suitable data for uncommon building materials like straw, for example.

However, straw has similar moisture storage capacity to wood (Bigland-Pritchard, 2005). It was proved, that wood and wood processed materials, due to its large moisture absorption potential in the hygroscopic region (region A), can have its sorption isotherm easily extrapolated in the region B up to free saturation point w_f without loss of accuracy (Schmidt, 2001).

H.1.3 Moisture region C

This is so called supersaturated region.

> "In this region there is no unique functional relation between relative humidity and moisture content. The relative humidity is always 1 (100% - ed. author), and the moisture content varies between

wf and wmax. The moisture content thus doesn't depend on the relative humidity, it is determined by the boundary conditions: it increases under condensation conditions and decreases under evaporation conditions." (Schmidt, 2001)

The supersaturated region can occur in porous building material, due to air pockets in it's pore system. After point of free water saturation w_f had been reached within a material, the air pockets in its pores could be further filled with water.

Because supersaturated region is characterized by constant relative humidity of 100%, it's gradient across the building component is 0 and thus capillary transfer to move the moisture around becomes also non existent. Künzel (1995) proved by laboratory test, that the moisture transfer is in this region indeed negligible.

However, the moisture transfer that could be pronounced in supersaturated region is seepage flow effected by gravitation (Künzel, 1995) and that doesn't effect one dimensional calculation (see Section H.2.2).

H.2 Moisture transfer mechanisms

Moisture can be transferred through porous material either as vapour or as liquid water, assuming that the solid moisture, the ice, is not movable (Pheukuri, 2003). Heat and moisture transfer is driven by a range of different potentials (see table H.1 and fig. H.2).

Phase	Transfer form	Driving potential	Considered by
Vapour	water vapour diffusion	vapour pressure	Glaser, WUFI
	thermal diffusion	temperature	-
	effusion	vapour pressure and temperature	-
	convection	total pressure gradient	-
Liquid	capillary conduction	capillary tension (rel. humidity)	WUFI
	Soret effect	temperature	-
	surface diffusion	rel. humidity	WUFI
	seepage flow	gravitation	-
	hydraulic flow	total pressure gradient	-
	electrokinesis	electrical fields	-
	osmosis	ion concentration	-

Table H.1: Forms of moisture transfer in porous media. From Pheukuri (p.20, 2003) and Künzel (p.5, 1995).

Moisture or heat moves through the wall assembly from the higher to the lower potential. Rate of change of the potential represents gradient. For example, the red and blue curves on fig. H.2 show temperature, water vapour pressure and relative humidity gradients as they were measured during winter in actual straw bale wall in Blanden (see Section 4.2.2).

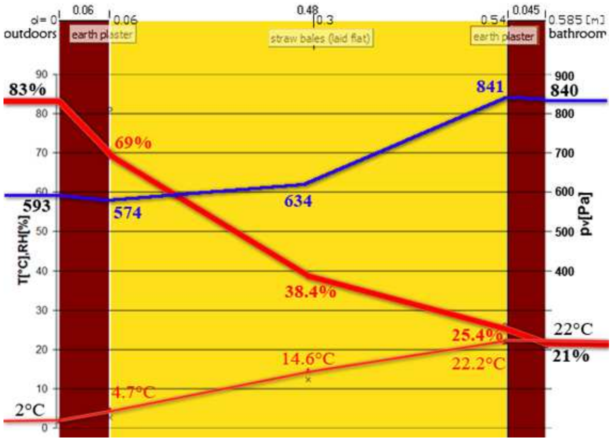


Figure H.2: Relative humidity (**thick red** curve), temperature (**thin red** curve) and vapour pressure (**blue** curve) gradients across the straw bale wall in Blanden as it was monitored by dataloggers. The vapour pressure was determined from relative humidity and temperature measurements by psychrometric chart from CIBSE (2001) Guide C. The values are average over 2 months period in winter 2006.

In winter, the temperature and water vapour pressure in Blanden wall has always higher value on the inside of the building. Relative humidity, on the other hand, is higher on the outside rather than on the inside, which results in moisture transfer running in opposite direction (Pheukuri, 2003).

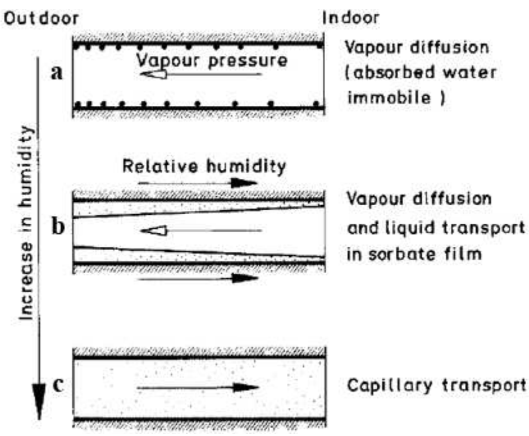


Figure H.3: Schema demonstrating moisture transfer in pore (cylindrical capillary) of the building material with the gradients of water vapour pressure and relative humidity running in opposite directions.

What happens in a porous material when relative humidity gradient runs in opposite direction to gradient of water vapour pressure is demonstrated by schema of cylindrical capillary on fig. H.3. When dry, the building material has it's pores empty and the vapour diffusion predominates the moisture transfer (see fig. H.3, **a**).

When the level of humidity rises, the water vapour absorbs to the pores of building material. As soon as it starts to cover the pore surface in film more than one molecule thick, water molecules become mobile. The film is thicker on the outside than on the inside, because there is in this case higher relative humidity on the outside of the building component (see fig. H.3, **b**).

The thicker the film, the more mobile liquid water in pores become and more easily it moves from the thicker film sections to the thinner ones. This transfer is called surface diffusion. Increasing surface diffusion reduces vapour diffusion so that at certain point surface diffusion starts to set in and the total moisture transfer through building component is reversed.

In wet conditions, when the pore is filled with water (see fig. H.3, **c**), the moisture transfer is governed by another process, called capillary conduction (Künzel, 1995).

The fig. H.3 shows an example, when the single gradients across the building component don't change direction. In reality, all gradients are "naturally transient and the direction of local heat and moisture transport can alternate globally and/or locally. At the same time, the material is locally exposed to alternating processes of ab- and desorption." (Pheukuri, p. 13, 2003).

Pheukuri (2003) further points out, that water vapour and liquid water transfer can be combined in pores of building material. Künzel (1995) argues that in the sorption moisture region of most building materials liquid and vapour transfer don't influence each other "since vapour diffusion takes place mainly in the larger pores, while liquid transfer - independent of vapour diffusion - takes place via the micropores and on the pore walls" (Künzel, p. 14, 1995).

H.2.1 Water vapour transfer

Water vapour diffusion

In theory, according to table H.1, the water vapour diffusion through building material, assuming negligible total pressure gradients[1], consists of:

- water vapour diffusion driven by temperature gradient
- water vapour diffusion driven by by gradient of water vapour pressure in the air

Water vapour diffusion driven by temperature gradient

[1]Buildings in general are exposed to negligible total vapour pressure gradients

Due to negligible effect that temperature gradient has on the total vapour transfer in building component (∼0.005% of total moisture transfer (Pheukuri, 2003)), WUFI omits thermal diffusion in it's calculation.

Water vapour diffusion driven by gradient of water vapour pressure

In case the vapour transfer through building component happens exclusively through air, water vapour diffusion driven by gradient of water vapour concentration in the air g_v can be described by Fick's law:

$$g_v = -\delta \Delta p \tag{H.1}$$

, where δ [kg·m^{-1}·s^{-1}·Pa^{-1}] is water vapour diffusion coefficient in air and p [Pa] represents water vapour pressure gradient.

In reality the vapour diffusion through building component happens exclusively through air only in large pores (radius $> 10^{-6}$m). Within much smaller pores (radius $< 10^{-9}$m), the water vapour molecules start to collide with pore walls and the transfer is predominated by so called effusion (see table H.1). In pore sizes between those two limits there is a mixed vapour transfer.

> "Nevertheless as far as the building physics is concerned, the effects of the microstructure and the interaction of effusion and Fick's diffusion on the water vapour transport through porous media can be allowed for by simply introducing a water vapour diffusion resistance factor (or water vapour diffusion coefficient, see 5.6 - ed. author), which is characteristic for each building material." (Künzel, 1995)

$$q_v = \frac{\delta \Delta p}{\mu} \tag{H.2}$$

[2]

, where μ is water vapour diffusion coefficient (see Section 5.2.1).

Equation H.2 could be easily obtained by combining two equations 5.1 and 5.6 from Section 5.2.1 in previous Chapter, which indicates that WUFI takes similar approach to water vapour transfer as Glaser's model. The only difference is that unlike in Glaser's model, the equation H.2 and thus WUFI's calculation is independent of temperature, as discussed in Section 5.2.1 (see equation 5.6).

[2]The equation H.2 is further modified to fit WUFI's moisture balance equation (see following Section 6.4.2).

Although water vapour diffusion coefficient μ is temperature independent, it is dependent on the relative humidity (or moisture content). This fact WUFI model ignores:

> "Since this is furthermore phenomenon that occurs only at higher water contents when capillary conduction dominates over vapour diffusion, it seems reasonable to remain with the concept that the vapour diffusion resistance (or water vapour diffusion coefficient - ed. author) does not depend on moisture" (Künzel, 1995)

Air convection in straw bale walls

Another aspect of water vapour transfer is air convection and it is discussed in detail in sections 4.1.7 and AirInfiltration1.

WUFI's major limitation relies in ignoring air convection within a wall assembly and its associated energy and moisture flow (Straube and Burnett, 2001).

H.2.2 Liquid water transfer

Surface diffusion

Liquid transfer begins with critical moisture content usually at relative humidity levels above ca. 30% for paper and 60% for sandstone, when the adsorbed film on materials pores becomes mobile (see fig. H.3b). This kind of liquid transfer is called surface diffusion and it's driving force is gradient of relative humidity (Künzel, 1995).

Capillary conduction

Whenever the pores of hygroscopic material start to be saturated with liquid water in capillary water region, the transfer becomes capillary conduction (see fig. H.3c) driven by surface tension of the water in the meniscus at the interface between water and pore air. This potential is called capillary tension (Künzel, 1995).

> "There exists a functional relation between the capillary tension and the equilibrium humidity in the pore air above the meniscus, i.e. the driving force in the liquid phase corresponds to a certain relative humidity in the gas phase. Thus instead of capillary tension, relative humidity can be used as driving potential for capillary conduction." (Schmidt, 2001)

Each material has its surface diffusion and capillary conduction included in sorption isotherm (see sections 3.7 and H.1), which is the material characteristic required for WUFIs calculation.

Liquid transfer caused by temperature gradient

Besides two main liquid transfer mechanisms mentioned above there is also liquid transfer due to temperature gradient. According to Pheukuri (2003) it has two aspects:

- The transfer based on fact that the viscosity of a liquid decreases for increasing temperatures. The result is increasing liquid transport for increasing temperatures.
- The transfer caused by soret effect

However, those two effects are minimal compared to the effects caused by relative humidity gradient and WUFI doesn't consider them in its calculation (Pheukuri, 2003; Künzel, 1995).

Liquid transfer caused by gravitation

WUFI, as one dimensional model, deals with moisture transfer only in one point, horizontally through section of building component (see Section 6.2). It means that the calculation doesn't consider vertical moisture flow caused by gravitation, even though it seems to play an important role in straw bale wall moisture performance (see Section 4.1.3).

When simulating the moisture transfer in mid-height of the straw bale wall for example, it has to be taken into account that in the highest (or the lowest) portions of the wall, moisture content will considerably vary from the simulated results.

"Other" liquid transfer

Since building science still doesn't completely understand the following influences on moisture transfer through building materials and since they represent the values affecting only very special cases in the building practice, WUFI furthermore omits (Künzel, 1995):

- hydraulic moisture flow driven by total pressure gradient
- moisture flow due to electrokinesis driven by electrical fields
- moisture flow caused by osmosis driven by ion concentration

H.3 Moisture transfer mechanisms, WUFI's solution

The reasons why WUFI model considers only few out of numerous moisture transfer mechanisms were discussed in previous Section. Except water vapour transfer caused by air flow, WUFI takes into account all the essential moisture movers: water vapour diffusion and liquid transfer caused by surface diffusion and capillary conduction (see table H.1).

Because vapour transfer can go against the transfer of liquid (see fig. H.3), it is necessary to assign to vapour and liquid transfer different driving potentials. The vapour diffusion is driven by vapour pressure, which could be easily derived from values of temperature and relative humidity. The liquid transfer, on the other hand, is considered to be temperature independent and thus it's driving potential becomes just relative humidity.

This way all main moisture transfer is driven by only two potentials: relative humidity and temperature. In contrast to moisture content, for example, which is discontinuous between two different materials, relative humidity and temperature have a great advantage of being continuous across the whole building component. Furthermore the models input in form of material properties and boundary conditions can be easily defined in terms of these quantities (see Section I).

H.4 Moisture transfer in straw

Moisture transfer through fibrous organic materials like hemp, reed or straw isn't generally different from the moisture transfer in porous mineral materials (WUFI, 2005).

Although straw bales have preferred transport direction due to specific fibre folding technique during baling, WUFI doesn't consider the changes in directions due to its one dimensional character.

WUFIs manual (2005) mentions that determining liquid transfer coefficient for organic fibrous materials might be difficult, or even impossible, because they could change consistency in high moisture content levels (during caking, for example). Nevertheless, liquid transfer coefficients could be ignored in normal conditions until capillary conduction becomes a major form of transfer. This simplification is adequate in the sorption moisture region which is anyway the main field of interest for the fibrous organic materials since they have to be prevented from getting saturated.

H.5 Moisture transfer below frost level

H.5.1 Vapour diffusion

According to Künzel (1995) the vapour diffusion resistance becomes apparently obscured by frost formation only if the pores are filled with ice to 60% of their volume.

> "For that reason, the influence of ice formation on vapour diffusion can be disregarded in most cases." (Künzel, p.22, 1995)

H.5.2 Liquid transfer

Liquid transport below frost level is a different matter. Smaller the diameter of capillary, the lower the temperature of freezing point, so that at below 0°C the liquid transfer still happens in hygroscopic material.

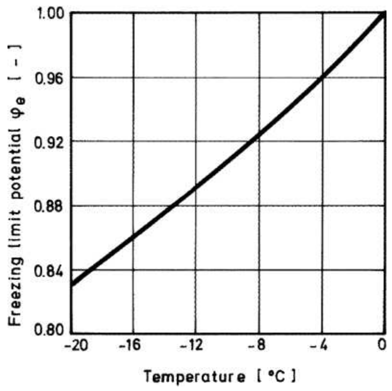


Figure H.4: Relationship between temperature and freezing limit potential, which corresponds to the relative humidity above the pore water in the largest still unfrozen pores. From Künzel (p. 23, 1995)

WUFI considers freezing limit potential, that is relative humidity above menisci of the pore water just at the point of freezing. In case the material is saturated (relative humidity of 100%), the temperature of freezing point is 0°C. Freezing point moves to lower temperatures with decrease of moisture content (relative humidity) within a material. Dependence of freezing limit potential on temperature is shown on fig. H.4.

WUFIs calculation based on freezing limit potential and moisture storage function derives the maximum content of still movable liquid water at corresponding temperature.

H.6 Heat storage and heat transfer in moist building material

H.6.1 Moisture dependent thermal conductivity

Building physics is capable of describing thermal behaviour of building component without any problem when it is dry (see Section 5.2.1). Nevertheless WUFI concentrates on moist conditions within a material and those are going to affect it's thermal properties. Everybody knows that woolen sweater, for example, doesn't keep warm when it is wet and the same could be said about other hygroscopic materials.

Thermal conductivity λ depends on water content and WUFI needs to deal with it. In many mineral materials, such stone or brick for example, thermal conductivity increases linearly with moisture content and their moisture dependent thermal conductivity can be easily calculated (Künzel, 1995). However, insulation materials like mineral wool for example have unique and irregular relation of thermal behaviour on moisture content and thus the moisture dependent thermal conductivity of many insulation materials needs to be determined in the guarded hot plate apparatus (Schmidt, 2001).

Sufficient results for moisture dependent thermal conductivity of straw from guarded hot plate test are not known to author. Although, many tests determining thermal conductivity of straw bales had been done so far, the conclusions regarding dependence of thermal conductivity of straw to its moisture content can't be drawn, because many variables affecting the thermal efficiency of straw (type of straw, fibre orientation, density, moisture content) make independent tests on straw bales with different properties incomparable.

H.6.2 Heat content

Heat content of moist material H is a sum of heat content of a dry material plus heat content of all the water in that material.

$$H = H_s + H_w \tag{H.3}$$

To calculate heat content of a dry material is simple. In temperature range typical for building physics the heat content of dry material is linearly dependent on temperature:

$$H_s = \rho_s \cdot c_s \cdot T \tag{H.4}$$

, where H_s [J·m^{-3}] is heat content of dry building material, ρ_s [kg·m^{-3}] is its density, c_s [J·kg^{-1}·K^{-1}] is its specific heat capacity and T [°C] is temperature (Künzel, 1995).

To determine heat content of all moisture in a material is on the other hand difficult, because the water exists within a building material in a various physical states, which are constantly changing, especially in micropores (Tuller et al. 1999).

> "The exact determination of the enthalpy (heat content - ed. author) of a phase mixture is possible only when the pore radius distribution or the moisture storage function of the building material is known." (Künzel, p. 26, 1995)

$$H_w = \left[(w - w_e) \cdot c_w + w_e \cdot c_e - h_e \cdot \frac{dw_e}{dT} \right] \cdot T \tag{H.5}$$

, where H_w [J·m^{-3}] is heat content of moisture in dry building material, c_w [J·kg^{-1}·K^{-1}] is specific heat capacity of liquid water, c_e [J·kg^{-1}·K^{-1}] is specific heat capacity of ice, h_e [J·kg^{-1}·K^{-1}] is specific melting heat, w is total water content, w_e is content of frozen water and T [°C] is temperature (Künzel, 1995).

The content of frozen water in moist building material w_e is possible to calculate from material moisture storage function and relationship between temperature and freezing limit potential (see fig. H.4)

H.6.3 Transfer of heat with a phase change

In order to explain WUFI's approach to calculation of heat content in real ambient conditions, Künzel (1995) shows an example of heat balance in a wall exposed to driving rain under following specific conditions:

- outside air temperature = 2°C
- solar radiation on the wall = 40 W·m^{-2}
- total driving rain 200 kg·m^{-2}
- room temperature 20°C
- thermal resistance of the materials within the wall assembly = 2 m^2·K·W^{-1}
- short wave radiation absorption value of materials surface = 0.7

According to equation 5.1, the rate of heat transfer from the inside to the outside is 9 W·m^{-2}. The heat transfer by radiation is $40 \cdot 0.7 = 28$ W·m^{-2} (see fig. H.5).

With the given amount of driving rain, which is presumably completely absorbed by the material, the liquid heat transfer through the rain screen is less than 0.2 W·m^{-2} (Künzel, 1995).

When the rain stops, drying of the liquid water absorbed by the rain screen results in heat loss 32 W·m^{-2}.

> "This example shows that in practice the enthalpy (heat content - ed. author) flows as the result of liquid transport play a negligible role in comparison with other thermal flows, while vapour diffusion connected with phase changes, such as drying processes can be of great importance in terms of heat balance." (Künzel, 1995)

While heat content flows related to liquid transfer can be ommited by WUFI, model needs to calculate on the vapour diffusion connected with phase change:

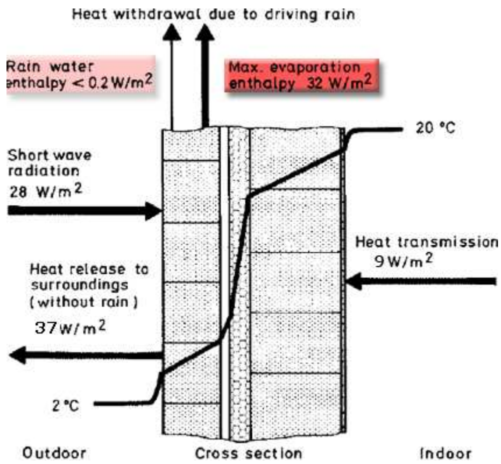


Figure H.5: Steady state heat balance in two layered exterior wall exposed to driving rain. From Künzel (p. 23, 1995)

$$S_h = h_v \cdot \Delta g_v \tag{H.6}$$

, where S_h [$J \cdot m^{-3} \cdot s^{-1}$] is heat source/heat sink due to condensation/evaporation, h_v [$J \cdot kg^{-1}$] is latent heat of phase change and Δg_v [$kg \cdot m^{-2} \cdot s^{-1}$] is water vapour diffusion gradient.

Latent heat of phase change is a sum of specific evaporation heat content of pure water (h_v = 2500 $kJ \cdot kg^{-1}$ and sorption heat content of material which, in contrast to evaporation heat content of pure water, can be disregarded (Künzel, 1995).

H.7 Surface transfer coefficients in advanced theory

H.7.1 Exterior and interior heat and vapor transfer coefficients

surface	**heat transfer** α [$W \cdot m^{-2} \cdot K^{-1}$]	**water vapour transfer** β [$kg \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$]
exterior	17	$75 \cdot 10^{-9}$
interior	8	$25 \cdot 10^{-9}$

Table H.2: Surface transfer coefficients considered by WUFI. From Schmidt (2001).

Surface transfer coefficients were already introduced in previous Chapter (see Section 5.2.1). In principal, those coefficients are representing a boundary air layer right at the surface acting as an intermediary between exposed material and the exterior or interior climate. In advanced theory of moisture and heat transfer those coefficients are dependent on wind and moisture content at the surface level. However, because the transfer resistances at boundaries are in any case very small compared to the resistances of the individual material layers (Schmidt, 2001), WUFI counts in all cases on average values (see table H.2).

H.7.2 Energy absorption factor and rain water absorption factor

Because WUFI considers effect of driving rain and solar radiation, there are other two surface transfer coefficients that needs to be kept in mind. These are an energy absorption factor and rain water absorption factor.

Energy absorption factor depends on colour of the surface and represents the fact that only a part of solar radiation is transmitted as a heat into material. Bright coloured surface has energy absorption factor of about 0.4 and dark surface about 0.6—0.8 (Schmidt, 2001).

Rain water absorption factor allows for the water, that splashes off the materials surface and runs off due to gravity. It depends on angle under which the driving rain hits the surface and on precipitation absorptivity of a material (Künzel, 1995). According to Schmidt (2001), the appropriate value of rain water absorption factor for vertical material surface is 0.7.

Appendix I

Input data for WUFI simulation in Chapter 6

Further reading in this Section was partially adapted from WUFI (2005) - pro 4.01 Online Help file. Paragraphs dealing particularly with the case in Blanden are *emphasized*.

I.1 Time step

Time step is a time interval of input climate conditions. The output data are calculated in accordance with the input climate conditions, so that they have the same time step as input data. According to WUFI (2005) there is no limit to the choice of time step. The choice of time step however influences calculations accuracy.

> "...time steps between ca. 10 minutes and ca. 24 hours may be adequate, depending on the problem at hand. With smaller time steps, computing time increases markedly, with larger time steps, the results may become inaccurate." (WUFI, 2005)

In Blanden, the climate boundary conditions were monitored every 30 minutes, for that reason the time step was adjusted to 0.5h.

I.2 Climate data

For each time step WUFI needs following climate data:

- *Rain load* [$l \cdot m^{-2} \cdot h^{-1}$] vertically on the exterior surface.
- *Solar radiation* [$W \cdot m^{-2}$] vertically on the exterior surface.
- *Temperature of the exterior* and *interior air* [°C]

- *Relative humidity of the exterior* and *interior air* [0...1] fraction.
- *Barometric pressure* [hPa] specification of a mean value over the calculation period.
- *Long wave atmospheric counterradiation* [$W \cdot m^{-2}$] in case there is a significant radiative cooling influencing the construction during the night.

I.2.1 Exterior climate data

The exterior climate data need to be assigned to model as a climate file either as a file from WUFI's database (WUFI offers weather data from number of locations in the USA and in Europe), or from any other file containing data in proper order and magnitude. The data must be in .KLI format. They can be completely artificial, describing laboratory conditions for example, or they can be conventional weather data from meteorological station. WUFI is able to automatically convert data from conventional weather data formats such are: .WET, .TRY, .DAT, .IWC and .AGD.

In case of monitoring in Blanden, the data were downloaded from monitors in .txt format, adjusted into acceptable form in spread sheet of Microsoft Excel and then exported as data file to .txt format again. By simply overwriting .txt for .KLI the data were converted into WUFI format.

The rain load and radiation obtained from conventional weather data are usually measured on horizontal surface. That is why WUFI needs to adjust those loads according to orientation and inclination of the building component, which happens automatically.

Driving rain load is calculated from rain load on horizontal plane, wind velocity and direction.

The wall in Blanden was chosen to minimize requirements for extensive weather data, which would be difficult to collect. Measured wall is north facing. This fact completely eliminates the effect of solar radiation. Furthermore, due to almost non existent south blowing wind in the Blanden area, northern wall under investigation almost never receives driving rain and that eliminates the need for rain load data.

For the reasons mentioned in previous paragraph the exterior climate data file in case of Blanden wall consists of temperature and relative humidity values measured every 30 minutes during period of monitoring. Barometric pressure was estimated as an average value during the period of monitoring.

I.2.2 Interior climate data

Interior climate as an input for WUFI simulation can be specified the same way as exterior climate (from measured data) or estimated by WUFI's simplified option (WUFI, 2005).

Simplified option is for the purpose of benchmarking the model irrelevant, because the interior relative humidity and temperature in Blanden were collected during period of monitoring every 30 minutes. Similarly to exterior data, interior data were downloaded from monitors in .txt file and converted into acceptable format.

However, due to the unfortunate position of monitor #4 measuring the interior conditions in Blanden, the interior input data had to be adjusted (see Appendix F).

I.3 Surface transfer coefficients

Those coefficients indicate into which extent the climate conditions affect heat and moisture transfer through the surface of a building component.

I.3.1 Vapour diffusion thickness [m]

So called s_d value represents the air layer thickness with the same resistance to water vapour diffusion as has the coating on a surface of a material. It can be used in case the material has a paint, wallpaper, vapour barrier, or any other impregnation that influences pore space on the surface.

Earth plaster in Blanden wasn't painted or impregnated by any means, thus $s_d=0$.

I.3.2 Short wave radiation absorptivity [-]

It characterizes surface property dependent on brightness and reflectivity of materials surface. It represents a fraction of total incident solar radiation that is absorbed by the component as a heat.

There isn't any incident solar radiation on north facing wall in Blanden. Short wave radiation absorptivity is in this case irrelevant.

I.3.3 Long wave radiation emissivity [-]

It considers night time emission of radiative cooling from the materials surface. Due to radiative cooling temperature of the surface drops considerably during a clear night.

According to WUFI (2005), long wave radiation emissivity can be neglected, because it has a very minor effect on the calculations results.

I.3.4 Rain water absorption factor [-]

It takes into account the fraction of the water that splashes off the surface.

As was discussed earlier, the north wall in Blanden doesn't receive any rain load, so the rain water absorption factor becomes irrelevant.

I.4 Wall assembly

In this dialog researcher specifies all the components of a wall assembly under investigation. Specification is concerned with the thickness of a component as well as with other parameters (see table 6.3) which are assigned to particular materials from preset database.

Fig. 6.1 presents the wall assembly in Blanden as it was set in programs dialog.

I.4.1 Monitor positions

WUFI will provide relative humidity and temperature data as a calculation output only in specific places—monitor positions.

Monitor positions were chosen to coincide with the positions of dataloggers (real monitors) in actual wall in Blanden (see fig. 4.22), so that real and calculated data could be compared (see fig. 6.1).

I.4.2 Grid

WUFI offers a choice of coarse, medium or fine grid structure, that is set automatically over each material of the component. In special cases, grid can be adjusted manually.

In case of Blanden wall component, "medium" grid was set to allow for satisfying accuracy (see fig. 6.1).

I.4.3 Orientation, inclination, height of the component

Those inputs need to be specified for calculation of solar radiation and driving rain. The wall in Blanden doesn't consider solar radiation nor diving rain, so it is irrelevant to consider those items.

Appendix J

WUFIs equations

WUFI calculates the dynamic heat and moisture transfer in building components by following coupled differential equations:

$$\frac{\delta H}{\delta T} \cdot \frac{\delta T}{\delta t} = \frac{\delta}{\delta x} \cdot \left[\lambda \cdot \frac{\delta T}{\delta x}\right] + h_v \cdot \frac{\delta T}{\delta x} \cdot \left[\frac{\delta}{\mu} \cdot \frac{\delta p}{\delta x}\right] \tag{J.1}$$

$$\rho_w \frac{\delta u}{\delta \phi} \cdot \frac{\delta \phi}{\delta t} = \frac{\delta}{\delta x} \cdot \left[\rho_w \cdot D_w \cdot \frac{\delta u}{\delta \phi} \cdot \frac{\delta \phi}{\delta x}\right] + \frac{\delta}{\delta x} \cdot \left[\frac{\delta}{\mu} \cdot \frac{\delta p}{\delta x}\right] \tag{J.2}$$

, where equation J.1 represents **heat transfer** and equation J.2 **moisture transfer**

and where D_w [$m^2 \cdot s^{-1}$] is liquid transfer coefficient, H [$J \cdot m^{-3}$] is heat content of moist material, h_v [$J \cdot kg^{-1}$] is evaporation heat content of water, p [Pa] is partial water vapour pressure, u [$m^3 \cdot m^{-3}$] is materials water content, δ [kg·m·s·Pa] is water vapour diffusion coefficient in air, T [°C] is temperature, λ [$W \cdot m^{-1} \cdot mK^{-1}$] is thermal conductivity of moist material, μ [-] is water vapour diffusion coefficient, ρ_w [$kg \cdot m^{-3}$] is density of water, ϕ [-] is relative humidity.

Both equation have on their left sides ***storage capacity***:

- In the equation J.1, **heat storage** consists of heat capacity of dry material and heat capacity of all the moisture present in material.
- In the equation J.2, **moisture storage** shows mathematical description of moisture storage function as discussed in Section H.1.

The right sides of both equations describes ***transfer functions***:

- In the equation J.1, **heat transfer** comprises moisture dependent thermal conductivity and heat transfer due to vapour flow of heat content. Vapour flow of heat content considers the latent heat absorption during evaporation in one place, diffusion of this water vapour into another place where it releases latent heat during condensation.

- In the equation J.2, **moisture transfer** consists of liquid transfer and vapour diffusion.

  - **Liquid transfer**, as was mentioned in Section H.2, happens through surface diffusion and capillary conduction, both driven by gradient of relative humidity.

  - **Water vapour diffusion** is on the other hand dependent on temperature (see Section H.2).

Appendix K

Letters

K.1 From: Martin Hammer, Saturday, April 08, 2006 1:33 AM

mfhammer@pacbell.net

Dear Jakub -

In any case, I send it to you now as an attachment. I also relate to you the following anecdote regarding a small, unheated, straw bale storage building I designed and built on a College campus in 1999:

A moisture problem occurred that relates in part to the stack bond. Moisture content was monitored on all walls during the rainy season. Generally, the straw moisture content was well under 16%, but the top half of the west wall had alarmingly high readings of 18-39%. It was determined that the joints between bale stacks acted as chimneys, allowing the west sun to heat air in the bales, with whatever moisture it had wicked from the plaster or entered through small cracks, and drive it up to the top of the wall where it was trapped by a layer of plastic which was unwittingly installed as a second line of defense under the metal flashing wall cap. Uncapping the wall, removing the plastic, and drilling ventilation holes in the plywood top plate has apparently solved the problem. (I could send you photos of this building if you like.)

Also, I had recent experience with a single bale (rice straw) that has been stored under my house sitting on 2 pieces of wood (approx. 4cm thick) on a concrete slab. The face of the bale that faces the slab developed fungus and moisture content within the first 2 cm of the surface of 20-35%. There may have been some contact of the bale with the slab in between the wood supports. I could give you more detailed information and a photo if it would be useful. This discovery disturbs me some. To my knowledge the bale was never in contact with liquid moisture. Of course there was no moisture barrier between the slab and the bale as there normally is with a straw bale wall. My discovery certainly suggests that such a moisture barrier is necessary.

Thats all for now. Please let me know if this has reached you in time to be useful, and if you require any more information from me. Thanks very much for doing this important work, and I look forward to seeing the results.

Sincerely,

Martin Hammer, Architect Berkeley, California, USA

K.2 From: Tim Padfield, Saturday, November 12, 2005 10:55 AM

tim@padfield.dk

Dear Kuba

Thank you for your letter.

I have not investigated straw bales but many other people have. I know that a Danish company, I think it was Ramboll (ramboll.dk), has put measuring instruments within straw bales in an experimental house. It was shown on Danish television, but not the scientific results - that rarely gets on TV.

I would expect the sorption isotherm to resemble that of wood, near enough for rough calculations. The water vapour diffusion coefficient must depend on the state of compression, for diffusion through the voids. But diffusion into the fibres will not change. The vapour has to penetrate the cell walls of the parallel fibres. I would expect a similar diffusion rate to wood. It doesn't matter that much. If diffusion through the straw skin is not fast, the vapour will diffuse deeper into the mass through the air voids, so the buffering effect is still large, just delayed.

Whatever the details, straw bale with earth or lime plaster, unpainted must have an enormous water vapour capacity. This will protect it against long periods of locally high RH which would cause rotting.

I would expect a similar performance to the wood shaving insulation that is very common in Swedish houses. That works ok for many years.

As for the compression ratio of the straw. The moisture buffering over the long term can only be better, because there is more stuff per cubic metre. Short term buffering over the daily cycle may not be affected much. Indeed, 3cm of lime plaster is a formidable hindrance to propagation of the daily cycle of indoor airborne moisture. My thesis shows the movement of water into lime plaster on a daily RH cycle.

Best wishes
tim

K.3 From: Dirk Scharmer, Wednesday, April 19, 2006 10:14 AM

ds@fasba.de

Dear Kuba,

I'm happy that you do this work. We're doing some moisture research too.

- Moisture/ temperature monitoring on 4 houses - one is being monitored since November, 2004.
- Dynamic moisture transport simulation with WUFI
- Mold analyzing of embedded straw

The goal is to find the best prevention against moisture failure of a straw bale construction and to get this in a buidling code.

In the next weeks we'll start a comprehensive research project with more simulations, monitoring and analyzing. Our work and your work would fit together perfectly to describe the complex mold problem of straw bales. Your way to come more from the practical side may be the more significant one for the building site. The way of simulating and mold analyzing for me seems to be a good way to fit the requirements of the german building authorities. Our first general approval for straw bales as an insulation material is mainly based on simulations. Unfortunately we were not able to prove the mold resistance of directly earth plastered straw bales, but we hope to do this with the upcoming research. We are working together with the Fraunhofer Institut fuer Bauphysik, www.hoki.ibp.fraunhofer.de.

Greetings,
Dirk

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Appendix L

Questionnaires