THE MOISTURE PERFORMANCE OF STRAW BALE CONSTRUCTION IN A TEMPERATE MARITIME CLIMATE

by

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ABSTRACT

This thesis is an investigation into the moisture performance of straw bales used in the construction of buildings.
The principle of taking bales of straw off the field and stacking them up on themselves to form the walls of a simple building is a practise that started over a hundred years ago.
The modern form of this building method is more sophisticated, and is spreading world wide from its origins in the arid regions of America.
Despite advances in modern methods of construction there has been concern and doubt over the suitability of straw bale for use as a building material in a temperate maritime climate. The main concern being that the higher levels of environmental moisture will have the potential to damage the straw over time. In order to assess the moisture performance of the straw bales in the walls of a building in this damp climate, a simple and effective means of measuring the moisture in-situ has been developed as part of this research.

The overarching methodology for this research is to develop a more accurate version of a probe that uses a block of wood to measure moisture. An environmental chamber in the laboratory has been used to establish the hygrothermal relationship between the timber to be used in the probe, and samples of the straw used in construction. This is the first time that a continuous set of sorption and desorption isotherms have been created for samples of straw and timber simultaneously, a process that took six months to complete.

This data was used in the design of a new wood block probe, and examples of the new probes were installed in the walls of a straw bale house with a known moisture history. The resulting readings from the new probe were compared to those from a professional agricultural straw moisture probe. These results could be checked against the readings of the relative humidity and temperature in the wall. Forty-eight pairs of the new wood block probe were calibrated in the laboratory.

Fourteen diverse examples of straw bale construction were selected as case study buildings. Having been surveyed for this research, a number were then selected to have the new probes installed, and evidence of their moisture performance was recorded.

Sufficient data was acquired through this process to confirm the suitability of straw bales for use in the construction of buildings, in a temperate maritime climate.

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UNITS USED IN THIS THESIS

mm	Millimetre
ppm	Parts per million
Kg/m^3	Kilograms per cubic metre (Density)
MJ/kg	Mega Joules per kilogram (Embodied energy)
$kgCO_2/kg$	Kilos of Carbon Dioxide per Kilo (Embodied Carbon)
W/mK	Watts per metre kelvin (Thermal conductivity (lambda))
W/m^2K	Watts per metre squared Kelvin (U Value)
db	Decibel (Intensity of sound)

Moisture expressed as 'dry' or 'wet' basis

Throughout this thesis there is reference to the moisture content of straw. When measuring the moisture content of straw the result is expressed as a percentage of the mass of the straw, but there are two ways to convey this; one is as a percentage of the dry mass of the straw, known as 'dry basis' (Db) and the second as a percentage of the wet mass or 'wet basis' (Wb).

If the moisture content as a percentage is published, it is essential to know whether it was done on a dry or wet basis, as there is a significant difference that increases with the moisture content. For instance, a moisture content of 10% Wb is equal to 11% Db, which is not a large difference, but 20% Wb is equivalent to 25% Db, which is more significant, and when the fibre saturation point of the straw is reached, this could be expressed as either 27% Wb or 37% Db (Summers, Blunk and Jenkins 2002). There is clearly additional potential for confusion when researching the literature for references to moisture in straw; the building industry typically uses dry basis moisture content but the food and agriculture industry more often uses wet basis. If the percentage moisture content is not specified, then a supposition can sometimes be made according to where the literature originated.

All the moisture content percentages quoted in this paper are on a dry basis (Db) unless otherwise stated.

ACRONYMS DEFINED IN THE THESIS

RH	Relative Humidity
MC	Moisture Content
Db	Dry basis (moisture content)
Wb	Wet basis (moisture content)
COSH	Code for Sustainable Homes
CMHC	Canada Mortgage and Housing Association
GSBN	Global Strawbale Building Network

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1. INTRODUCTION

The human population of the earth is rising. The United Nations World Population Report (2009b) states that “world population is projected to reach 7 billion in late 2011, up from the current 6.8 billion, and surpass 9 billion people by 2050”.

This population is currently dependant on the hitherto cheap and abundant energy provided by fossil fuels; coal, gas and most importantly, oil. There is a finite supply of this energy, and the indications are that global oil production has reached a peak. Extracting what remains will become increasingly difficult and expensive (Hayward 2010).

The increasing use of fossil fuels as a primary energy source has resulted in rising levels of carbon dioxide in the atmosphere from a pre-industrial value of about 280 ppm to 379 ppm in 2005 (Pachauri and Reisinger 2007). The levels of atmospheric carbon, along with other greenhouse gases, are contributing to a measurable rise in the temperature of the atmosphere. Anomalous variations in weather patterns known as ‘Climate Change’ can be attributed to the rise in atmospheric temperatures; there is therefore a clear link between human activity and these changes in global climate. If it is accepted that these changes are based on human behaviour, then by changing our behaviour it may be possible to ameliorate, if not reverse, the worst effects of climate change (Helweg-Larsen and Bull 2007).

The construction industry has an important role to play in the reduction of atmospheric carbon as is clear from the following United Kingdom statistics. The first is the fact that in 2009, 27.5% of final energy consumption in the United Kingdom (UK) came from domestic dwellings (MacLeay, Harris and

Michaels 2009) and that 10% of the total energy used in this country is embodied in construction materials (Harris and Borer 2005).

It is clear from these statistics that the materials and methods used to build houses in the UK and the rest of the world have a significant effect on the environment.

In the UK, the government has introduced a range of policies to reduce the emissions from buildings with the expressed aim of making all new domestic dwellings ‘zero carbon’ by 2016. The leading policy is the ‘Code for Sustainable Homes’, which proposes a system of incremental improvements to move from level one to six where six represents a ‘zero carbon’ dwelling (Department for Communities and Local Government 2006a). There are many problems with this scheme, but one of the main concerns is that the focus is on lowering the energy used during the lifetime of new buildings. Less emphasis is placed on the embodied energy of the materials used in the building envelope. Embodied energy is the amount of energy used to take a material from its raw state to the finished product (Hammond and Jones 2008).

The additional technologies (such as mechanical heat recovery) that are a requirement under the code can also significantly increase the embodied energy of a house built to the highest level of the code (Code level six).

The less energy a building uses during its lifetime, then the higher proportion of its carbon debt will be in the materials used. There is therefore an increasing awareness of an imperative for architects and designers of low energy houses to take into account the embodied energy and the origin of their construction materials (Atkinson 2008).

One group of materials of increasing prominence with low embodied energy is that of renewable materials or “Non-Food Crops”, such as straw, hemp-shiv, flax, reed, jute and sisal (Yates 2006).

1.1 Research question

This thesis explores the suitability of straw bales in the construction of buildings in a temperate maritime climate.

Straw is the collective noun for the dry stalks of cereal crops. A straw bale is block of compacted straw that can be stacked up to form the walls in the construction of a building.

Using straw can reduce the carbon footprint of a building because it has a low embodied energy, and the low thermal conductance of the straw can reduce the primary energy demand of the building over time.

A temperate maritime climate is a climate with relatively small diurnal and seasonal temperature variation and increased precipitation owing to moist air from the sea.

The significance of climate for straw bale construction is that the use of straw bales in construction originated in the arid regions of the United States, and there is a concern that increased levels of atmospheric moisture in a temperate maritime climate will degrade the straw over time. This research is not looking at the implications for straw bale building in hotter, more humid climates, although there may be conclusions drawn from this research that can be applied to other climates.

The primary questions explored in this thesis are therefore:

1. What are the effects of high levels of moisture on straw?
2. How can you best directly measure the in-situ moisture levels in a straw bale wall?

1.2 Straw bale building

The use of straw bales in construction started in the wheat producing states of America at the end of the nineteenth century after the mechanical baling machine was introduced in the 1890's (Steen, Steen and Bainbridge 1994). First used to make temporary structures as protection from the weather in places where timber was scarce, the idea of using straw bales to build more permanent houses became popular as more people appreciated the combination of low cost, quick construction and high insulation (Magwood and Mack 2000). The popularity of straw bales as a building material started to decline after the nineteen twenties, until the energy crisis of the 1970's produced a desire to create more energy efficient housing, which has become more focused with current environmental concerns.

The use of straw bales in construction can reduce the embodied carbon of a building, as well as reducing primary energy needs, and therefore operational carbon emissions. The low embodied carbon stems from the fact that the straw bales are a co-product of the growing of food crops and despite increases in the uses found for the 9.5 million tonnes produced annually in the UK, there is normally a surplus (Copeland and Turley 2008). The crop from which the straw is derived will have absorbed carbon dioxide through photosynthesis (Jones 2007). This makes straw bales not just carbon neutral, but carbon negative. The low U-value achieved by a straw bale wall (typically 0.17 W/m^2K from a thickness of 450-500 mm) (Munch-Andersen and Andersen 2004) contributes to a low primary heat energy needed by providing a high level of insulation.

A straw bale wall is conventionally finished on both sides with a 30 mm layer of render, and this tradition has the effect of producing a self supporting structure that combines high levels of insulation with a quantity of thermal mass that has the ability to ameliorate the peaks and troughs of the heat load.

This thesis will demonstrate that a conventionally built straw bale wall both reduces and smoothes the heat energy needed by the building, and combined with a design that maximises passive solar gains, the building can comfortably exceed the UK governments definition of ‘zero carbon’ with out any additional technologies.

However, notwithstanding the aforementioned advantages, there are some concerns of the long term effects of moisture on these materials, particularly in a temperate maritime climate, such as the UK. Lawrence (2009), states that

“Firstly, prolonged wetness could cause structural damage. Secondly, mould growth associated with cellulose based materials can cause serious health problems. Thirdly, high levels of moisture can reduce the insulative value of straw”.

This thesis looks not just at the effects of moisture on straw and the analysis of methods of measuring the moisture content of straw bale walls, but will additionally investigate appropriate methods of construction in order to attempt to reach a conclusion on the suitability of straw bale construction in a temperate maritime climate.

1.3 Research aim & objectives

1.3.1 Overarching aim

The overarching aim of this research project is to investigate the effects of high levels of moisture on straw. It will also look at how best to measure and design out elevated moisture levels when straw is used as a construction material in low energy buildings in a temperate maritime climate.

1.3.2 Specific objectives

The specific objectives of this research project are:

- To provide an overview of straw used as a construction material, particularly as used for domestic housing in temperate maritime climates.
- Investigate the problems caused by moisture in straw when used as a construction material.
- Establish a methodology to monitor moisture content in straw when used as a construction material.
- Explore the development of a wood block probe as a means of testing moisture content in straw when used as a construction material.
- Establish hygrothermal measurements for straw in the laboratory
- Analyse the results of monitoring the moisture content in a number of case study buildings, where straw is used as a construction material.
- Formulate a series of recommendations to help avoid the potential for high levels of moisture in the design of low energy housing using straw as a construction material.

1.4 Contribution to knowledge

The original contribution to knowledge that has been outlined in this thesis is as follows:

1. *The development of a new form of wood block probe for the in-situ monitoring of the moisture content of straw bale walls*
2. *The creation of a full set of sorption and desorption isotherms for wheat and oat straw, demonstrating hysteresis.*
3. *Comparison of wheat and oat isotherms with isotherms for three species of timber, created at the same time.*
4. *The practical calibration of a Protimeter 'Balemaster' straw moisture probe against a sample of baled straw used in construction*
5. *Demonstration of the efficacy of a simple timber rainscreen in reducing the moisture levels in straw bale walls*
6. *Comparison and confirmation of the accuracy of the wood block probe against the laboratory results.*

1.5 Thesis outline

Chapter 2 provides an overview of straw bale building and covers the history of straw used in construction.

It looks at the benefits and energy uses of straw balanced by questions raised by the potential drawbacks and vulnerabilities. This chapter does not discuss the potential drawbacks of high levels of moisture in straw, as that is discussed in Chapter 3

Chapter 3 looks at the relationship that straw has with moisture in more detail. It will examine the definition of a temperate maritime climate and the implications for straw bale construction.

This is followed by an overview of the science of moisture and the ways that water vapour can travel through the construction layers of a building. The implications of moisture movement are then related to the specific qualities of straw bale walls.

Chapter 4 sets out the overarching methodology for the research.
There is an analysis of moisture measurement, both in-situ and in the laboratory.
This chapter discusses the role of isotherms in the study of the moisture behaviour of hygroscopic materials and analysis of existing isotherms for wood and straw. This is followed by a discussion on how that relates to the monitoring of straw bale walls. An overview of existing and previous moisture studies follows with an explanation of how that relates to the choice of case studies and the techniques used to monitor them.

Chapter 5 outlines the development of a new wood block moisture probe. Starting with the design of an existing probe that proved to be inaccurate, it describes the prototyping of different designs, and the role of the laboratory in finalising the design of an all-new wood block probe for the in-situ measurement of moisture in a straw bale wall.
The new probes are tested in the walls of a straw bale house and the results compared to gravimetric analysis, RH and Temperature readings from an agricultural bale probe

Chapter 6 looks at the results of the laboratory work, with a new set of sorption and desorption isotherms created in the laboratory at Plymouth University that will directly compare the moisture performance of two species of straw with three species of wood.

The results are discussed in the context of the use of straw in construction and the development of the new moisture probe detailed in the previous chapter. Experiments investigating the long term effects of elevated moisture levels on samples of straw in the laboratory are analysed and will be compared to the case studies of buildings which have suffered moisture ingress.

Chapter 7 moves from the laboratory to describe the selection and methodology used for the in-situ monitoring of the case study buildings. The pricipal case study is the Totnes House. The structure of the house is described in detail, and as it has been monitored continuously for the last three years, it establishes a reference for the other buildings.

Particular attention is paid to the various sources of moisture, both from the interior and exterior of a straw bale wall and their effects on the moisture gradient through the walls. Analysis of the long term drying of previously wetted walls, and the role of a rainscreen in protecting straw bale walls from moisture ingress is discussed.

Chapter 8 brings together the findings from the preceding chapters to present a concluding summary of the research.

These results will tie into the development of a set of construction details for future straw bale buildings and discuss the role of straw bale and other non-food crops in the future of low carbon building.

Suggestions for further work, including the viability of using data logging with the newly developed probe, and questions raised over the consistency of the wood species used will then bring the thesis to a close.

2. AN OVERVIEW OF STRAW BALES IN CONSTRUCTION

This chapter provides an overview of straw bale building and covers the history of straw used in construction.

Before the subject of the moisture performance is covered in detail in chapter 3, this chapter gives a summary of the benefits and energy uses of straw balanced by questions raised by the potential drawbacks and vulnerabilities.

2.1 Definition of straw

The Concise Oxford Dictionary (2008) defines straw as ‘dried stalks of grain, used as fodder or for thatching, packing, or weaving’.

Staniforth (1979) gives a more specific definition which describes a process whereby straw is the above-ground part of the cereal plant which remains after the grain has been removed. For the purpose of this thesis ‘straw’ is used as a collective noun for the dry stalks of cereal crops.

In the UK the principal cereal crops are wheat, barley and oats. Wheat is the largest crop with just over two million hectares being cultivated, one million for barley and 135 thousand hectares of oats. There is a small (27,000 hectares) but increasing amount of rye and triticale (rye hybrid) being grown (Defra 2009).

Although there are many similarities between the straws of the principal crops, there is an important difference pertaining to the use of straw in construction; Barley straw is significantly softer than the others and therefore lacks structural integrity even when baled (Staniforth 1979a).

Given the prevalence of wheat, and the unsuitability of barley, this thesis will assume that straw is from wheat unless otherwise stated.

The stalks of the different cereal crops vary in composition, but all feature a tube of woody fibre made up of cellulose, hemicelluloses and lignin with some silica. This material is very similar physiologically to wood, with the lower proportions of lignin making straw more comparable to a hardwood. (Miller 1999)

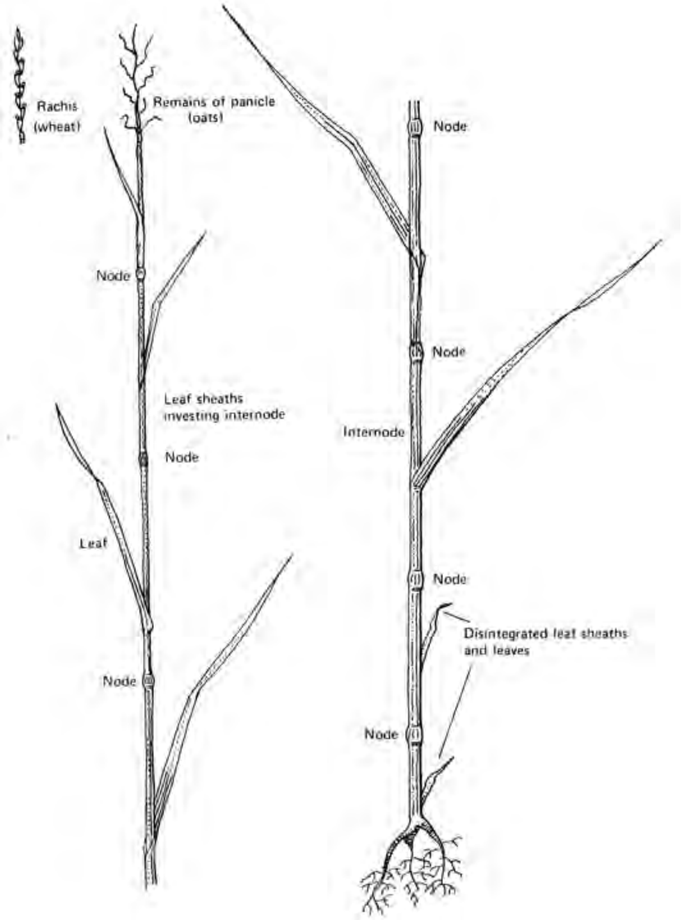


Fig.1 Typical stalks of the cereal plants that make up straw.
From Staniforth (1979a)

The stalks are generally slightly less than a metre long at the time of harvest, but the actions of the combine harvester and field baler will cut and tear the stalks resulting in lengths of between 250 and 500 mm. depending on the type of equipment used.

In section the stalk is clearly tubular, and according to Staniforth, all cereal stalks resist compaction. This is one factor that makes straw so suitable for construction; even when baled the straw will have a limited compression rate. In a load bearing structure this is considered to be around 3% when the load of the roof is taken by the walls (Jones 2007). Another aspect is that the insulation value of straw is due principally to the air trapped in the tubular structure and the resistance to compaction helps preserve the thermal resistance of the straw bale (Minke and Mahlke 2005).

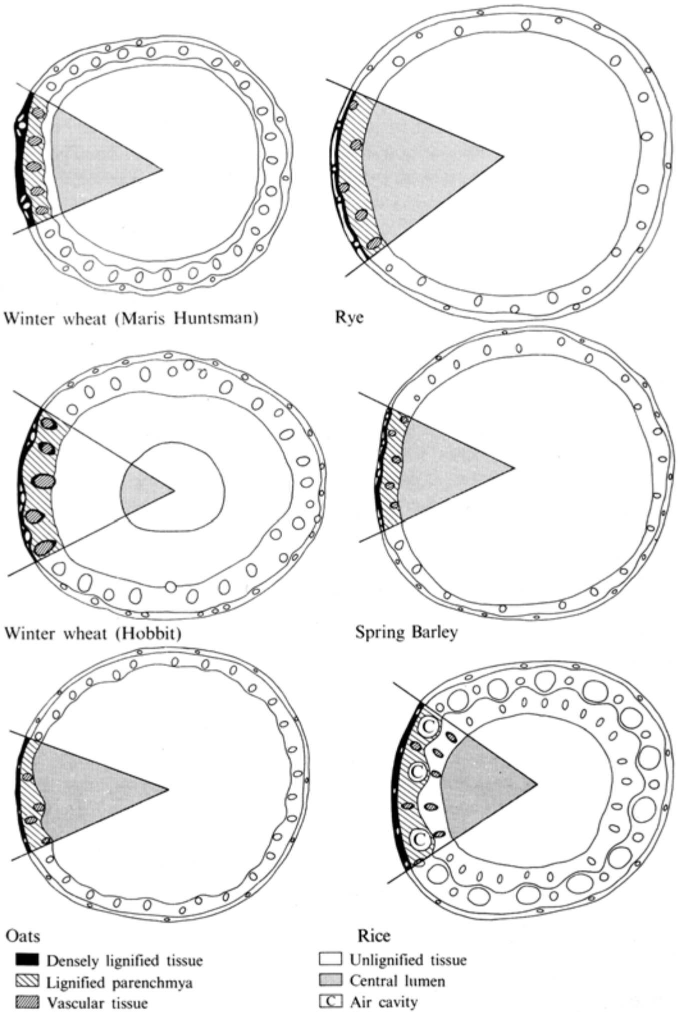


Fig.2 Sections through the stalks of different varieties of cereal. From Staniforth (1979a)

The sections illustrated are from the internodes of the stalk and show the tubular nature of the stalk with the body filled with a central lumen, the hollow core.

2.1.2 Make up of a typical straw bale

As previously stated, the use of straw bales in construction has come about directly from the use of the mechanical baling machine. The baler is the device that picks up loose straw from the field and forms it into compacted bales. In contemporary farming there are three types of baler used and these are known as the large round baler, the large square baler and the small square baler. The large round baler produces cylindrical bales of 1200 mm diameter and 1200 mm width. The large square baler (sometimes called ‘Hesston’ after the company that developed it) produces bales of up to 850 x 1200 x 2750 mm (AGCO 2008), and the small square baler typically produces bales of 360 x 450 x 1000 mm (New-Holland 2009). All these dimensions have degrees of variation as the different machines can be adjusted

The large round bales have been used occasionally in construction, for instance as structural columns in the Hastings Performing Arts Centre (Magwood, Spick, Boychuk and MacDougall 2009). Likewise, the large square bales have been used occasionally where space permits. One of the first houses built in the UK, for Brian Stinchcombe in Wales, used these larger bales (Jones 1999; Jones 2007).

However the majority of straw bale dwellings in the UK are built using the small square bales. There can be problems with supply of these small bales as most farmers prefer the more efficient larger balers.

To form the bale, the straw in the windrow (the row of cut straw left on the field by the combine harvester) is lifted by tines in the baler's pickup. This material is then dragged or augured into a chamber that runs the length of one side of the baler. A combination plunger and knife moves back and forth in the front end of this chamber. The knife, positioned just ahead of the plunger, cuts off the material at the spot where it enters the chamber from the pickup. The plunger rams the material rearwards, compressing it into the bales. A measuring device measures the amount of material that is being compressed and, at the appropriate length it triggers a mechanism (the knotter) that wraps the twine around the bale and ties it off. As the next bale is formed the tied one is driven out of the rear of the baling chamber onto the ground or onto a special wagon hooked to the rear of the baler.

The sections of straw created by the cutting and ramming process are known as flakes, and a straw bale can be subdivided along the long axis into its constituent flakes, which are generally 100 mm or so thick. This same process also introduces an orientation to the straws in the bale that gives a cut side and a folded side with the straws running in the same direction. Although the illustration below shows this orientation clearly, in an actual bale there is an element of randomness to the straw orientation (Atkinson 2008).

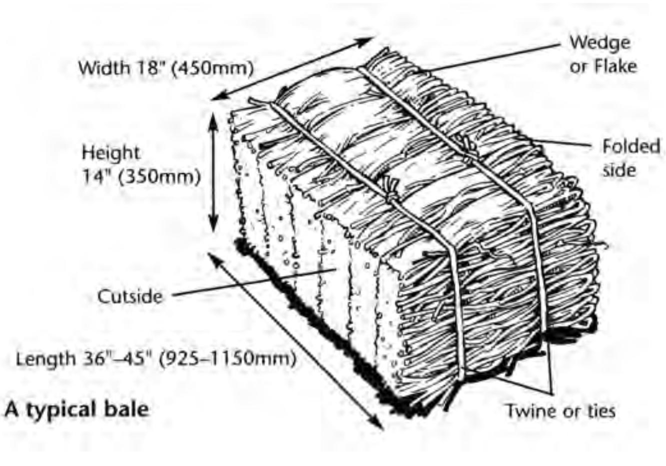


Fig.3 Illustration of a typical straw bale.
Drawn by Julliet Breeze, from (Jones 2007)

As well as the length, the density of the bale can be adjusted at the baler by adjusting the tension of the twine. At the start of the build process for the Totnes House, the bales used were sourced from a farm nearby and the baling machine was adjusted to give a wider ‘metric’ bale of 360 x 500 x 1000 mm.

The bales weighed on average 20 Kg which gave a density of 111 Kg/m^3, which is slightly above average given an expected spread of 80 to 120 Kg/m^3 for bales used in construction (Minke and Mahlke 2005).

When discussing the measurements of straw bales it is worth bearing in mind that they are made up from random lengths of organic material formed into fairly crude packages. Apart from the degree of adjustment, different manufacturers also vary the specification of their baling machines. All bales are different and there can be significant variation within a batch from the same machine and baled from the same field. Taha Ashour (Ashour 2003) gives the following coefficients of variation for wheat straw bales: Bale size +/- 7.2%. Bale weight +/- 25.1%. Bale density +/- 21% (plus or minus from average).

2.2 History of straw in construction

2.2.1 Before the baling machine

The use of straw in the construction of dwellings is likely to date back to the first time mankind gathered bundles of tubular plant stems to form simple shelters, or used a straw binder mixed earth to form walls or bricks. In the UK the use of the two traditions, in the form of thatch and cob, have been recorded since the thirteenth century (Clifton-Taylor 1972).

On the edge of Dartmoor, in the southwest of the UK, there is a particular example of rye straw thatch that is of interest when considering the question of the durability of straw. Higher Uppacott is a fourteenth century Devon stone Longhouse. This building is unique in the area in that it has not been converted or modernised so still retains it’s original layout with a cross passage and shippon (Beacham 2001). The house was originally built as a hearth house with no chimney and there are some areas of smoke blackened thatch still to be seen on the underside of the roof as shown in the figure 4 below. The later fireplace has been dated to the sixteenth century, which indicates that the bottom layer of thatch has been in place for at least five hundred years, and apart from the discolouration from the smoke, is in good condition. This demonstrates that in the context of straw used as thatch in a temperate maritime climate, longevity might not be a problem (Uppacott 2009).

Fig.4 Five hundred year old smoke blacked thatch at Uppacott

2.2.2 Since the baling machine

The first examples of buildings using straw bales to form their walls were built in the Sand Hills region of Nebraska, United States, at the end of the eighteenth century. Much of the early history of straw bale building is entwined with the history of poor, often illiterate subsistence farmers and pioneers, so there is little contemporary documentation (Lacinski and Bergeron 2000). Much of what is known is from verbal sources, but there are a small number of photographs in existence. There are some slightly later, early twentieth century buildings still standing.

There are likely to be three main factors that came together to lead to the building of the first straw bale house.

The first was the invention of a hay baler by Charles Withington in 1872 (Myrhman and Knox 1993a). Withington's baler was a horse-drawn machine that compressed the mowed hay into square blocks, much like the machine displayed below in Fig.5. When the blocks were ejected to the back of the machine, they were hand tied with baling wire.

Fig.5 Early horse powered stationary baling machine photographed by Solomon Butcher in 1904 in Dawson County, Nebraska.
From (Steen et al. 1994).

The second important factor was the lack on timber suitable for building in this specific area. The open prairies of Nebraska supported very few trees so the expensive imported timber was used only when essential for roof timbers and larger framed structures (Steen *et al.* 1994).

The third factor was the local tradition for ‘soddies’ or sod houses. Built by stripping the turf from an acre of land, the turf was cut into sods that were then used to build up the walls, and laid over a simple rafter system for the roof as shown below in Fig.6 (Dick 1954).

Fig.6 A typical Nebraska 'Soddy'.
From http://www.nebraskastudies.org/

The reason why these factors came together in the sand hills region of Nebraska, leading to the use of bales in place of sods in the local indigenous houses, was simply that the sandy soil was too weak to hold the sods together. Some unrecorded but resourceful individual chose to build a shelter using the newly created bales (in this case of meadow grass hay) in place of the sods (Welsch 1973). Myrhman and Knox observed that using bales as an alternative to sod had the benefit of avoided the stripping away of at least an acre of the valuable grazing land that would be needed for the sods (Myrhman and Knox 1993a).

Myrhman, Knox and Welsch all discuss what sorts of bales were used in these early houses, with contemporary references to both hay and straw bales. The sand hills were used to grow meadow grass for horse fodder, and this is the most likely material to have been baled at the time, as there are contemporary accounts of cattle feeding from the walls of buildings (Myrhman and MacDonald 1999).

The earliest documented example of a hay or straw bale building was a schoolhouse built in Scotts Bluff County, Nebraska in 1886 or ’87. A report by the State Superintendent in 1902 described ‘Walls of baled straw, a sod roof and a dirt floor’ (Welsch 1973). A contemporary photograph of a typical straw bale dwelling is shown below in fig.7

Fig.7 Contemporary photograph of the Simonton House, Purdum, Nebraska during construction in 1908.
From Lacinski and Bergeron(2000).

These early dwellings were often seen as temporary shelter until the owners could afford a ‘real’ house. An example is the Burke Homestead (1908) shown in Fig.8 below. This simple building was only rendered on the inside. The exterior walls were left unplastered for ten years. The house was occupied until 1956, and it was still standing in 2004.

Although the early straw bale houses were seen as temporary shelter for the poorest settlers, in many cases the house became permanent homesteads, and it was often the thermal performance that persuaded the residents to stay (Myrhman and Knox 1993a).

Fig.8 The Burke Homestead. Abandoned in 1956, but still standing (as of 2004) From Bigland-Pritchard (2005).

As the century developed, more sophisticated straw bale dwellings were built culminating in the Burritt mansion in 1936. Up until this point all the known straw bale houses were built as load bearing, where the weight of the roof is borne entirely by the straw in the walls. This method has become known as ‘Nebraska style’ (Magwood and Mack 2000). The Burritt mansion was the first straw bale house where the bales were used to infill a timber and stone structure to form a two storey house. (Steen *et al.* 1994)

Fig.9 The Burritt Mansion. The first two storey framed straw bale house (1936) From Steen et al(1994).

The years from 1890 to 1936 could be described as the ‘historic period’ and during this time there were a relatively small number of dwellings built. No more than thirty have been fully documented (Myrhman and Knox 1993a), with perhaps a further twenty unrecorded, but likely to have existed (Welsch 1973).

It is not clear exactly why the tradition for building with straw died out after the 1930s. Apart from a couple of buildings constructed by returning soldiers after the second world war (Bigland-Pritchard 2005), there was very little building with bales until the 1970s. It has been suggested that the increasing availability of concrete blocks as a material combined with a desire to build a ‘modern’ house, something a little less rustic, led to this decline (Myrhman and Knox 1993b).

The next phase in straw bale building could be described as the ‘revival period’. This was prompted by the publication in 1973 of a seminal counterculture book simply called ‘*Shelter*’ (Kahn 2000). The book describes many alternative building techniques and included an article called ‘Baled Hay’ by Robert L. Welsch which is quoted as being the prime mover in the revival of straw bale building in the USA (Lacinski and Bergeron 2000). The first house built in this revival period was also the first straw bale house in the northeastern USA. Known as the Hay House, and pictured below, it was originally planned to last only five years, but is still occupied by its second owner (Lacinski and Bergeron 2000)

Fig.10 The Hay House, built in 1974.
From Lacinski and Bergeron (2000).

The modern period could be said to have started with the publication of the first issue of '*The Last Straw'* magazine in 1993 (Knox and Myrhman 1993). This was the point at which what had been seen as an 'underground' movement started to become more mainstream and marked the beginning of the organised dissemination of technical knowledge through *'The Last Straw'*, and the publishing of seminal books such as '*Straw Bale Building*' by Steen, Steen and Bainbridge (1994), and Myrhman and McDonalds '*Build It with Bales*' (McDonald and Myrhman 1995)

The first recorded straw bale dwelling built in the UK was a cabin built by Bob Matthews in 1995 (Matthews 1995). Since then, interesting developments have come about through buildings that make more innovative use of the structural elements, such as the Sworders auction rooms in Stansted, UK that uses a hybrid wall construction where the load of the roof is shared between the straw bales and the timber framing (Jones 2007). Another innovation comes in the form of structural straw bale panel systems versions of which have been developed by ModCell (ModCell 2010b) and Ecofab (Ecofab 2010). The

ModCell panels have been used in a pioneering research building called 'BaleHaus' built on campus at the University of Bath and pictured below.

Fig.11 'BaleHaus' a pioneering building using ModCell panels. From (ModCell 2010a).

2.3 Different forms of construction

The previous section has mentioned some of the methods of building with straw bales. Until the more recent development of panel systems as illustrated by the 'BaleHaus', there were essentially the two choices demonstrated by the Burke house and the Burritt mansion. These two alternatives, of either using the straw walls as load bearing elements, or taking the weight of the roof and walls on a frame are still broadly speaking the main options in straw bale construction today. Load bearing, also known as 'Nebraska style', is seen as having an historical precedent and is also promoted as being simpler and more cost-effective for the unskilled self builder and in someway more ethical (Jones 2007). Paul Lacinski (Lacinski and Bergeron 2000), author of 'Serious Straw Bale' talks about builders "who think they did something admirable by not inserting a dozen posts to hold up the roof!" Other writers have pointed out that the drawbacks to using the load bearing method outweigh the supposed benefits; even the argument that load bearing uses less timber is countered by a study done of two near identical buildings in Arizona that discovered that contrary to expectation, the load bearing version actually used more timber than the framed one (Weiner 1994).

A key factor, particularly for a straw bale builder working in a temperate maritime climate, is that a framed structure allows the roof to be covered over before the walls are built (Goodhew, Carfrae and de Wilde 2010). This ensures a higher level of protection from the rain to the straw walls during construction, which otherwise have to be protected by tarpaulins as during the building of load bearing walls the straw is vulnerable to water ingress, especially from the top of the wall (King 2006a).

2.4 Arguments for and against straw bale construction

In order to be of value as a construction element the straw bale has to fulfil the requirements defined by its purpose, and this research considers its primary purpose to be that of an insulating element.

McMullan (2002) lists some of the properties required for insulating elements in a building

- Thermal insulation suitable for the purpose
- Strength or rigidity suitable for the purpose
- Moisture resistance
- Fire resistance
- Resistance to pests and fungi
- Compatibility with adjacent materials
- Harmless to humans and the environment

The list covers the physical attributes of the material, but does not consider the question of sound insulation, or the embodied energy of a material.

The following sections will look in more detail at how these requirements are met as well as some of the other considerations.

2.4.1 Thermal insulation

There have been six pricipal studies into the thermal resistance of straw as a material on its own. Stone (2003) provides a useful summary of some of the earlier North American studies, not all of which have been published separately The first was by John McCabe in 1993 using a hot-plate test performed on whole bales. This first test performed to US standards gave a conductivity (lambda) value of 0.061 W/mK for straw running parallel to the heat flow, and 0.046 W/mK if the straw is perpendicular.

The significance of measuring the conductivity in both directions is that in load bearing construction the bale has to be placed on its flat, or long side, which means that the straws that make up the bale are largely running horizontal to the ground and therefore parallel to the heat flow. In framed construction the builder has the option of placing the bales on their edge with the straws running vertically and perpendicular to the heat flow. Looking at the summary of research into the thermal resistance of straw bales shown in the table below, it can be seen that despite the variation in the results published by the different institutions there is always a lower conductivity for straw running perpendicular to heat flow.

The six studies conducted into thermal resistance of straw on its own were:

Study	Thickness of sample (mm)	Density (kg/m^3)	Orientation of straw	Conductivity (W/mK)	Calculated U-value for rendered wall (W/m^{2}K)
1.	127	133	Horizontal	0.061	0.13
	380	83	Vertical	0.046	0.12
2.	480	81	Unknown	0.054	0.12
3.	380	81	Horizontal	0.082	0.17
4.	Unknown	90	Vertical	0.057	0.15
	100	101	Horizontal	0.068	0.15
5.	150	90	Vertical	0.038	0.10
	150	90	Horizontal	0.060	0.13
6.	100	90	Vertical	0.056	0.15
	100	90	Assumed Vertical	0.038	0.10

Table.1 Summary of thermal conductivity test performed on straw bales (Adapted from Bigland-Pritchard (Bigland-Pritchard 2005))

1. *J. McCabe in 1993 (USA)*
2. *R.U. Acton at Sandia Labs in 1994 (USA)*
3. *J. Christian at ORNL in 1998 (USA)*
4. *Haus der Zukunft in 2000 (Austria)*
5. *By og Byg in 2001 and 2003 (Denmark)*
6. *Fachverband Strohballenbau in 2003 (Germany)*
   References: 1&2. (Stone 2003) 3. (Christian, Desjarlais and Stovall 1998) 4. 5. (Munch-Andersen and Andersen 2004)

In order to compare the results of the different tests, this thesis has calculated the total U-value (Hagentoft 2001) for a rendered wall in the last column of the table above. This calculation assumes a bale with a long side of 450 mm, which would be the depth of the bale if the straws ran parallel to the ground, and a short side of 360 mm with the straws running perpendicular. The results show that, with the exception of the Danish tests, the greater conductivity of the straws running parallel is balanced by the greater thickness of the wall and vice-versa.

The tests carried out in the table above were performed on samples of straw bales on their own with the U-value calculated to give a theoretical result for a finished wall build-up. The results, which give an average U-value of 0.13 W/m^{2}K are very encouraging in that they give a result equal to, or better than any super insulated wall standard (AECB 2007) but in contrast to the above results there have been tests conducted on completed straw bale wall sections, which all give a higher U-value, and these are summarised in the table below

Study	**Year**	**Procedure**	**Orientation of straw**	**U-value (W/m^{2}K)**
1.	1995	Heat flow monitoring	Parallel	0.21 W/m^2
2.	1996	Guarded hot box, full wall, to ASTM C236	Parallel	0.32 W/m^2
3.	1997	Guarded hot box, full wall, to ASTM C236	Parallel	0.26 W/m^2
			Perpendicular	0.19 W/m^2
4.	1998	Guarded hot box, full wall, to ASTM C236	Parallel	0.21 W/m^2
5.	2001	Hot box, full wall, to ISO 8990	Parallel	0.22 W/m^2
			Perpendicular	0.19 W/m^2

Table.2 Summary of U-value tests performed on complete straw bale walls (Adapted from (Bigland-Pritchard 2005))

Study	***Reference***
1. Watts and Wilkie Canada 1995	*(Bigland-Pritchard 2005)*
2. ORNL California USA 1996	*(Commins and Christian 1998)*
3. CEC/ATI California USA 1997	*(Stone 2003)*
4. ORNL California USA 1998	(Stone 2003)
5. By og Byg Denmark 2001	(Munch-Andersen and Andersen 2004)

The U-values shown in the last column of the table above display an average of 0.23 W/m^{2}K, which is very different from the 0.13 W/m^{2}K average U-value of the straw tested on its own. Stone (2003), who took part in the tests at ORNL (Oak Ridge National Laboratory), has suggested that U-values for individual insulation materials used in “standard” walls are generally much lower than the U-value for the wall as an assembly of disparate materials. Given that there were also problems with Danish wall tests (Munch-Andersen and Andersen 2004), it is arguably sensible that the California Energy Commission now officially regards a plastered straw bale wall to have an R-value of 30 (U-value 0.17), and this is also accepted by UK Building Control (Saich 2006).

2.4.2 Capacitive insulation

Combining the resistance of the constituents of a wall structure to produce a U-value yields a static result. The thermal performance of an external wall in a heated building is in a dynamic state, with constantly changing values (Hens 2007). A possible reason why the reported performance of straw bale buildings exceeds their specification is due to their thermal diffusivity. This is a measure of the speed at which a material can absorb heat from its surroundings, or release it back. Diffusivity gives an indication of the capacitive insulation of a wall build up (Incropera and DeWitt 2002). Stone (2003) mentions unpublished research by three UC Berkeley grad students (Carter, Jain and Hou). In 1996, their analysis of the Real Goods Living Center in Hopland, California, determined the thermal lag (the time it takes for a “pulse” of heat to travel through a straw bale wall) was about 12 hours. Goodhew and Griffiths (2005) describe a straw wall with 240 mm of additional mass (clay straw) on one side and a layer of bricks on the other that they calculate to have a ‘Decrement factor time lag’ of 16.91 hours. This thermal capacity will greatly improve the performance of a straw wall compared to a lighter wall with a similar U-value.

During an imaginary diurnal cycle of a cool night and warm day as illustrated in Fig. 12 below, the difference between the straw bale wall with a twelve hour time lag and a wall with a purely theoretical zero mass is made clear. The main consequences of this lag is that by the time the heat energy from the interior of the house is reaching the exterior of the wall, the exterior air temperature is at the opposite, warmer, phase of its cycle, and less energy is lost from the exterior. This continuing cycle results in less energy being lost from the house compared with a low mass wall with an equivalent level of insulation (Hagentoft 2001).

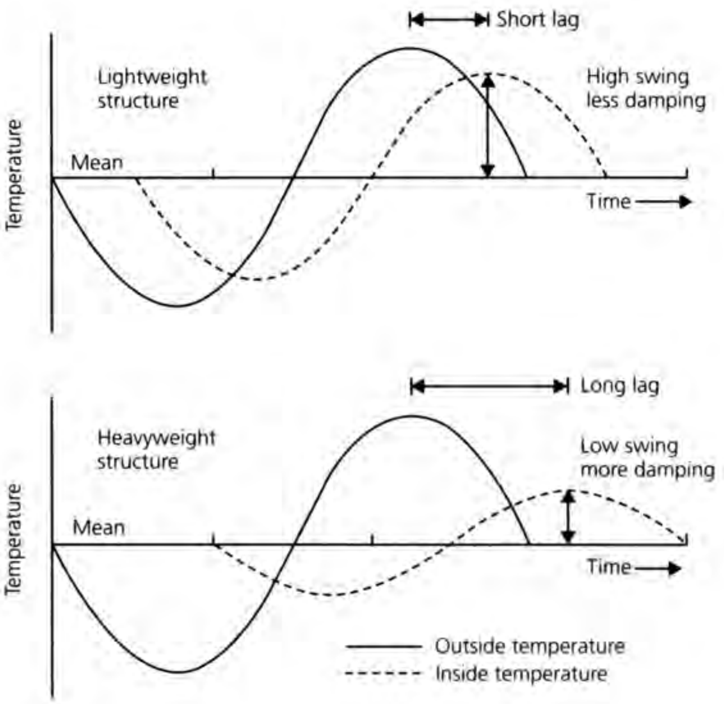


Fig.12 Twenty-four hour cycle showing effect of thermal capacitance on an external wall (after McMullan (2002))

2.4.3 Strength or rigidity

There have been a number of studies (King 2006b) into the load bearing properties of straw bale walls, which assume that the straw wall is being used as a structural element. This traditional form of building, described earlier in this chapter, is not within the scope of this thesis.

As far as this thesis is concerned a more appropriate use of straw bales is as a self-supporting insulative element within a framed structure. In this context, a straw bale wall rendered on both sides could be defined as a stressed-skin panel (Lacinski and Bergeron 2000), with the bales and render working together to carry live and dead loads.

2.4.4 Fire resistance

Of all the perceived risks associated with living in a straw bale house, the one that seems to be most commonly raised is that of fire risk. It is known that loose straw is highly flammable, and it seems logical that a bale of straw, or a wall composed of straw bales, will burn well. However, it is oxygen that controls the rate of burning, and it is the lack of oxygen that prevents the compacted straw in a bale from doing more than charring (Lacinski and Bergeron 2000)

Another sort of fire risk comes with the use of a layer of plasterboard or cladding, either externally or internally. If the straw is left unplastered behind the cladding, there could be an air gap between the straw and the cladding. Fire could break through to the air gap and then there is a risk of accelerating the flames through the thermal chimney effect caused by a column of air between materials (Straube 2000b).

There have been many fire tests on straw bale walls, in different countries over the years. A summary can be found in ‘Design of straw bale buildings’ (Theis and King 2006). The results are presented in the table below

Originator	Year	Where	Standard	Wall type	Duration of test (minutes)	Result
SHB Agra	1993	Scandia, New Mexico	ASTME E-119	Unplastered	30	Passed
				Plastered	120	Passed
University of California	1996	California	ASTME E-119	Plastered	60	Passed
GrAT Wein	2001	Vienna	German F90	Plastered	90	Passed
Santa Fe Fire Dept.	2000	New Mexico	1093ºC	Unplastered	30	Failled
				Conventional timber stud wall	35	Burned
				Plastered	40	Passed
Danish Fire Technical Institute	2001		1000ºC	Plastered with exposed studs	30	Passed (only 1ºC rise on unexposed side)
AUSBALE	2002	Australia	Australian Bushfire code AS 3959	Plastered	Unknown	Qualified as incombustible, Passed
DCAT	2006	Texas	ASTME E-119	Earth plaster	60	Passed
				Lime/cement Plaster	120	Passed

Table.3 Summary of fire tests on straw bale walls (Theis and King 2006)

Looking at the results in the table above, the only failure of a fire test is of an unplastered bale wall. The best protection against fire is a well-applied render. Rather than how well a structure burns, the important factor is how long will a wall retain its structural integrity in the case of a fire. This is in order to allow time for the occupants to leave safely. In all the above tests, the plastered walls have survived for more than thirty minutes, which is the pricipal requirement for safety in a building, and satisfies UK building regulations (Billington, Simons and Waters 2004)

2.4.5 Resistance to pests

Rodents are a known problem with the storage of straw bales on a farm. Vermin are not generally attracted to the low carbohydrate content of straw (there are no seeds or grain left in the straw), but it provides an excellent habitat for small animals and insects. There are also species of small insects and moths that feed on the fungi that can grow on moist straw (Wiener 2000).

A lime based render that is applied to both surfaces of the straw bale wall will discourage access by rodents. The vapour permeable properties of lime render will also provide an internal atmosphere that is without enough oxygen, and is too dry, for most insects.

Notably insects that are present in fresh straw die out after a single hatching due to the drying out of the bale wall (Wiener 2000). As is commonly found the best protection for a straw bale wall in this context is a lime based render. Rob Gulley, a Devon farmer has told the author that he has seen rats gnaw through cement if they know that food is on the other side, but they won’t touch lime because of its higher alkaline astringency. The careful application of a lime render therefore protects against pest, insect and rodent infestation (Bigland-Pritchard 2005).

2.4.6 Sound Insulation

One of the often-quoted positive attributes is the effectiveness of straw as a sound insulator. Jones (2007), King (2006), Lacinski (200) and many of the other authors of books on straw bale building report on the perception of peace and quiet in a straw bale building. For this reason one of the uses to which people have put straw bale buildings is as a music studio, an example of which is the ‘Strawdio’. This is a relatively simple structure at the bottom of a garden in

Bristol built by a composer of film and TV soundtracks, Piers Partridge. Partridge chose straw for the sound insulating properties. He was also attracted to it because of the perceived ease of use in a self-build project (Hilton 2007).

Fig.13 The 'Strawdio', a self-built music studio in Bristol. From Hilton (2007).

The acoustic properties of straw were informally measured at a straw bale music studio built by John Glassford in Sydney, Australia, and proved to be effective in reducing the sound levels of both the street noise as heard inside the studio, and of a loud band playing inside the studio with a sound level of 114-117 db, which was recorded on the outside of the studio at 60-62 db (A weighting) (Dalmeijer and King 2006).

King (2006) also describes tests carried out to measure the transmission loss of an earth plastered straw bale wall by Jasper van der Linden in 2003. The tests were performed according to ISO 140-3 and found that the wall had a Sound Transmission Class (STC) of 55 db with an A weighting. This is better than a solid 200 mm dense concrete block wall, and is equivalent to a purpose-built sound isolating wall composed of two layers of 12 mm plasterboard on each side of a staggered timber stud wall with batt insulation (Dalmeijer and King 2006).

Further tests were performed on the straw bale walls of the Genesis Centre, an educational facility in Somerset, UK. Carried out to ISO 140: 4 – 1998 and Approved Document E (ADE) and therefore covering the requirements for the UK building regulations. The results of the tests, which were performed on three different internal straw bale walls, were very consistent, with a range of values of 48– 50 dB. This exceeds the minimum requirement for a party wall under the UK building regulations, which is 45 db (Deverell, Goodhew, Griffiths and de Wilde 2009).

2.4.7 Co-product of cereal production

Straw is a renewable resource. A new cereal crop grows each year, and each crop is grown for the seed head, so the redundant straw is a co-product of the food industry (Defra 2009). The UK produces a combined total of 9.5 million tonnes of wheat, barley and oat straw each year of which 5.7 tonnes are surplus after livestock demand (straw is used as bedding and as a fibrous contribution to fodder). Biofuel power stations that use straw are increasing their demand on the surplus, but current use is still less than a million tonnes (Copeland and Turley 2008), Demand for straw is likely to rise as oil and gas become more expensive or less available.

Nonetheless, if the amount of surplus straw after other uses is still more than 4 million tonnes, then that is enough to build the walls of 450,000 houses of 150m^2 floor area per annum (Bigland-Pritchard 2005).

The straw used in a building is also recyclable to a certain extent. It might be difficult to retrieve full bales from a redundant building if they have been rendered, but being used in a wall does not physically alter the straw, so in theory it could be used in one of the processes described above with livestock, as biofuel, or simply returned to the soil (Lacinski and Bergeron 2000).

2.4.8 Embodied energy

Embodied energy, recorded in MJ/kg, is the amount of energy used to take a material from raw state to the finished product and can be either measured to the point at which the material leaves the factory (cradle to gate), the point at which it arrives at the building site (cradle to site), or the point at which the building is demolished (cradle to grave). The embodied carbon ($kgCO_2/kg$) is the amount of carbon released into the atmosphere as a result of this process and is also known as the embodied CO_2 coefficient (Alcorn 2003).

The difference between the embodied energy and embodied CO_2 coefficient is affected by factors such as the type of fuel used in the processing of the product (Hammond and Jones 2008). A third factor that applies to most organic materials is the amount of carbon sequestered by the material. In the case of straw this is the amount of carbon absorbed by the plant through photosynthesis whilst growing, This carbon is then locked into the material until it is released through combustion or composting (Magwood and Mack 2000).

In the UK, The Inventory of Carbon & Energy (ICE) is a database of the embodied energy and carbon coefficients of building materials published by the University of Bath. According to the inventory straw is listed as having an embodied energy of 0.24MJ/kg, and an embodied CO_2 of 0.01 $kgCO_2/kg$

(Hammond and Jones 2008). These figures are lower than any other insulant in the database, but would be lower still if the sequestered carbon was included. In fact the embodied CO_2 coefficient would be a negative figure as Andrew Alcorn states:

"Timber products are calculated in two ways. They are calculated in the normal manner for the energy embodied up to the factory gate, and for the CO_2 emitted in this production process. They are also calculated to account for the CO_2 sequestered by the growing tree. This means that timber products have a negative CO_2 emission coefficient, representing the net CO_2 absorbed by the production of the product, including the growing of the tree" (Alcorn 2003).

This statement refers to timber, but the same applies to straw.

The Bath ICE does not give any figures for sequestered carbon, and Alcorn only gives figures for timber with -1.665 kg/CO_2/kg for untreated air-dried pine. Atkinson in her thesis on the energy assessment of a straw bale building quotes a thesis by Musset as giving a figure of -1.36 kg/CO_2/kg for straw.

Even taking into account the embodied CO_2 coefficient of the lime render on a typical straw bale wall, it has still stored 80kg/m3 of CO_2 in the walls, and with careful choice of the other materials, a straw bale building has the potential to be carbon neutral at the point of construction (Atkinson 2008).

2.4.9 The width of a straw bale wall

A wall built with standard two string straw bales and rendered on both sides has a minimum thickness of 400 mm if the bale is set on its edge, and the render is just 20 mm thick. If the bales are set on their flat side and the render is a more generous 30 mm thick, then the width of the wall goes over 500 mm. This width can be a limiting factor with smaller buildings. It is not unusual for prospective builders to consider a small utility building as a suitable straw bale project without realising that even for a relatively generous shed of 3.8 square metres, half the internal floor area will be taken up by the width of the walls.

The value of the width of a straw bale wall in a house is in its thermal performance, and here it can be compared to a typical wall build up with the same U-value. Most loose-fill and batt insulants used in timber frame construction have a Lambda (thermal conductivity) of around 0.034 W/m K. In order to be equal to the 0.17 W/m^{2}K U-value of straw the insulation in the wall would be 200 mm thick. Allowing for a build up with a vented external cladding and internal plasterboard, the finished wall would be about 275 mm thick, a saving of 125 mm over the minimum straw wall. If the straw wall is compared to a conventional concrete block wall with polyisocyanurate insulation and a 50 mm cavity, then the wall thickness would be a more comparable 370 mm.

2.5 Summary of chapter 2

Straw bale building started as a basic vernacular style, and was revived in the 1970’s by the counter-culture movement. It could be argued that this is a positive aspect, and that we need simple self-build alternatives, especially low energy ones. Yet it is likely that the image of an ageing hippy building a straw bale shack in the woods (Rinaldi 2008) is hindering acceptance of straw bale construction into mainstream building culture.

Straw bale walls have excellent thermal properties, but at the expense of having extra wall thickness compared to more conventional forms of building. However, a rendered straw bale wall will have a combination of good thermal resistance with thermal capacitance. Add to this the fact that straw bales can be insulating and structural at the same time, and you have a compelling argument for their use in a low energy building especially when combined with their negative carbon coefficient.

Increasing use of straw in building will not put any additional strain on natural resources. If resource management is considered, and straw is used as a replacement for the cementitious and petrochemical building products used in the conventional concrete block cavity wall filled with polyisocyanurate (PIR) foam insulation (Celotex 2010), then the builder will have saved the carbon dioxide released in the manufacture of those products.

2.5.1 Moisture and straw

The ingress of moisture is potentially the greatest challenge to the continuing structural integrity of straw used in construction, and therefore the rest of this thesis concerns itself with the relationship between moisture and straw, starting with a background to the science of moisture in straw that follows in chapter 3.

3. MOISTURE IN STRAW

This chapter looks in more detail at the definition of a temperate maritime climate and the implications for straw bale construction. This is followed by an overview of the science of moisture and the ways that water vapour can travel through the construction layers of a building. The implications of moisture movement are then related to the specific qualities of straw bale walls. The chapter ends with an overview of the published reports on the monitoring of the moisture content of straw bale walls.

The following quotes confirm the view that the biggest threat to the longevity of a wall made from straw bales is the ingress of moisture.

“Water is the main enemy of straw” (Lacinski and Bergeron 2000).

“The moisture content of straw is the decisive factor in determining the rate of decomposition of straw” (Lawrence et al. *2009).*

“Moisture control is particularly significant for straw bale builders because of the moisture sensitivity of the materials” (Straube 2006).

“A more serious risk may arise if the structure becomes too damp for too long a period of time. High moisture content permits fungal growth within the bales.” (Bigland-Pritchard and Pitts 2006)

3.1 Straw bale construction in a maritime climate

This thesis is looking at the use of straw bales in construction specifically in a temperate maritime climate. This is significant because, as outlined in chapter 2, the tradition for building with straw bales started in the Sand Hills region of Nebraska where the climate is very different.

The classification of climate formulated by Wladimir Koppen in 1900 is still widely used today to define climatic regions (Peel, Finlayson and McMahon

2007), and the climate in the Sand Hills region of Nebraska is defined in the Koppen system is ‘BSk’ or semi arid. The definition of BSk is:

- B = Arid
- S = Steppe
- k = Cold (Mean average temperature less than 18ºC)

A maritime climate is a general term applied to a climate influenced by the ocean, and a temperate maritime climate is one that falls within the temperate regions of the globe. The Koppen classification uses the code ‘Cfb’ to describe the climate found in all the areas coloured green in the map shown below (fig.14). Within the Koppen system, Cfb can be defined as:

- C = Temperate
- f = without a dry season
- b = warm summer

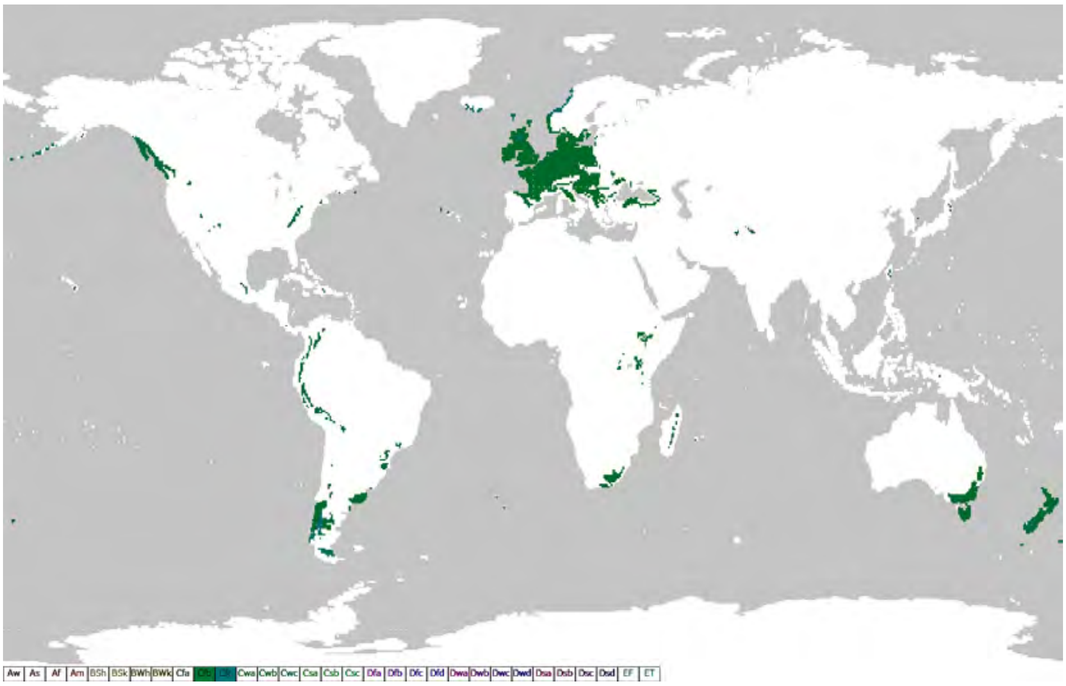


Fig.14 Map showing the areas of the globe enjoying a temperate maritime climate shaded in green.

As can be seen from the map above, although this climate type is dominant in the whole of the UK along with most of Western Europe and therefore includes a large population, it is relatively unusual globally.

This research is based in the south-west peninsula of the UK, and Perry(1997) differentiates within the Cfb region further to give the south-west peninsula a more specific climate, mainly due to the influence of the Gulf Stream. Typical characteristics of this region include relatively small diurnal and seasonal temperature variation and increased precipitation owing to more moist air when compared to the rest of the UK (Allaby 2006).

This research is not looking at the implications for straw bale building in hotter, more humid climates, although there may be conclusions drawn from this research that can be applied to other climates.

3.1.1 Implications of building in a temperate maritime climate

For builders living in a typical temperate maritime climate contemplating the use of straw, the question is whether the increased precipitation combined with high RH levels within a relatively narrow band of temperatures presents a threat to walls made from bales of straw.

Straube (2006) lists the four major sources of moisture and water ingress for a building:

1) Precipitation, particularly through driving rain, or splash back from the ground. Direct ingress of water through poor design, or poor implementation of construction details.

2) Water vapour in the air, either transported by direct air movement through the structure, or adsorbed through porous materials. This can occur from either the inside or the outside of the building
3) Built in or stored moisture either through accidental wetting during the construction process, or moisture brought in via previously wetted bales or as part of the building process. For example, rendering of the bales can introduce a lot of water.
4) Ground water (rising damp) either as a liquid or water vapour, wicking up from the foundations, or through the external cladding touching the ground.

Of the above modes of moisture transport into the straw bale walls of a building, the matter of precipitation is perhaps easier to deal with. Rain is visible and ingress is controllable, in fact, providing shelter from rain is one of the fundamental purposes for a building, so there is a long tradition for dealing with it (Tayler 1997). However, there are still concerns over the effects of driving rain on porous finishes such as lime or earthen renders (Straube 2000a).

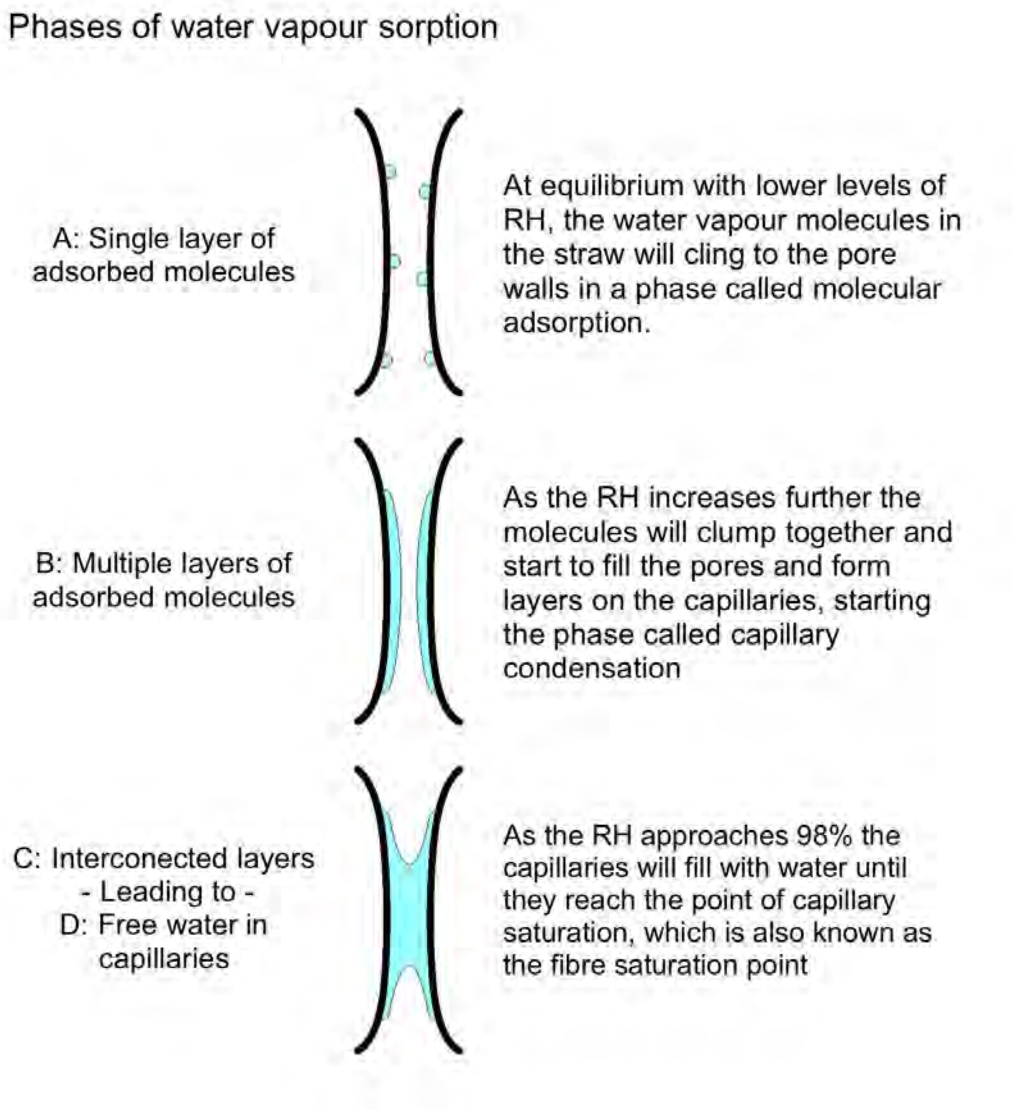
Ground water ingress is conventionally controlled through the use of an impervious plastic membrane. For builders wishing to avoid the use of petrochemical by-products there are alternatives such as slate (Jones 2007), or if a structural frame is used the whole building can be suspended off the ground (Carfrae, deWilde, Littlewood, Goodhew and Walker 2009).

The introduction of moisture into the building during the construction phase should be avoidable through sensible planning. Although the water contained in the render as it is applied is unavoidable, there are no recorded cases of it being a long-term problem.

Assuming that the sources of direct water access to the straw bale walls can be avoided through appropriate design and construction, it is likely that it is the level of water vapour in the environment around the straw that represents the greatest danger to the longevity and structural integrity of the straw (Minke and Mahlke 2005).

3.1.2 Moisture behaviour in straw

Straw is a hygroscopic material that will adsorb moisture vapour from the air that surrounds it. As the relative humidity (RH) of the air changes, the moisture in the straw will tend towards equilibrium with the moisture in the air surrounding it (Stromdahl 2000). As the straw reaches equilibrium with increasing levels of RH, the way that the water vapour behaves in the internal structure of the straw will go through different phases (Hens 2007). These phases are illustrated in Fig.15, below.



At equilibrium with lower levels of RH, the water vapour molecules in the straw will cling to the pore walls in a phase called molecular adsorption.

As the RH increases further the molecules will clump together and start to fill the pores and form layers on the capillaries, starting the phase called capillary condensation

As the RH approaches 98% the capillaries will fill with water until they reach the point of capillary saturation, which is also known as the fibre saturation point

Fig.15 Phases of water sorption in a hygroscopic material, such as straw. Redrawn from Hens (2007).

The final stage of the sorption of water vapour establishes the maximum moisture content of the straw before water starts to condense out of the air at 100%RH (Straube 2006). At this point water droplets will form around the straw and free water (water outside the structure of the individual straws themselves) will be found in the straw. The phases of moisture activity, illustrated in Fig.15 above, can be arranged alongside the curve that represents the mass of water adsorbed by the material at increasing levels of RH. The results are illustrated in fig.16 below.

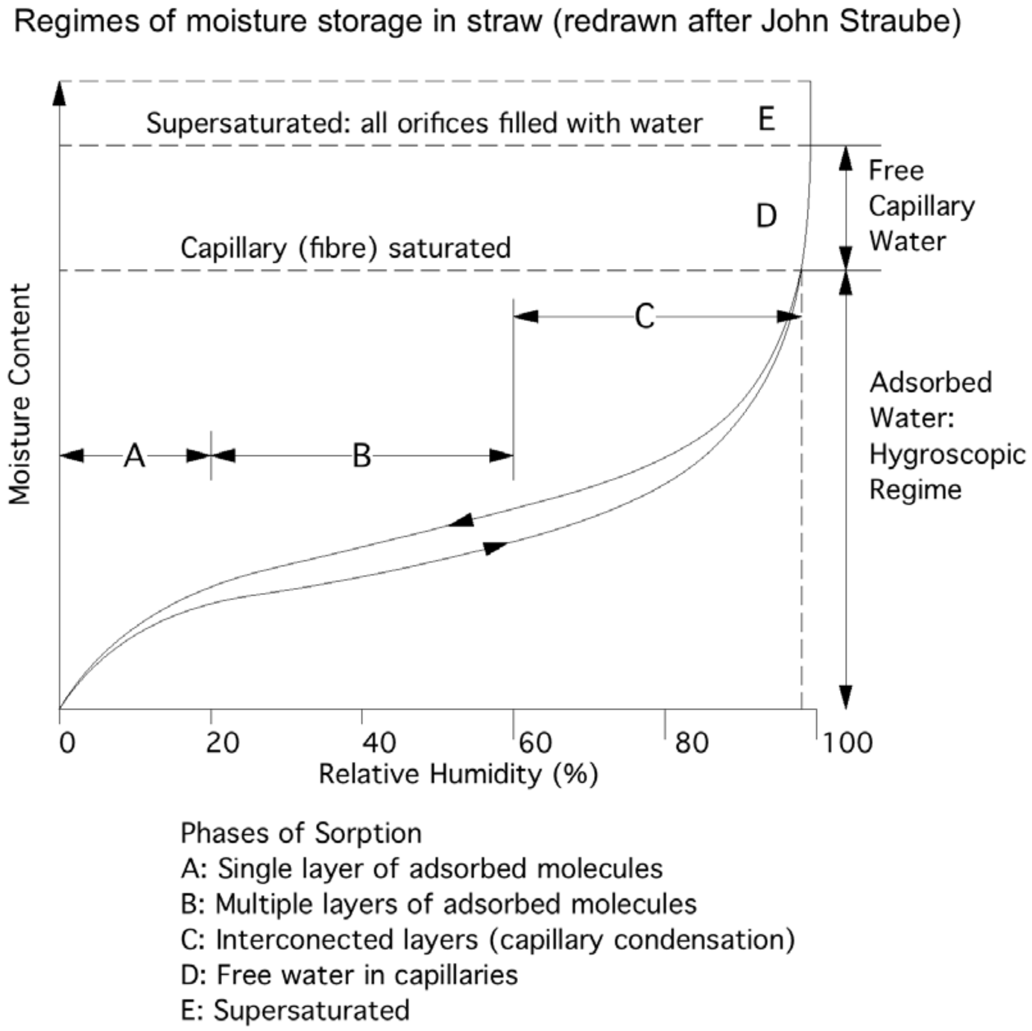


Fig.16 Stages of moisture storage in porous hygroscopic material shown against the isotherm
Redrawn from John Straube (2006).

3.1.3 Sorption and desorption isotherms

As discussed in the section above, there is a direct relationship between the moisture content of a hygroscopic material such as straw, and the RH of its immediate environment. This relationship is expressed as an isotherm.

Straw will adsorb moisture vapour from its immediate environment, and at any given relative humidity will reach an equilibrium moisture content which equates to the vapour pressure of it’s surroundings. A series of equilibrium moisture contents are plotted on a graph, and the resulting sigmoid curve forms the sorption isotherm.

3.1.4 Existing wood and straw isotherms

In order to create an isotherm, a laboratory mechanism has to be used to artificially sustain a given RH at a set temperature. The current European standard for the determination of hygroscopic sorption properties, BS EN ISO 12571 (2000a) describes two methods. The first uses the properties of various salts to establish a known level of RH in a sealed container called a desiccator, and the second uses an environmental (or climatic) chamber which uses an external source of water vapour to control the internal humidity (Stromdahl 2000) (see section 6.1).

Sain and Broadbent (1975) created an adsorption isotherm for rice straw using a method that involved grinding the samples to pass through a 2mm sieve, then using vacuum desiccators containing sulphuric acid to provide the required relative humidities, a method that is no longer supported by the current standards. Their isotherm shows a consistently lower level of moisture content than the other published isotherms shown in Fig.17, below. However, this may be because the isotherm is for rice, not wheat, straw.

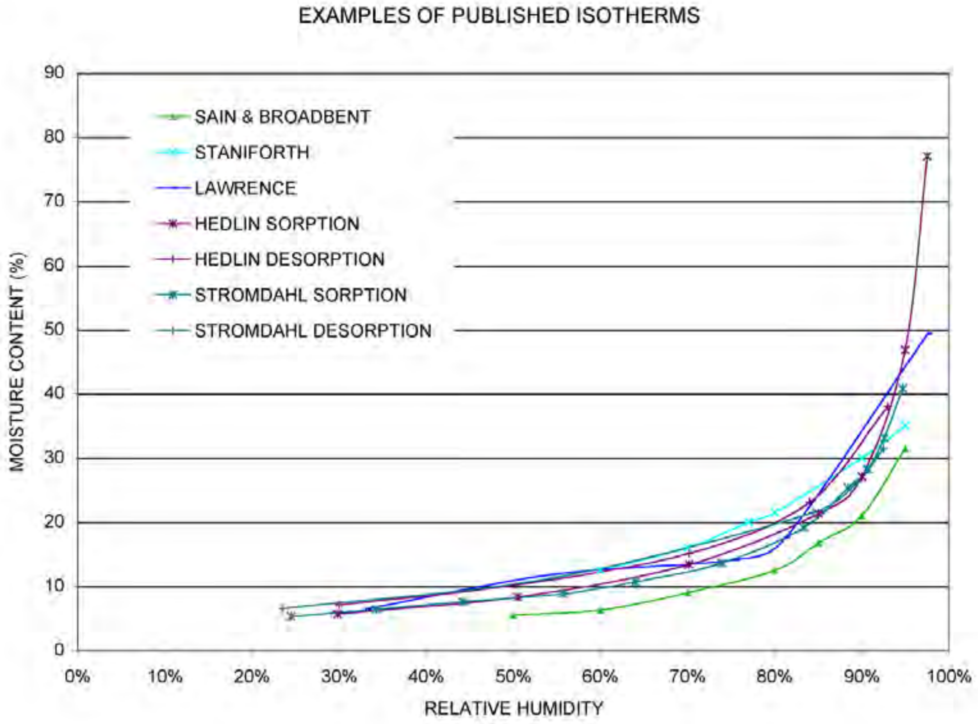


Fig.17 Published isotherms for straw

The Staniforth isotherm (1979b) does not specify the method used, but Hedlin (Hedlin 1967)used a jacketed air bath and Stromdahl (Stromdahl 2000) used an environmental chamber. These two methods are similar in that they rely on a controlled source of water vapour. Lawrence (Lawrence *et al.* 2009) used saturated salts to achieve the correct RH levels.

Comparing the isotherms for wheat straw, which is all of them except Sain and Broadbent, the general patterns of development up to 90% RH show broadly similar levels.

Stromdahl (2000) makes the following points about the relative merits of using a climatic chamber over the saturated salts method:

- It can be difficult to control the relative humidity inside the desiccators
- Climatic chambers can be bigger, and allow larger samples to be assessed

- Samples can be weighed within the chamber
- Temperature and RH can be continuously monitored through a data port.

3.1.5 Effects of high levels of moisture in straw

Straw will quickly deteriorate if exposed to consistent levels of bulk water (Ahn, Richards and Glanville 2007), but that should be a rare occurrence in the context of a straw bale building. Even if water has been allowed to enter the straw, the hygroscopic nature of the straw will encourage it to spread and be absorbed through the wall (Marks 2005). This reaction to bulk water has been confirmed in this research, see section 7.6.

Rather than the obvious dangers of bulk water, this research is concerned with the potential dangers associated with high levels of water in the form of water vapour. The danger here is from the effects of microbial activity, where the straw is gradually broken down by the activity of the mould spores growing on it, or the spores themselves that can present a health risk to humans (Bigland-Pritchard and Pitts 2006).

The mould that presents the highest level of risk to the health of people working with straw, or living in a straw bale house is Stachybotrys atra (Gallimore 2000), which causes ‘Farmers Lung’. The Health and Safety Executive, a department of the UK government (2006b) lists the long term effects as including chronic bronchitis, asthma and damage to the heart.

These spores need three ingredients to thrive; Oxygen, warmth and moisture (Wihan 2007). The main body of research in this area has been produced by Matthew Summers (2002; Summers, Blunk and Jenkins 2003; Summers 2006). The first phase of the research was to record the levels of CO_2 produced by samples of rice straw in controlled conditions, as a measure of microbial activity. In this experiment CO_2 production was minimal for straw at 25% moisture content or lower, with a marked increase at 33% moisture content, with rates of CO_2 production increasing rapidly above the fibre saturation point where free water is available. The next experiment looked at the rate of organic matter loss in samples of rice straw, again as an indicator of microbial activity and degradation of the straw. These results confirmed that high rates of decomposition only occur when free moisture is available in the straw. The safe limit for the moisture content of the straw in a straw bale wall advocated by this research (Summers 2006), is 25% moisture content on a dry basis. Below this level there is virtually no risk to the integrity of the straw, and the health of any human inhabitants.

3.2 Vapour permeable construction

In modern methods of construction there are essentially two approaches to the way that an exterior wall handles moisture. The first method is to use finishes on both sides of the wall that are impervious, therefore, keeping the interior of the wall completely sealed against the ingress of water. The problem with this is that it is virtually impossible to completely seal a wall, and once moisture has entered, it is hard for it to escape, which can degrade the wall.

The alternative is to use a form of construction known as a ‘breathing’ wall (Harris and Borer 2005). The finishes used on the wall should be airtight but vapour permeable, which will allow the water vapour that is created inside the building to migrate to the outside without becoming trapped inside the wall. This has benefits for the indoor air quality, but more importantly, it is generally recognised that a vapour permeable finish is important in protecting organic materials such as wood and straw, in that it mitigates against any build up of moisture and the potential for damage that would ensue (Straube 2000a). When detailing a wall build up of this kind, it is important that the degree of permeability of the different finishes on each side of the wall is balanced. In a temperate climate, the warm interior air will almost always contain more moisture, with a higher vapour pressure than the cooler air outside. The moisture from the inside will travel through the wall to the lower pressure on the exterior face of a building. So to avoid the water vapour building up to the point where it can condense into water droplets (known as interstitial condensation), it is important that the inside face of the wall should be less permeable than the outer, always encouraging the flow of vapour to the outside (Harris and Borer 2005).

In straw bale building this vapour permeability is created by the use of lime based renders. Research by John Straube (2000a) has shown that lime based renders can have a significantly higher permeability than cement based renders. As shown in Fig.18, his tests renders made with pure slaked lime and sand had 12 times the permeability of a render made with cement and sand in the same ratio, with different mixes of cement and lime falling between the two.

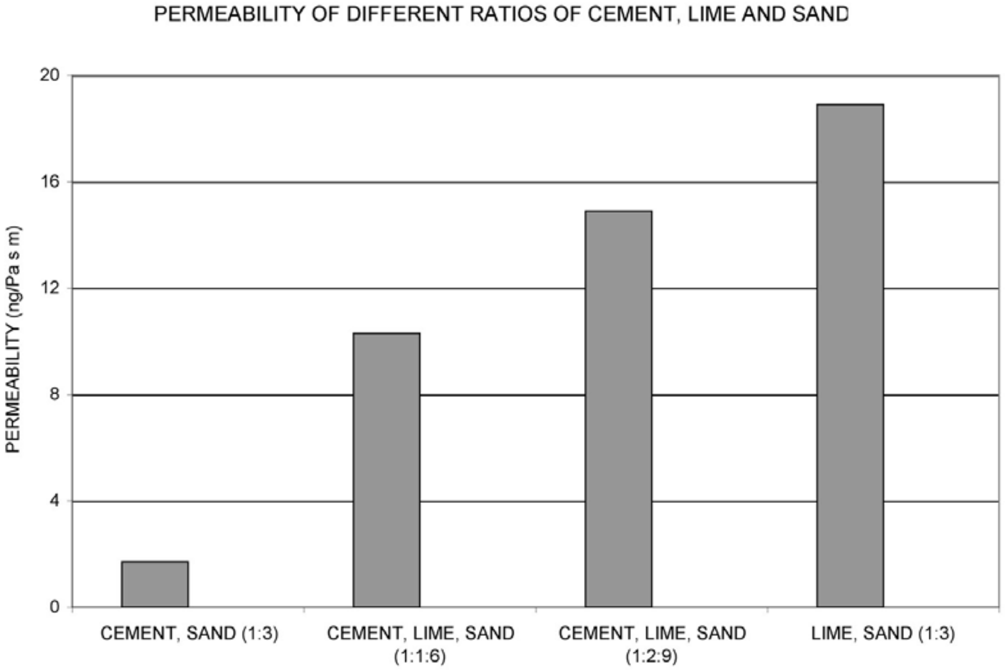


Fig.18 Graph showing the considerable difference in the permeability of renders using varied combinations and ratios of cement, slaked lime, and sand (Straube 2000a).

3.2.1 Moisture gradients

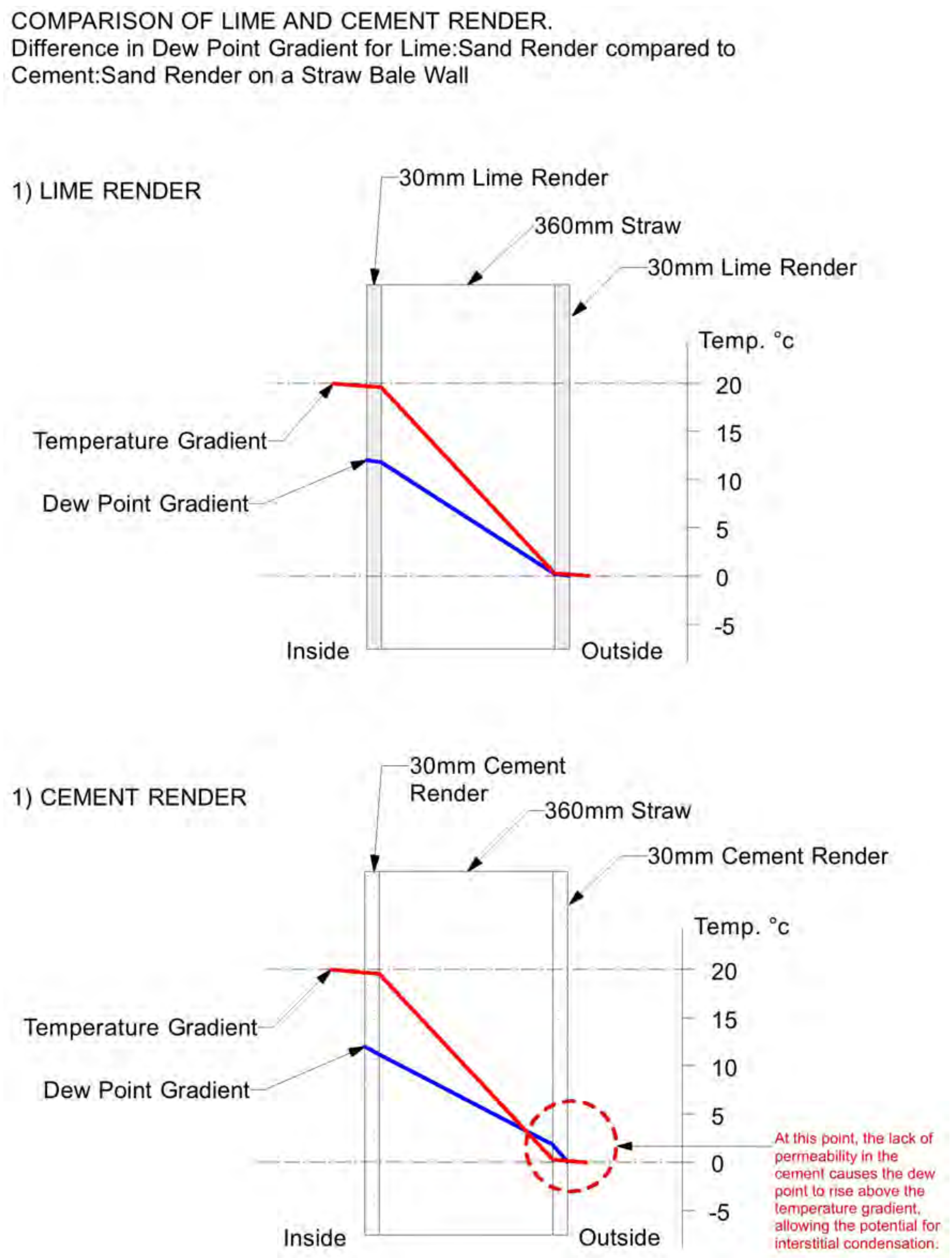


Fig.19 The effects of permeability on the dew point gradient and the potential for interstitial condensation

The significance of a highly permeable finish to a straw bale wall is illustrated in the comparative diagram in Fig.19 above.

The temperature gradient is the same in each case, as the thermal resistance of cement and lime renders are very similar (Parsons 2005). The dew point gradient traces the changes in vapour pressure through the wall, and therefore the amount of water vapour in the air around the straw (McMullan 2002). If the vapour resistance of the render is higher, then there will be greater amount of water vapour trapped in the straw behind it. If the dew point gradient is higher than the temperature gradient at any point through the wall, this indicates the potential for water to condense out of the air around the straw. In the wall sections shown in the diagram, the lower wall has a cement:sand render with a higher vapour resistance (lower permeability) than the lime:sand render on the first wall and therefore there is a risk of condensation where the dew point gradient crosses the temperature gradient at the outside edge of the straw in the wall.

The reasons for a vapour permeable finish should be balanced against the potential for moisture from driving rain to enter the wall from the outside. Although the excess moisture would normally evaporate from the surface of the wall between periods of rain, there can be an increase in the moisture levels in the wall if the cycles of wetting exceed those of drying. When rain is constant, this build up of moisture can become dangerous to the straw, as was documented in the case in the weather wall of a house in an exposed coastal situation in France (Wihan 2007), and of a building in the rain shadow of Dartmoor, England (Goodhew, Griffiths and Woolley 2004). A building in an exposed position will need additional protection from the weather, such as that afforded by a rainscreen.

3.2.2 Additional protection afforded by a rainscreen.

The use of an external rainscreen as the outer layer in the build-up of a wall is an established way of protecting the walls of a building (Ching and Adams 2001). A more advanced form is known as a pressure equalised, or vented, rainscreen (Surash Kumar 1999). Attention has to be paid to wind loads but if these wind induced air pressure difference across the wall are minimised by appropriately venting the rain screen, a more effective rain barrier can be achieved. (Surash Kumar, Stathopoulos and Wisse 2003).

Because of the tradition for a rendered finish on a straw bale wall (Steen *et al.* 1994), rainscreens have not been widely adopted, although they are advocated by Lacinski (1999) and Straube (2001).

In the UK, one of the best known straw bale dwellings, because it was featured on ‘Grand Designs’ (a popular UK television program), is known as the Woodland House and was built with a full timber cladding (Law 2005). The first comparative research on the use of a rainscreen to protect the walls of a straw bale house was published by the author of this thesis (Carfrae, Goodhew, deWilde, Littlewood and Walker 2009).

3.3 Existing straw bale monitoring

Having established that the moisture content of a straw bale wall is fundamental to its longevity (Bigland-Pritchard and Pitts 2006), there follows an overview of the sources of the information on straw bale moisture studies, and an analysis of the recorded levels of moisture found in buildings that have already been monitored.

3.3.1 The Last Straw

‘The Last Straw’ is a quarterly magazine described by the publisher as the *“Central depository of the dynamically expanding storehouse of practical knowledge and information about strawbale”* (Knox and Myrhman 1992). The magazine has been in continuous production since the first issue appeared in the winter of 1993.

While ‘The Last Straw’ is not a peer-reviewed journal, it is a valuable source of information even if much of it is by word of mouth or apocryphal in origin.

The magazine has detailed problems associated with excess moisture in straw bale buildings, and thus has played a role in developing moisture monitoring techniques. The magazine has also highlighted the separately published reports detailed below. The first detailed description of a moisture survey not described elsewhere in the literature is in issue no.8 which was dedicated to moisture problems in straw bale construction.

In an article on the monitoring of a building in New York State, USA, Clarke Sanders (Sanders 1994) describes using a Delmhorst model F5 hay moisture meter with a 10-inch (250 mm) probe (Delmhorst 1990).

The moisture probe was inserted through holes drilled in the 3-5 inch (75-125 mm) cement render which means that the probe was only able to measure the moisture content of the straw to a maximum depth of six inches from the inside face of the render. The results showed a wide range of moisture levels from 12% up to 30%, the maximum recorded by the meter. Sanders concludes with a description and illustrations of an overall theory of the patterns of moisture in a straw bale wall that is currently the only one published (see section 7.4.1).

3.3.2 Canadian pilot study

The first separately published survey of the moisture content of the walls of straw bale buildings came from the Canada Mortgage and Housing Corporation (CMHC) and was called ‘Pilot Study of Moisture Control in Stuccoed Straw Bale Walls’ (Platt 1997).

This report was concerned with the examination of buildings that use a “stucco-strawbale sandwich wall”, that is straw bale walls finished with a cement based render. The buildings were situated north of Quebec, and the report makes the point that this is a very different environment than the “rather ideal conditions” on the dry planes of Nebraska where the straw bale building tradition started. The report says that the study was looking at the worst case scenarios, where water ingress has occurred, and comparing them with examples from the same building where the straw is undamaged. The methodology involved identifying areas were water damage appeared to be occurring and cutting away a 100mm square section of render. The straw behind the render was examined visually, probed with a ‘Delmhorst’ hay moisture meter, and then samples were bagged and removed for further analysis.

The study found cases where the straw behind the render appeared damaged, with a blackened or grey colour and a mouldy smell. Probing with the ‘Delmhorst’ meter gave readings of between 20% and 30% where the straw appeared damaged, and 15% to 17% where the straw retained its golden colour and had no smell.

The discussion at the end of the report pointed out that all the damage found could be attributed to faults in the design or construction of the buildings, and went on to comment that straw is not a suitable material for use in basements or as insulation below foundation slabs.

3.3.3 The CMHC strawbale moisture monitoring report

The CMHC were also responsible for the next two publications; the first was a detailed report on the monitoring of nine houses, eight in Alberta and one on the west coast of Washington State (Jolly 2000). The second publication was issued as part of the CMHC Technical Series (Fugler 2000), and is a summary of the research conducted into straw bale moisture monitoring by the CMHC. It included the previously published results from Quebec and Alberta.

The Jolly report is the first to include results from RH sensors that have been placed at different depths through a straw bale wall. These were mostly on the exterior and interior, with the occasional addition of a mid wall sensor.

This report also included some results from the wood block probe developed by CMHC (Fugler 1996), which is discussed in chapter 5.

The long term recordings of RH levels in the straw bale walls of the houses in Atlanta showed an overall pattern of seasonal changes with increased levels of moisture during the summer months, caused by the higher RH levels that are a feature of the Atlanta climate

The levels of moisture recorded by the wood block probes were low, with maximum readings of only 9% from one of the probes during the spring and summer of 1998. This discrepancy between the results from the Canadian design wood block probes and the expected moisture levels was borne out by this research and is covered in section 5.2.1

The Technical Highlights report, as well as summarising the Quebec and Alberta reports, included results from a study in Nova Scotia which used the wood block probes to record average moisture levels of between 10% and 12%, with a highest reading of 15% on the outside of a wall. There was also an example of a wall suffering from water ingress where a reading of 19% was recorded. The final study included in the report was carried out in five houses in British Columbia. Using the wood block probes, typical readings were said to be around 12%, with a highest of 14%. These readings were said to show no seasonal variation.

In the conclusion of the report it was noted that “Straw in the bale walls in wet coastal climates will experience higher moisture contents” (Fugler 2000). However, none of the studies were in areas with a temperate maritime climate.

3.3.4 Wood block sensors in the UK

Between October 2000 and March 2002 the moisture levels in the walls of a straw bale barn in Devon, UK, were recorded using a development of the wood block sensor used in the Canadian reports. In contrast to the Canadian studies this building in the south west of the UK is in an area that benefits from a temperate maritime climate.

The results were published as ‘An investigation of the moisture content in the walls of a straw bale building’ (Goodhew *et al.* 2004). This paper starts with the calibration of the wood block sensor that is stated to have an accuracy of +/-1%.

The monitoring of the straw bale walls of the barn revealed high levels of moisture (25%) recorded by the probe installed at the outer edge of the bottom of the south wall. This wall faces the prevailing winds and therefore receives the most precipitation. A hole was made in the wall and the straw that was removed was described as feeling ‘damp’, and gravimetric analysis revealed the moisture content of the straw to be 27%. Apart from this unusually high reading, all the results showed higher levels of moisture than were found in the Canadian buildings. These were commensurate with higher average RH readings both inside and outside the building.

3.3.5 Californian winery monitoring

‘Monitoring the Hygrothermal Performance of Strawbale Walls’ (Straube and Schumacher 2003) is a detailed report on the readings from combined RH and temperature sensors embedded in the walls of a light industrial straw bale building in California. The commercial winery building is used principally as a barrel storage room, with some ancillary spaces.

Unlike the Canadian and UK reports summarised above, this study recoded only the RH and temperature, and made no attempt to relate these figures to the actual moisture content of the straw (Goodhew *et al.* 2004).

The researchers installed ‘stacks’ of three each of the sensors at the top, middle and bottom of each of the walls at thirteen different locations. This has provided a lot of detailed information on the variations in the RH levels in the walls.

The readings were made between June 1st 2002 and July 5th 2003. Seasonal changes in RH were recorded with increasing levels seen between January and May. High fluctuations in the temperature of the render were observed at points that were exposed to direct sunlight, but these didn’t affect the RH at the same point to the levels that were expected. There were increases in the RH immediately behind the render after steady rain, which would probably be due to the high permeability of the earthen render used in this building.

Despite these variations in external environmental conditions, the greatest impact on the long term internal RH levels in the walls came from the relatively high levels of RH found in the barrel storage room. These were the result of the industrial processes involved in the use of the building.

3.3.6 Use of a moisture probe in Ohio.

In a thesis on the viability of straw bale houses as a form of affordable housing in southeast Ohio (Marks 2005), there is s section on the monitoring of the moisture content of the walls of three houses using a Delmhorst moisture meter (Delmhorst 2000). This Delmhorst model differed from the one used by Sanders (Sanders 1994) in that it had an 450mm probe.

The readings show a seasonal variation with lower levels of moisture recorded during the winter months, rising through May to a maximum in September. The walls were measured at three heights to give a pattern of moisture content. Typical readings ranged from 12-13% at the top of a wall to 17-20% at the bottom. Readings above 20% were only recorded at sites where there was a fault or failure in the construction. A shallow moisture gradient from interior to exterior was noted.

3.3.7 Comparison of two European houses

Another Masters thesis, this time from the UK, discusses two case study buildings; the first was a domestic dwelling built in an exposed situation on the coast of Brittany, France, and the second in Belgium (Wihan 2007).

A severe storm exposed the French house to prolonged horizontal rain during two days in December 2005 which left visible damp patches on the exterior and interior of the lime rendered walls. This indicates that the moisture had penetrated all through the wall. A single combined RH and temperature probe was inserted into the middle of the wall on the 25th January 2006, eight weeks after the storm. During the time that the sensor was working correctly, It recorded fairly steady levels of around 80% RH, falling to 75% only after eight months. Wihan postulates that the RH in the wall could be expected to be as high as 100% immediately after the storm, which means that in the first eight weeks it fell by 20%, or 10% per month, only to remain steady after the probe was inserted. It may be that the damp patches seen on the inside surface of the walls had another cause. It was also observed that the lime render had not carbonated fully, and was crumbly to the touch.

The second case study was of the earth rendered walls of a house in Blanden, Belgium. This was on a more sheltered site, with only half the annual rainfall of the French house. The monitoring exercise used a total of five RH and Temperature sensors. Three of them placed were inside the straw wall of the bathroom, and the remaining two measuring the environment immediately inside and outside the wall. The three sensors inside the wall were placed line astern in the same hole spaced out to record the RH and temperature of the straw just under the interior and exterior face of the render and in the centre of the wall. This wall had suffered no unusual weather conditions, or problems with the construction, and therefore displayed a steady moisture profile through the wall that varied little over the six-month monitoring period. What was more interesting was the way that the render appeared to react much more quickly and strongly than the straw to changes in RH.

3.4 Modelling the moisture performance of straw bale construction

Both Wihan (2007) and Bigland-Pritchard (2005) have included sections on the modelling of moisture in straw bale walls in their theses.

Wihan used a piece of software called ‘WUFI’ (Kunzel 2005) to create a dynamic model of a wall section into which he had also inserted RH and temperature sensors. This allowed a comparison of the software model with actual measurements taken at the inside and outside edges of the straw as well as the middle. This showed that the software results were close to the actual measurements in the middle and inside edge of the straw wall, but there were major inaccuracies in the RH levels shown by the model in the outside edge of the wall, which, as has been discussed in section 3.2.1, is generally the area with the greatest risk of elevated moisture levels. Wihan described drawbacks in the use of the software as it failed to take account of convection currents in the materials of the wall, and the effects of vapor penetration into the construction due to infiltration. Another factor that could have affected the problems in the model was the inaccuracy of the external climate input data at the specific area of the house being monitored (Wihan 2007).

Bigland-Pritchard is concerned with creating a mathematical model for the hygrothermal processes in a straw bale wall, but has the same problem as Wihan with the potential for convection currents within the material. He states that:

> *“If convective (as well as conductive) heat transfer takes place within a bale wall, a reliable model must take account of it. However, given the complexities of convective flow geometries, an accurate model of the convective element of heat flow cannot be provided here” (Bigland-Pritchard 2005)*

Bigland-Pritchard also describes the installation of RH and temperature sensors in the walls of a straw bale building, but does not publish results to compare with his model due to a lack of consistent readings.

3.5 Summary of Chapter 3

The published monitoring of straw bale walls can be summarized through the following points

- Straw bale walls with measured moisture contents that remain under 15% can be considered safe, but may only be found in dry areas of the globe, like Nebraska in the American southwest (Steen *et al.* 1994).
- Straw bale walls with moisture contents of more than 25%, even if they are not saturated, will deteriorate if they remain at that level of moisture for a significant length of time (Jolly 2000, Summers 2003).

- It is not known how long straw can survive those sort of elevated moisture levels (Jolly 2000).
- It has been recorded that if a straw bale gets wet, or even saturated with water, but then dries back to a ‘safe’ level, then it may not suffer permanent problems (Platt 1997).
- If a bale does start to rot, it will turn black and the damage will be highly visible (Platt 1997).
- The unknown area is what constitutes a ‘safe’ level. It is not known if straw can tolerate a long term moisture content of between 20% to 25% and remain undamaged (Lacinski and Bergeron 2000).
- It is not known if there are climatic regions where straw will adsorb high levels of moisture caused by high levels of environmental RH (Fugler 1998).

4 METHODOLOGY

This chapter describes the background to the research and sets out the overarching methodology for the research. There is an analysis of moisture measurement, both in-situ and in the laboratory. This chapter discusses the role of isotherms in the study of the moisture behaviour of hygroscopic materials and analysis of existing isotherms for wood and straw. This is discussed in relation to the monitoring of straw bale walls.

4.1 Background to the research

From the start of this research, full access to a straw bale and timber house in the market town of Totnes in the south west of the UK has been available. During the build process the University of Plymouth installed probes to monitor the moisture content of the straw to be used in the walls.

The method chosen was to use a version of the wood block probe used in the Canadian studies described in chapter 3. Two of these probes were supplied before construction of the house had started, and these were installed in two of the bales of straw that had already been harvested and stored in a barn ready for use on the house.

In 2006, a year after the house was completed, a further 24 probes were supplied. This time the probes were in pairs of one long and one short, designed to measure the moisture in the wall at two depths, the short probe close to the interior face of the wall and the longer one giving readings close to the exterior face of the wall. The probes were installed in pairs as described, with one pair at the base of a wall in the first 100 mm of the straw, and a second pair at the top of the wall, 2200 mm from the finished floor level.

Assuming that the moisture gradient through a straw wall was consistent, this would establish a pattern of moisture content for a wall from inside to outside and top to bottom.

Monitoring of these probes started in November 2006 and continued through to May 2007, with the readings from the probes showing a consistent pattern of moisture in the walls of between 10% and 14%, with an average of all the probes showing 12.05%.

In May 2007 a commercial straw bale probe called a ‘‘Balemaster’’ was used to measure the moisture in the walls that had had the wood block probes installed in them and the results were significantly higher than those shown by the probes. Comparisons with readings from structural timber elements both inside and outside the walls of the house, and consulting the literature, suggested that the consistently low results from the probes were inaccurate; a view that was reinforced after the ‘‘Balemaster’’ was calibrated.

The initial focus of this research then became the need to design a more accurate wood block probe, while continuing the monitoring of the Totnes House with the ‘Balemaster’, and this is described in chapter 5.

In order to gain a greater understanding of the relationship between the wood block probe and the straw, it was decided to create a new set of sorption and desorption isotherms for wheat and oat straw. Isotherms provide a graph showing the moisture content of the material at a series of increasing and decreasing RH and Temperature levels.

The resulting isotherms could be compared to the results from timber isotherms and thus provide a means of calibrating an improved probe.

The isotherms were created in an environmental chamber, and samples of different species of timber were added to the chamber to directly compare the hygrothermal performance of timber to straw. This process took from June to November 2007 and is described in chapter 6.

While the probes were being produced, a further series of experiments took place in the laboratories at Plymouth. Tests were performed in the environmental chamber to gauge the response time of the samples of straw to changes in RH at different temperatures, and an experiment was set up to look at the effects of continuous elevated moisture levels on straw. This experiment included a sample of straw coated in a lime render to replicate the configuration of a typical straw bale wall.

The comparison of the timber and straw isotherms was made to help demonstrate whether the original wood block probe was under-reading because of an incorrect choice of timber species, or because of a problem with its physical form. In order to establish what effect the structure of the probe was having on its performance a series of design prototypes were created to try and determine the best configuration for an improved probe. These prototypes were tested in the walls of the Totnes House during the period that the isotherms were being performed.

In January 2008 a new probe was built that combined the most successful design prototype with the species of timber that had produced the isotherm closest to straw, and these were installed in the walls of the Totnes House. The trials of the new probes were completed towards the end of 2008, and in early

2009 a batch of the new probes were constructed in the workshops at Plymouth. The new probes would use the same system of using pairs of short and long probes to establish a moisture profile through the wall that are described in chapter 7.

Sets of the new probes were also installed in a selection of straw bale buildings in different locations around the UK. The owners of these case study buildings were left with instructions on how to record the moisture using a form that was provided, and these results were compared to readings from the Totnes House to provide a comprehensive picture of the moisture performance of straw bale walls in a temperate maritime climate.

4.2 Overarching Methodology

The literature discussed in chapter 3 has described a number of surveys of straw bale buildings, but the results have been inconclusive, particularly with reference to buildings in a temperate maritime climate. In order to understand more about the performance of straw bale walls in these elevated moisture levels, it was evident that a simple and effective method of measuring the moisture content of a straw bale wall needed to be developed

4.2.1 Current methods of moisture measurement

There are three methods of ascertaining the moisture content of the straw in a straw bale wall that could be of use to the builder or owner of a straw bale building:

- Directly through gravimetric analysis.
- Indirectly by measuring the relative humidity in the wall.
- Using a purpose made agricultural probe
- Measuring the electrical resistance of a small piece of timber placed in the straw.

These are discussed in detail in the following four sections:

1) The most accurate method of finding the moisture content of a non-homogenous organic substance such as straw is through gravimetric analysis (Lawrence *et al.* 2009). A sample of moist straw is first weighed, and then dried in an oven at 105˚C until successive weighing gives the same result (usually to within 0.1%) (BS EN ISO 12570 2000b). The result is subtracted from the weight of the sample before drying, which gives the weight of the water in the moist sample, and the moisture content is then expressed as a percentage.

2) The second method involves installing hygro-thermal sensors in the wall to record the relative humidity (RH) and temperature of the air surrounding the straw. Using a set of sorption isotherms, the moisture content of the straw can be calculated. Individual RH and temperature sensors can be installed in batches in a straw bale wall, and would typically be connected to a data-logger. An alternative would be to use a hand held meter with an integral sensor.

3) The third method to determine the level of moisture in a straw bale wall uses an instrument that can measure the electrical resistance of the straw.
   Electrical resistance measurement is a well-established technique for determining the moisture content of timber (Glass and TenWolde 2007). There is a direct relationship between electrical resistance and moisture

content (Forsen and Tarvainen 2000), with a lower resistance revealing a higher moisture content. Meters that are calibrated to translate the resistance of the material into moisture content are commonly used to measure the moisture content of timber, and there are commercial versions of these adapted for use in agriculture that come in the form of a probe attached to a separate meter such as the Protimeter ‘‘Balemaster’’ (GE Sensing 2006).

4) An fourth method has been developed for the remote monitoring of building structures by using small pieces of timber inserted into the structure with leads connected back to a resistance meter (1993). This has been adapted for straw bale construction by means of a small piece of timber either in direct contact with the straw and embedded in the wall during the construction phase, or contained in a perforated tube (Lacinski 1998; Lacinski and Bergeron 2000). This method works on the assumption that the piece of timber placed in the same environment as the straw will take on an equivalent amount of moisture, which can then be measured using a timber moisture meter. A probe built on these principles can be made in large numbers and left in-situ, giving a more cost effective method of establishing the moisture patterns in a straw bale building.

4.2.2 Problems with the current methods

1) The gravimetric method works well in the laboratory, but is harder to implement in the field when a sample of straw needs to be extracted from the wall of a straw bale building, which makes it an excessively invasive technique. It is difficult to get an idea of the moisture gradient

through the wall using this method because of the difficulty in removing consistent samples from the same area.

2) The use of RH and temperature probes is easier to implement than the gravimetric analysis if the individual sensors can be installed during the build process, but they are too delicate for use in a situation that requires retrofitting where the hand held meter would be more suitable. Although individual sensors are not particularly expensive, they would have to be installed in large enough numbers to give a useful picture of the moisture profile of a building. This, coupled with the cost of the data-logger, could prove prohibitively expensive. For example a typical set up as used by the University of Bath to monitor a prototype straw bale building used sensors that cost £100 (Pounds Sterling) each, coupled with a data-logging hub that cost £2,000, for a total of £8,000

3) The disadvantages to using agricultural straw bale moisture probes are firstly the relatively high cost (£300) compared to the equivalent timber moisture meter (£150), and secondly that the probe is not designed to be left in-situ for continuous monitoring. However, the ‘Balemaster’ as an example of this type of probe, has been used successfully as a portable device for surveying the buildings covered in this research.

4) Using a piece of timber embedded in the straw to make a comparative reading of the moisture content relies on the accurate calibration of the species of timber used against the moisture content of straw at any given RH and temperature.

4.3 Isotherms

A method that could tie together all the methods outlined above is through the use of isotherms.

The principal use for the isotherm in this research is that it enables the RH reading from a hygrothermal probe to be translated into a value for the moisture content of the straw.

A series of isotherms can also be used to compare the results for different species of timber with straw, which enables a more accurate wood block probe to be calibrated.

Because the relationship between RH and moisture is fundamental to this research, it was decided to create a new set of isotherms in the laboratory at the university of Plymouth. These isotherms would create a new reference for comparisons with hygrothermal sensors, and would be the first time that samples of different varieties of straw could be compared directly with different species of timber in the same process, at the same time.

4.3.1 Further drawbacks to using RH and temperature probes

The use of RH and temperature probes has two further drawbacks.

The first is that as they measure the moisture of the straw indirectly. This means that they are recording the RH of the environment that the straw is in, not the straw itself.

Fugler (2000), points out that an RH probe reacts faster than straw or a wood block probe will, and therefore can give a misleading reading if there has been a sharp rise or fall in RH that the straw hasn't responded to.

(Straube and Schumacher 2003).

The net result of this is described in this quote from Rob Jolly:

"In the field, moisture contents were consistently lower than what would be predicted by the recorded RH levels. Depending on the monitor location, diurnal variances in RH could be extreme. Even after moisture content values had been adjusted for temperature, and for the type of wood used in the sensor, moisture content consistently fell slightly below what would be predicted by the sorption graph. 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 2000).

The other drawback to the use of RH and temperature sensors to monitor moisture levels in straw, is that they can't reveal the effects of hysteresis.

The Hysteresis phenomenon (Kwiatkowski, Woloszyn and Roux 2009), is exhibited in straw where at any given RH, the actual moisture content of the straw will vary according to its moisture history.

The Concise Oxford Dictionary defines hysteresis as:

"The phenomenon in which the value of a physical property lags behind changes in the effect causing it, as for instance when magnetic induction lags behind the magnetizing force" (2008).

Hysteresis is a relatively simple phenomenon to observe, but is complicated to describe scientifically (O'Kane and Flynn 2007).

In the case of sorption and desorption isotherms for straw, hysteresis has been recorded by Hedlin (Hedlin 1967), and Stomdahl (Stromdahl 2000) (see Fig.17). This phenomenon is illustrated by the isotherms shown in chapter 6.

For the reasons outlined above, it was decided to concentrate on the development of an improved version of the Canadian probe, as developed by Goodhew (Goodhew *et al.* 2004) as a means of monitoring the moisture content of the walls of straw bale buildings.

4.4 Choice of case study buildings

The Totnes house will form the basis for the monitoring program, but it will be compared to a selection of other straw bale buildings to compare and contrast the findings.

These buildings were chosen to represent a range of building types and include residential dwellings, studios, workshops and experimental structures.

The case study buildings also provide examples of the different methods of straw bale construction, load-bearing and framed structures, and they include professionally built examples as well as buildings built by their unskilled owners. Some of the case studies are fully occupied, heated domestic dwellings, others are occupied and heated on a part-time basis, and one is an unheated garage. These buildings should provide a range of environments to compare the effects of occupation patterns on moisture performance. They are situated in different parts of the UK, and facing different variations on a temperate maritime climate thus helping to determine what effect local weather patterns may have on the moisture content of the walls.

4.5 Summary of Chapter 4

The overarching methodology for this research is to develop a more accurate version of the wood block probe used in the Canadian studies. The environmental chamber in the laboratory at Plymouth University can be used to establish the hygrothermal relationship between the timber to be used in the probe, and samples of straw.

The finished probe will first be installed in the walls of the Totnes house and the resulting readings compared to those from a ‘Balemaster’ probe along with RH and temperature readings.

The calibrated wood block probe can be used in a series of case study buildings to collect evidence of their moisture performance in a temperate maritime climate.

5. DEVELOPMENT OF WOOD BLOCK PROBES

This chapter outlines the development of a new wood block moisture probe. Starting with the design of an existing probe that proved to be inaccurate, it describes the prototyping of different designs, and the role of the laboratory in finalising the design of an all-new wood block probe for the in-situ measurement of moisture in a straw bale wall. The new probes have been tested in the walls of a straw bale house and the results compared to gravimetric analysis, RH and readings from an agricultural bale probe

5.1 Development of existing probes

An inexpensive and easy to build timber block probe for measuring the moisture content of the straw in a straw bale wall was first developed in Canada, and the design was published in 1996 by the Canada Mortgage and Housing Corporation (CMHC) (Fugler 1996). Further details appeared in the Spring 1998 issue of The Last Straw (Fugler 1998). This paper discuses two prototype probes designed by Vandrish of Instruscience, Inc. The first one of these used a relative humidity meter that was taken apart and the sensor embedded in the wall, the second one used a small piece of Balsa wood encased in a perforated tube. Habib John Gonzalez (CEO Sustainable Works) published a simplified version of the second design using a timber disc (Gonzalez 1998), and it is this design that has been used more recently by Goodhew et al (Goodhew *et al.* 2004), and is the model that was initially installed in the Totnes House (Carfrae, deWilde, Goodhew, Walker and Littlewood 2008). Goodhew had made revisions to the 1998 design including some small differences in the way that the probe was constructed, and another important modification in that the variety of timber used was changed from the White Pine used by Gonzalez to European oak, following comparative testing. (Bryant 2004)

5.1.1 Design of the original probe

The design of the Canadian probe as modified by Goodhew incorporates a small disc of timber with a diameter of 22 mm, and a thickness of 5 mm, held in a perforated plastic tube, which can be inserted into the straw bale wall. (see Fig.20)

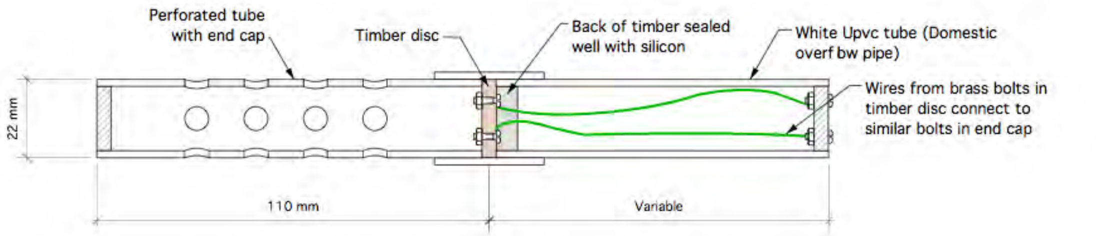


Fig.20 Section through original probe modified from the Canadian design.

The probe is designed to work in the following way:

As the probe stabilises the air in the perforated tube will be at equilibrium with the air surrounding the individual pieces of straw in the wall and the relative humidity of that air will be adsorbed by the timber disc to give it the same moisture content as the straw. A pair of wires are attached to small stainless steel or brass bolts fixed 12 mm apart in the timber disc and the other ends of the wires are attached to similar bolts fixed to the end cap of the tube. When inserted into the wall, a reading can be taken with a timber moisture meter from the bolts in the end cap, or flying leads of up to 5 metres can be taken to a central terminal block where more than one probe can be monitored without affecting the reading by more than 1% (Lacinski and Bergeron 2000).

Depending on the length of the different sections of the probe, and the number and spread of the perforations, the probes can be tuned to read the moisture content at different depths into the wall. In the case of the Totnes House, the probes were used in pairs of one 350 mm long and one shorter at 150 mm, inserted into the wall about 100mm apart thus measuring the moisture at two points, close to the inside face of the wall, and towards the outside. This gives the start and end-points of the moisture gradient through the wall.

5.2 Testing of existing probes

5.2.1 Totnes House

A total of 12 pairs of long and short probes were installed at the Totnes House in groups of four, one pair at the top of the wall, and another pair at the base so as to get a picture of the moisture spread both through the wall and from top to bottom.

The moisture content of the timber encased in the probes was measured with a Protimeter ‘Timbermaster’. This is an example of the type of meter previously described that measures the electrical resistance between a pair of sharp stainless steel pins inserted into the timber. The advantage of this meter is that it can be calibrated for different species of timber, and corrections can to be made for changes in temperature. The Timbermaster has a button to select settings for different species groups, and comes with instructions for temperature compensation. It also has a clear digital readout accurate to 0.1%, which compares favourably with meters that use variations on a simple bar graph, like the ‘Timbercheck’ meter that was used in the earlier research in Canada (Jolly 2000).

The probes, installed as the Totnes house was completed, were used to monitor the house over a period of seven months from November 2006 through to May 2007. During this period the probes were giving figures of between 10% on the interior side of the wall and 13.7% on the exterior for the moisture content of the straw. According to the literature, the moisture content of the straw in the walls could be expected to be within a range of 12% to 17%, and compared to the figures from the monitoring of straw bale houses already published (Fugler 2000), the results from this initial monitoring are lower than expected. Looking at published isotherms for straw and relating them to the figures for the internal and external RH confirms this (Hedlin 1967; 2000; Jolly 2000; Stromdahl 2000; Minke and Mahlke 2005; Straube 2006).

5.2.2 Straw bale cabin

Similar examples of the Goodhew probes had also been installed in a straw bale cabin constructed by Carol Atkinson in West Yorkshire (UK). Single probes at 350 mm long were embedded in the walls of each of the three rooms in the cabin, to read the moisture levels towards the outside edge of each wall.

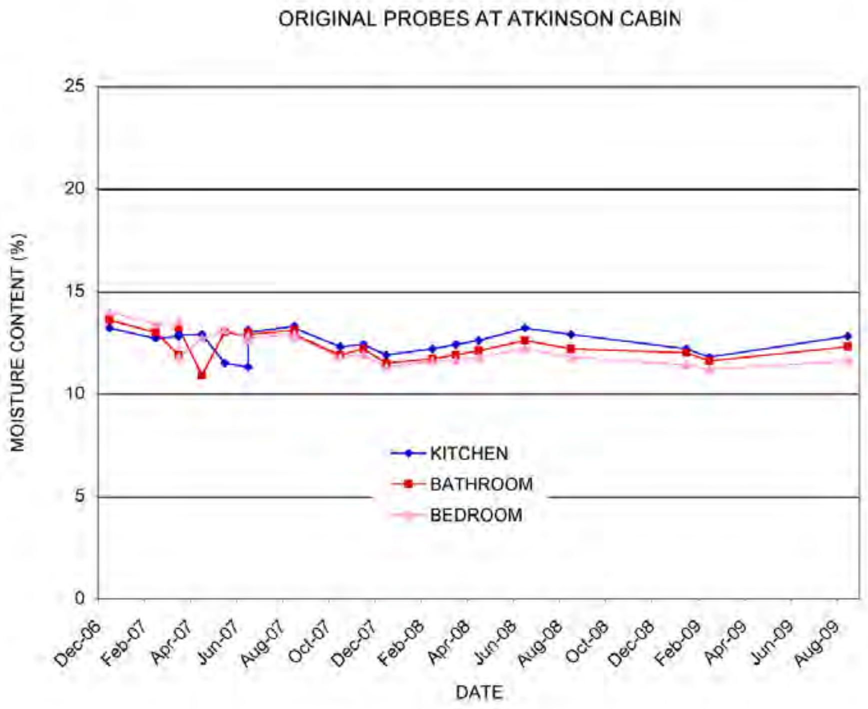


Fig.21 Readings from Goodhew probes in straw bale cabin.

Over the two and a half years that the probes have been installed, the readings (see fig.21) from the three probes installed in the kitchen, bathroom and bedroom have shown a fairly consistent level of moisture, with an overall average of just under 12.5%. This result is consistent with the readings from the Goodhew probes at the Totnes house, and again, is lower than might be expected.

5.2.3 Compare probes to ‘‘Balemaster’’

Practical confirmation of the discrepancies between the moisture levels being recorded by the original probes and the theoretical figures came in March 2007 with the acquisition of a Protimeter ‘‘Balemaster’’. This device is an adaptation by Protimeter of their Timbermaster moisture meter (the same model that was already being used to measure the original probes), but instead of a pair of pins designed to be pushed into timber, the meter is attached by a cable to a separate 600 mm long, 10 mm diameter, stainless steel rod with a pointed tip that can be pushed into the centre of a straw bale, and records the moisture by measuring the resistance at the tip of the rod, which has its last 20 mm separated from the rest of the rod by a 10 mm section of plastic. The ‘‘Balemaster’’ is calibrated to work with wheat straw and although the manufacturers confirm that it will work with oats and barley, there is no calibration supplied for the different types of straw.

A series of readings were taken with the ‘‘Balemaster’’ at the same locations as the original probes, and the results are shown in Fig.25

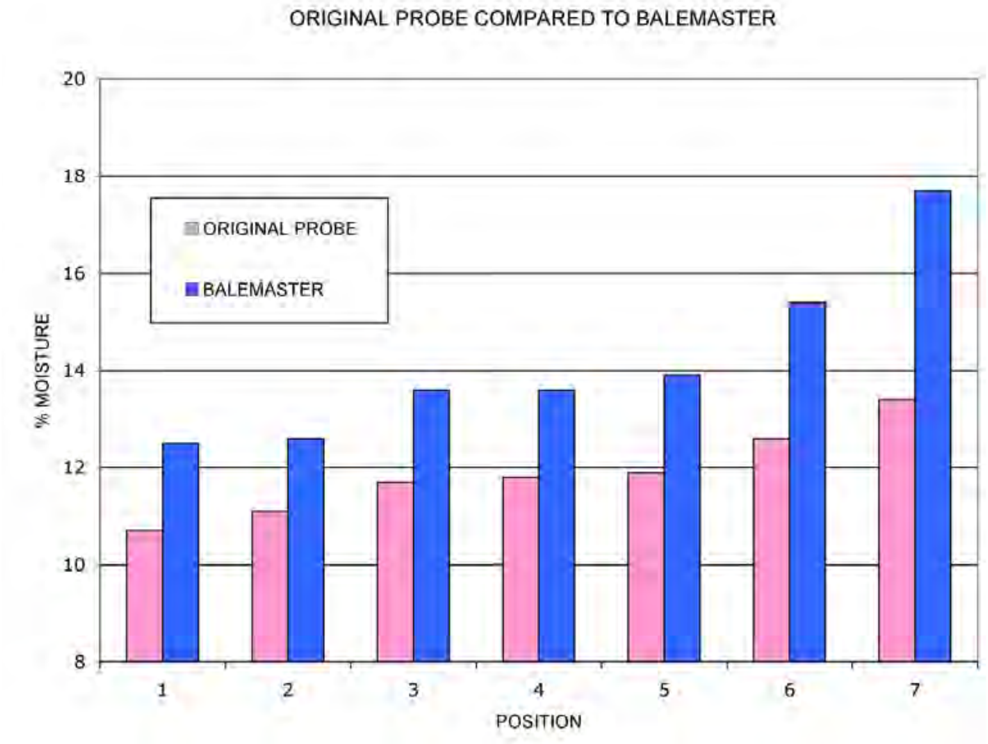


Fig.22 Comparing the original probes with the "Balemaster"

These measurements were taken at seven different locations through the house and are arranged according to the moisture content at each site. When the original probes are compared with the "Balemaster" the results are consistent, with the percentage of difference increasing from around 14% to 24% at the highest moisture content.

Change in section order, 5.2.4 has been swapped with 5.2.5 to introduce 'Balemaster' before description of calibration.

5.2.4 The 'Balemaster' in use

The 'Balemaster' consists of a 600 mm long stainless steel probe attached to a separate meter (see Fig.23, below). The probe has a diameter of 10 mm and a sharp pointed tip to facilitate insertion in dense bales of straw. The 20 mm end section with the pointed tip is separated from the rest of the shaft by a nylon collar. The measurement of the electrical resistance is taken between the tip and the rest of the shaft, which means that the Balemaster is recording the moisture content of the straw at the end of the probe. The electrical resistance is translated by the attached meter, and displayed as the percentage of moisture content of the straw on a dry basis.

Fig.23 Balemaster probe with attached meter

The ‘Balemaster’ was prepared by marking off the 600 mm long probe at 50 mm intervals starting at 100 mm from the tip, as shown in Fig.23 above. This could then be inserted into a straw bale wall through an individual hole drilled through the interior plaster (sealed with a cork bung when not in use) and propelled through the wall at predetermined intervals. When the ‘Balemaster’ was inserted up to the line at 100 mm from the tip, it would be recording the moisture content 70 mm into the straw in the wall (allowing for the 30 mm render).

In practice it proved hard to get consistent measurements at 100 mm, possibly because the straw this close to the inside of the wall had too low a moisture content to be read accurately. Therefore measuring started at 150 mm (120 mm into the straw) and continued at 50 mm intervals until the probe reached the far side of the straw in the wall at 350 mm, as shown in Fig.24 below.

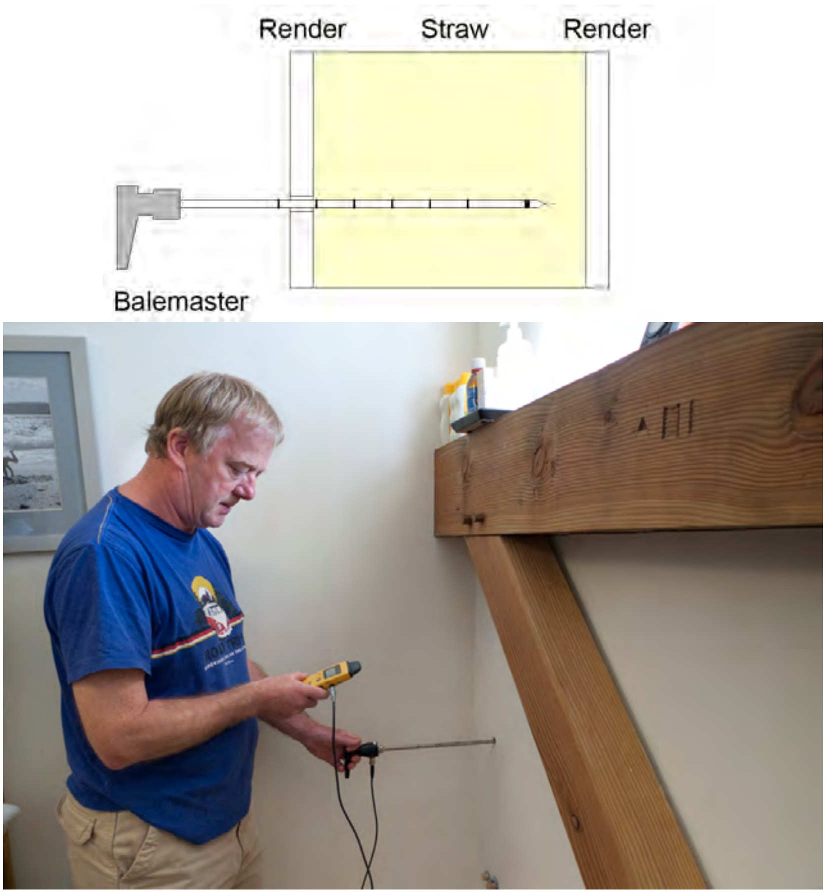


Fig.24 Diagram and photograph of 'Balemaster' in use

In order to get a more detailed picture of the moisture content of the walls an array of holes were drilled through the interior render of each of the rooms being monitored. Seven holes were drilled in a vertical line, 400 mm apart, starting at the base of the straw wall and ending up at a height of 2400 mm.

5.2.5 Calibration of ''Balemaster''

The printed instructions for the ''Balemaster'' state only that it is calibrated for wheat straw, and has a measurement range of 8.5% to 40% (GE_Sensing 2006). In practice the actual maximum it will measure to is 36.8%, and this was the same for another example of the probe when tested. A phone conversation with a technical representative of Protimeter confirmed that the 'Balemaster' recorded moisture content on a dry basis, but yielded no further information on the original calibration process or why the maximum reading was limited to 36.8%. A possible explanation is discussed in section 6.9 of this thesis.

The only reference to the use of a ‘Balemaster’ that has been found in the literature is in the form of a message from David Eisenberg (co-director ‘Development Center for Appropriate Technology’) on the Global Straw-bale Building Network (GSBN). This message discusses the accuracy of the ‘Balemaster’ and a similar device made by Delmhorst. Eisenberg describes how the readings from both devices varied according to the density of the straw, and states that an attempt was made to calibrate them, but that the results were not published.

In the light of this limited amount of technical information, coupled with the stated concerns over the accuracy of the probe in different densities of straw, it was decided to do a calibration of the ‘Balemaster’ using the same straw that was used in the construction of the Totnes House. The bales used were sourced from a farm close by in south Devon and the baling machine was adjusted to give a ‘metric’ bale which measured 0.36 m x 0.5 m x 1 m. The bales had an average weight of 21 Kg, which gives a density of 116 Kg/m^3.
In order to calibrate the ‘Balemaster’ over a range of densities a box with a lid that could be compressed into it was built (see Fig.23). This would enable a known weight and volume of straw to be compressed to a range of different densities.
The box had internal measurements of 142 x 321 x 44 mm, which gives a volume of .02 m^3. A series of holes were drilled into each side of the box to enable the ‘Balemaster’ to be inserted from all sides.
A sample bale was made up to weigh 1.91 Kg, and to fit closely in the box. This had been worked out as the size and weight that when compressed in the box to the level that the lid of the box was flush to the top, the density of the straw at

that point would be 116 Kg/m^3, to match the density of the bales used in the house. Before the sample bale was inserted in the box it was measured, weighed and moisture readings taken with the ‘Balemaster’.

Fig.25 Box with straw before compression

The sample bale was inserted into the box and the lid positioned ready for compression as shown in Fig.25. Some small voids between the bale and the interior of the box were unavoidable, so these were recorded and the final volume measurements adjusted accordingly. The lid was compressed into the box at measured intervals, and a series of readings taken with the ‘Balemaster’ at each stage.

Fig.26 Box with straw fully compressed showing 'Balemaster' inserted

The 'Balemaster' was inserted through the holes in the box and moisture content was recorded at 50mm intervals. An average of the readings from the central area of the straw was used, and the following table shows the results

Level of compression	Density (kg/m^3)	Average 'Balemaster' reading %
Loose bale	68.4	12.2
Lid + 10mm gap	95.2	14.7
Lid half down	108.7	15.8
Lid Flush	118	16.0
Lid -10mm	129.1	16.3
Lid - 20mm	142.5	16.6

Table.4 Results of 'Balemaster' calibration

On completion of the readings the mini bale was taken apart and three smaller samples of straw were teased out and placed in aluminium trays to be weighed and then oven dried at 105ºC for gravimetric analysis. After a series of weighings over 48 hours the straw had reached an oven dried equilibrium of +/- 0.1% of total mass as defined in EN ISO 12570 (2000b). The rate of drying demonstrated by the straw is shown in Fig.27 below.

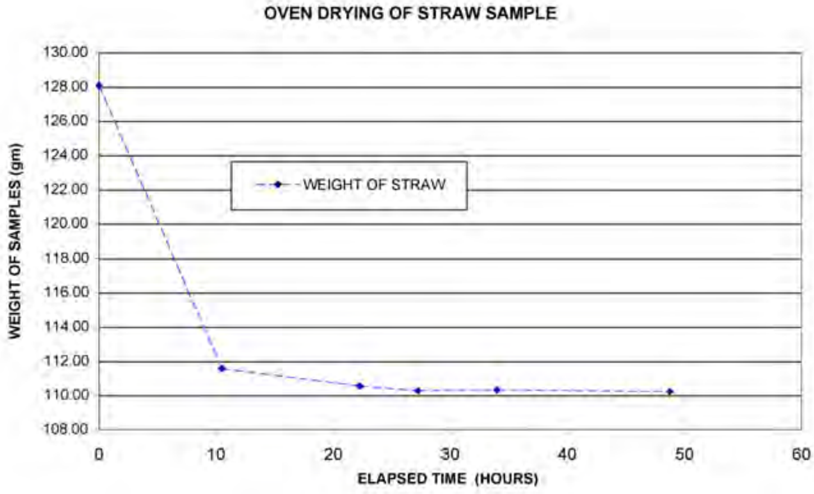


Fig.27 Time taken for straw to dry in an oven

Subtracting the dry weight from the wet weight of the straw gives an average moisture content of 16.2%.

Comparing the 'Balemaster' measurements with the gravimetric analysis (see Fig.28 below) we can see that the actual moisture content of the straw of 16.2% indicates that the 'Balemaster' is most accurate with straw at a density of 124 kg/m^3, which falls within the normal range of straw densities found in construction bales of 95 - 140 kg/m^3 (Jones 2007). Within this range of densities the 'Balemaster' displays an accuracy of +/- 1.5%. After some practice in the use of the 'Balemaster' as a tool to survey the straw bale walls of different buildings, an experienced user can make their own adjustments to the readings as the difference between these densities can be clearly felt when inserting the probe. At lower densities of 95 – 110 kg/m^3 the probe of the 'Balemaster' can be inserted easily with one hand. At medium densities of between 110 – 120 kg/m^3 the probe is appreciable harder to insert and from 120 to 135 kg/m^3 some body weight is needed on the handle of the probe to force it in. Above 135 kg/m^3 considerable force is needed, and it can sometimes be difficult to withdraw the probe. These differences were mirrored when using the probe to measure the straw in the calibration experiment.

The straw used in the Totnes House originally came from a bale at a density of 116 kg/m^3, which means that in the context of the Totnes House, we can assume that the 'Balemaster' will under-read by 0.25%, which is not significant.

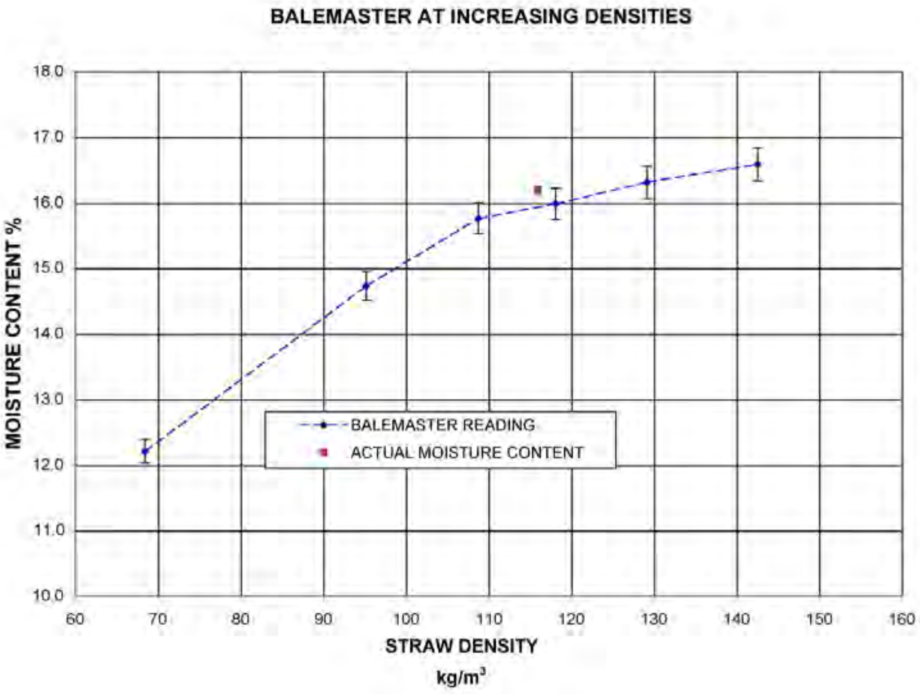


Fig.28 'Balemaster' readings at increasing densities

5.3 Development of improved probe

It seems clear from the comparison between the calibrated 'Balemaster' and the original probe shown in Fig. 22 (section 5.2.3) that the probes are under-recording the moisture levels in the walls. Assuming that the basic principle of using a piece of timber to mimic the moisture content of the straw is valid, the inaccuracy of the original probes could be caused by two different factors; the design of the probe, or with the species of timber used.

Looking at the original probe, it has been designed to keep the timber disc physically separate from the straw by shrouding it behind the perforated tube. This allows the disc to adsorb moisture from the air in the tube, not directly from the straw. This should work, because in theory the air in the tube would be at equilibrium with the straw surrounding it, and the argument behind the probe is based on the timber having the same hygric properties as the straw. However, if it is possible that the perforated tube surrounding the timber disc is affecting the relative humidity of the air next to the disc, then that could be one explanation of the inaccuracies found in the original design.

The other variation in the design to be considered is the effect of using different species of timber. Previous research at Plymouth had compared the performance of Douglas Fir, Beech and European oak in the original probe design (Bryant 2004), and found that European oak discs performed best when compared to straw, at a moisture content of 17%. This research will continue this comparison by comparing the results of different timber species alongside that of straw in an environmental chamber over a complete range of moisture contents.

5.3.1 Comparison of different design prototypes

In order to explore the hypothesis that the perforated tube is effecting accuracy, a series of prototype probes were made using oak as the timber. Two tubes were created with different versions of a shroud to keep the timber away from direct contact with the straw, but each one removing an element of separation between the timber and straw. A third was built that allowed the timber to have direct contact with the straw. The first probe has a simplified version of the original perforated tube, but made shorter, and with larger holes, so the timber disc is exposed to a smaller volume of air, and the ratio of closed space to open space (through the wall of the tube) is greater. The second probe still has a shroud, but it is simply a short extension of the tube, just keeping a physical separation between the timber and straw whilst still allowing a minimal separating air space. The third prototype changes the timber disc into a bullet shaped projection at the end of the tube that will force the timber into direct contact with the straw (Fig.29).

There are examples of timber being placed in a straw wall during the construction phase to measure the moisture content through direct contact with the straw (Lacinski 1998). The difference here is that the prototype probe with the bullet tip can be inserted into a wall at any time, and could also be removed and re-used without any damage beyond the necessary hole drilled in the interior finish of the wall prior to insertion (Carfrae, de Wilde, Littlewood, Goodhew and Walker 2011).

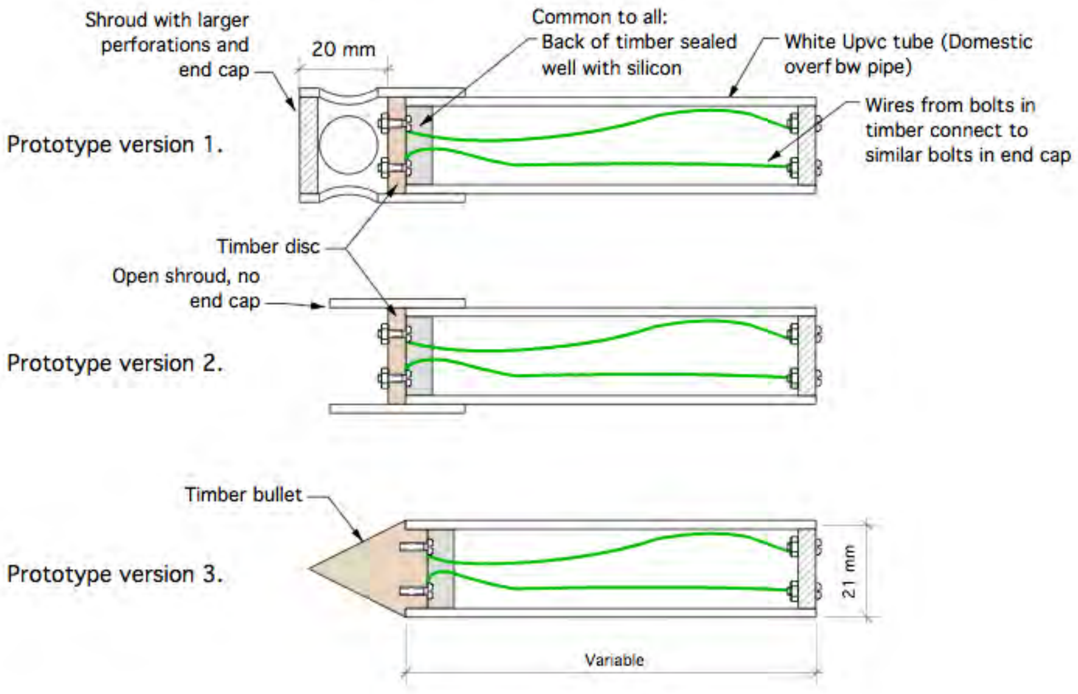


Fig.29 The three variations of the prototype timber block probes

The three prototypes were inserted into a section of the external straw bale wall of the Totnes House. Holes just large enough for the probes were drilled through the internal render along a horizontal line spaced about 100 mm apart. Alongside them a further two holes were drilled to allow the ‘Balemaster’ and a TES RH meter to be inserted, and finally, one of the original Goodhew probes was added to provide a reference for the measurements.

5.3.2 Testing the prototypes

The three prototype probes had been kept in the stable environment of the interior of the house for ten days before being installed in the wall of the Totnes House to allow them to settle at the relatively low internal RH of 50%, which meant that on insertion they would all be starting with the same moisture content of about 12%. Measurements with the ‘Balemaster’ of the interior of the wall showed that the moisture content of the straw was 15%. After insertion, the moisture content indicated by the probes was measured at 24 hour intervals.

After 20 days the readings from the probes had stabilised to within >0.5%, indicating that they had had long enough to reach equilibrium with the straw, and the following table shows the moisture content indicated by the different probes:

Original probe.	10.9%
First prototype (vented shroud).	13.4%
Second prototype (open shroud).	13.0%
Third prototype (bullet tip).	14.0%
Protimeter ‘Balemaster’	15.0%

As the accuracy of the ‘Balemaster’ had already been established it was used as a reference to compare the results from the different prototype probes. The bullet tipped probe was within 1% of the ‘Balemaster’. The other two prototypes were within 2%. The low reading of the original probe is confirmed again.

All the probes recorded lower moisture contents than the ‘Balemaster’. There are potentially two reasons for this; one of them is the hysteresis effect (Kwiatkowski *et al.* 2009). Hysteresis occurs during cycles of wetting and drying where a material will contain less moisture at a given relative humidity during adsorption than is found during desorption. If the straw in a wall is in a process of drying then it will have a higher moisture content than a probe that was previously dry even when they have both reached equilibrium at the same RH. The probe will therefore give a different reading than the surrounding straw, unless it has also been subject to exactly the same moisture history. Taking account of this hysteresis effect has been detailed in the calibration of the timber-block probes.

The other reason for the lower readings could be explained by looking ahead to the isotherms for three different timber species, created in the laboratory at Plymouth, and detailed in section 6.5. It is known that due to their similar physical make up, (Staniforth 1979a) straw and timber exhibit similar moisture behaviour, but as will be confirmed in the laboratory there are variations between different timber species. The laboratory results will confirm that a timber called ramin demonstrates the closest moisture performance to straw.

5.4 Testing the new probes In-situ

Following the completion of the laboratory isotherms, in January 2008 two new probes were installed in an exterior wall of the Totnes House. Combining the laboratory findings, and the testing of the different design prototypes, the new probes were constructed with a bullet shaped tip formed from ramin, fitted to uPVC tubes made up to a length of 350mm.

Fig.30 New probe with Timbermaster meter

When inserted from the inside into the wall, the construction of which consisted of 360mm of straw finished with 30mm of lime render on each side, the length of the uPVC tube would place the timber in the outside 50mm of the straw wall. The probes were inserted at a height of 50mm from the bottom of the wall, which was known to be the area with the highest RH following monitoring with a TES 1365 temperature and RH meter. The test set up is shown in Fig.31 below.

Fig.31 Setup for initial tests of the new probes
The devices inserted in the wall are as follows (L to R):
TES 1365 RH and Temperature meter, 'Balemaster' probe and the two wood block probes. In the foreground is the 'Balemaster' meter, and the Timbermaster meter for reading the moisture content of the timber bullets on the probes.

Prior to being installed one of the probes was moistened until it registered a moisture content of 25.6%, and the other was dried to a moisture content of 10.2%. This was done to see if the probes would show evidence of the hysteresis effect over time in the environment of the straw bale wall. If there were no hysteresis it would be expected that the probes would both show the same moisture content as they reached equilibrium with the moisture in the straw.

The graph in Fig.32 shows the temperature corrected readings from the two probes compared to the 'Balemaster' and the RH during the three months, from January to March, that the probes were installed in the wall. The RH at this location varied between 88% and 90.5%. Referring to the isotherms this would give an expected moisture content of between 20% and 22% on the desorption curve, and between 18% and 20% on the sorption curve. Looking at the readings from the two probes in the wall, the previously wetted one is reading between 20% and 20.5%, and previously dried one is reading between 18.8% and 19.8% (taken from the beginning of March, allowing a period of a month for them to stabilise). This resulted in readings from the probes that are almost exactly within the expected range, but they don't follow the variations in RH as closely as expected.

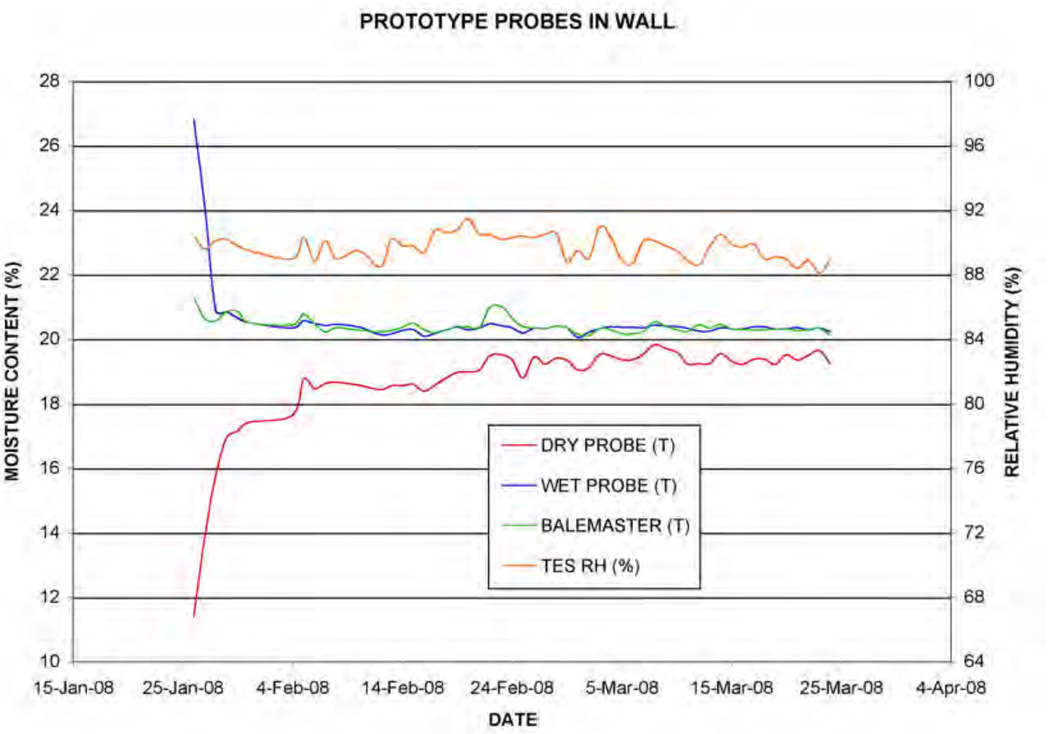


Fig.32 Two new probes compared to the 'Balemaster'

5.4.1 Hysteresis exhibited by the probes

The long term monitoring of the Totnes House had revealed an episode where the moisture levels in this wall had reached 26% (measured with the 'Balemaster') six months before this experiment. Therefore it was hoped that the probe that had been previously wetted to the same moisture content would give similar readings during the period covered in Fig.32. The previously wetted probe and the ‘Balemaster’ shows almost exactly the same readings, with the dry probe following the same variations, but remaining at least 1% lower, which confirms both the accuracy of the new probes in this situation, and that hysteresis appears to be continuing to effect the probes over time whilst inserted in the straw bale wall.

This test was repeated three times over the following months using different samples of the probes, but each time giving similar results.

5.4.2 Probes compared to RH and temperature

In Fig.32 above, it can be observed that the probes are displaying the same moisture content as the ‘Balemaster’, but they do not follow the changes in RH as closely as expected. However the overall accuracy in this situation was encouraging.

The first tests of the probes had been with a pair of probes the same length, installed in a wall with a known history of elevated moisture content. For the next test site the wall of the master bedroom was selected, where monitoring with the ‘Balemaster’ had established that moisture levels of the straw in the wall had stayed reasonable steady.

For this test, the probes were installed in pairs of different lengths in order to get a picture of the moisture gradient through a wall. The shorter probe was made with a tube 70 mm long, which, taking into account the 30 mm of render, placed the bullet tip in the first 50 mm of the straw in the wall. The longer probe had a tube 330 mm long. In practice the ‘Balemaster’ could be used to establish the actual depth of straw in a wall, allowing the tube for the long probe to be cut to suit.

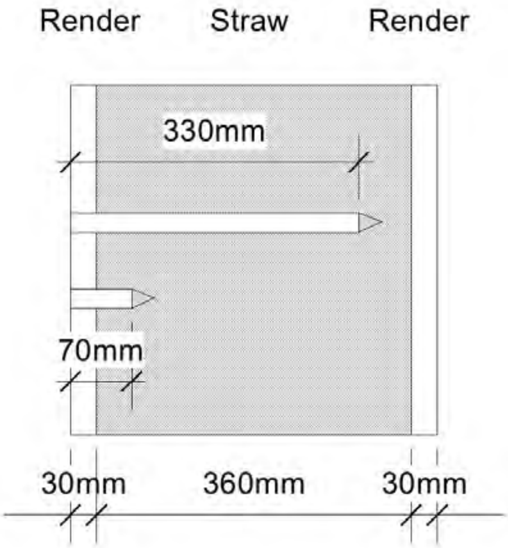


Fig.33 Section through wall showing relative depth of long and short probes

The bullet tips of the probes were pre-wetted to an equivalent moisture content to the straw in the wall, as recorded by the ‘Balemaster’. The probes were inserted in June 2009 with the long probe at 18% and the short probe at 13%.

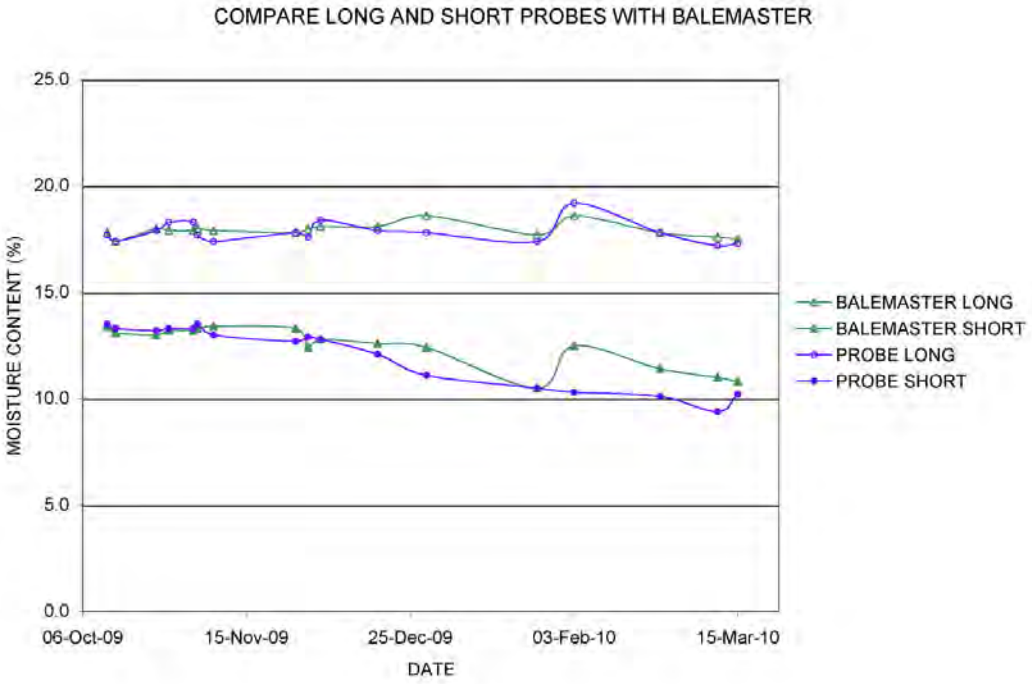


Fig.34 Long and short probes compared to ‘Balemaster’ in the wall of the master bedroom

Fig.34 above shows the results of readings taken at intervals between 12th October 2009 and 15th March 2010. At this point the probes had already been in the wall for four months and had time to settle into their environment. The results of the long probe compared to the 'Balemaster' show a similar level of accuracy to the earlier tests shown in Fig.33, with a deviation of plus 0.8, minus 0.6%. The shorter probe readings were not as close to the 'Balemaster' with a deviation of plus 2.2, minus 0.6%, but it was harder to get a consistent readings this close to the inside of the wall, possibly due to the lower moisture levels.

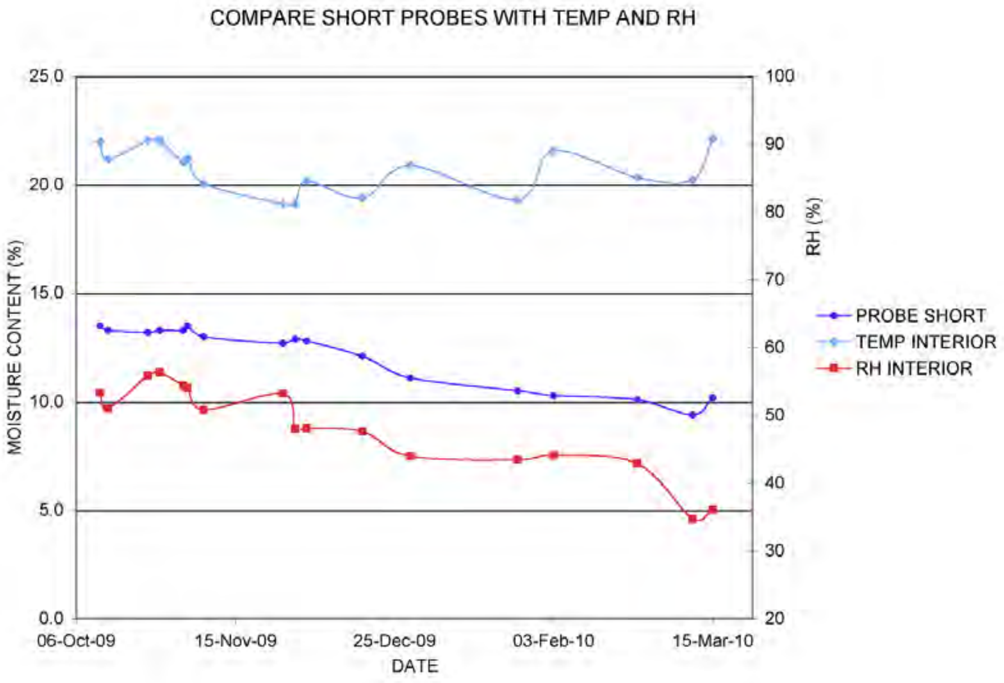


Fig.35 Short probe compared to RH and Temperature readings taken inside the house

In the graph shown in Fig.35, above, the readings from the short probe are compared to the RH and Temperature. The environment inside the house is the main influence on the moisture content of the probe, as it is just inside the interior face of the wall. This is displayed in the graph.

The moisture shown by the probe is gradually decreasing, from 13.5% to 9.4%, roughly in line with the interior RH, which descends from 55% to around 35%. The temperature in the house is not descending, thus it is the RH that appears to be the driver for the changes in moisture content.

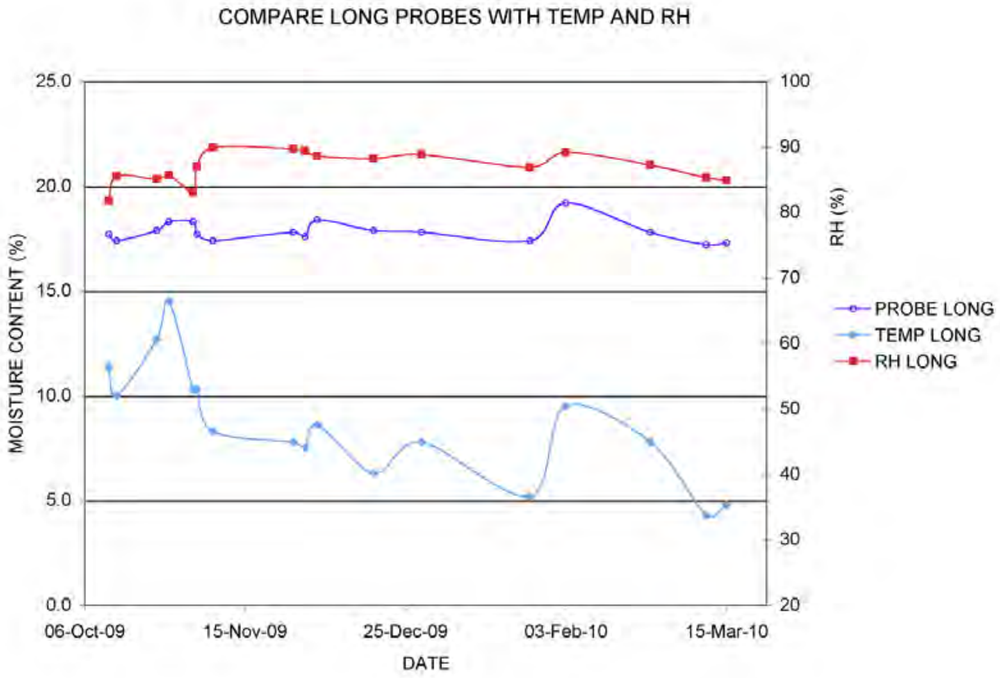


Fig.36 Long probe compared to RH and Temperature readings taken at the same depth

For the long probe (Fig.36), the RH and temperature readings were also made with the TES meter embedded in the wall at the same depth as the probes. In this case, the temperature shows a downward trend, whilst the RH and moisture content appear to follow each other as they did with the short probe. However, during the first two months, the results ran counter to each other, only running parallel from December onwards.

The readings for RH and temperature are relative to each other, in that the RH varies with temperature. Using a psychrometric chart, they can be combined in a figure that gives us the actual mass of the water contained in the air. The graph in Fig.37, below, shows this quantity of water plotted against the moisture content of the long probe.

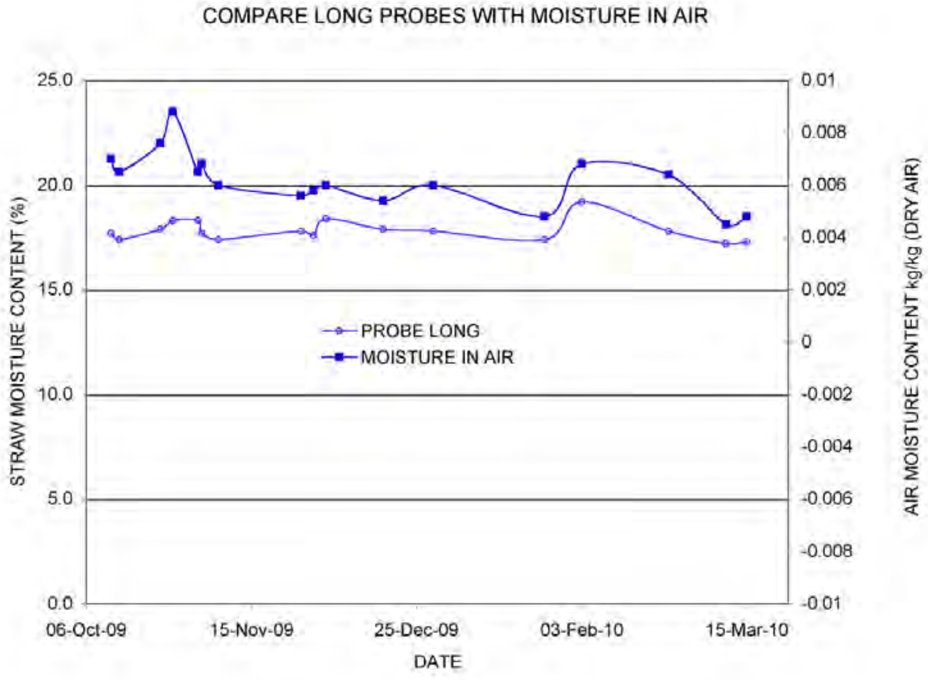


Fig.37 Readings from the long probe compared to the mass of water in the air at the same point.

The trace that describes the moisture content of the air follows more closely to that of the moisture content of the probe. The mass of water in air is analogous to the vapour pressure of the moist air. These results indicate that this might be the factor that has the most direct influence on the moisture content of the probe.

5.4.3 Comparing the use of the 'Balemaster' to the wood block probes

Although it would appear from the discussions in this chapter that the development of the wood block probes is rendered redundant by the efficacy of the 'Balemaster', there are some essential differences.

- The 'Balemaster' is better suited to use as a surveyors tool in that it can be used for on the spot measurements at different locations

- The probes are more suited to continuous monitoring as they can be built into a wall and revisited whenever the schedule demands
- The ‘Balemaster’ is an expensive item whereas the probes can be assembled in large numbers a little cost.

5.5 Summary of chapter 5.

The new wood block probe has been developed through a series of design prototypes. The finished probe has been tested in the walls of the Totnes House.

The ‘Balemaster’ probe has been calibrated against a sample of the same straw at a moisture content of 16%.

The new probe has been used to analyse the hygrothermal relationships in a typical straw bale wall.

6. LABORATORY WORK: ISOTHERMS AND DESSICATOR EXPERIMENTS

This chapter looks at the results of the laboratory work, with a new set of sorption and desorption isotherms created in the laboratory at Plymouth University. As described in the previous chapter, they will be directly comparing the moisture performance of two species of straw and three species of wood. The results are discussed in the context of the use of straw in construction and the development of the new moisture probe detailed in the previous chapter. Experiments investigating the long term effects of elevated moisture levels on samples of straw in the laboratory are analysed and will be compared to the field studies of buildings which have suffered moisture ingress.

6.1 Introduction

There are two methods used to establish an isotherm. According to BS EN ISO 12571 (2000a), the first method involves the use of saturated salts in a desiccator to provide the different levels of relative humidity. This method has the advantage of allowing more than one sample of straw to be tested in different relative humidities at the same time, thus shortening the overall time taken to establish the isotherm.

The second method, which was chosen for this research, involves the use of an environmental chamber. As set out in the ISO, three samples of straw are first dried in a laboratory oven at 105˚C (2000b) and weighed at intervals until all the moisture had been driven off, thereby establishing their dry density. They are then placed in the chamber and at a series of pre-set humidities and again weighed at intervals until they reach equilibrium. If the ‘dry’ weight of the straw is subtracted from this ‘wet’ weight this gives the mass of the water adsorbed at that humidity, and the percentage of water in the sample is ascertained.

The humidity of the chamber can then be increased in steps with each resulting weighing being recorded on a graph to give the adsorption isotherm. Once the environmental chamber has reached its highest humidity setting, the process can be reversed and a desorption isotherm can be plotted and compared to the adsorption curve. The advantage of using this method is that the same samples can be kept in the chamber continually allowing the complete arc of adsorption and desorption to be observed as a continuous sequence.

6.2 Use of environmental chamber

The ISO calls for three samples of each material to be tested, so six samples were prepared for the environmental chamber, three of wheat straw, and three of oat straw. The ISO specifies a minimum mass of 10 grams, and that specimens of materials with a dry density of less than 300 kg/m^3 shall have an area of at least 100 mm x 100 mm.

The samples used for the isotherms measured approximately 100 mm x 200 mm x 300 mm. The 300mm length samples were chosen to allow longer lengths of straw that included nodes and internodes to be included. The samples had a mass of between 100 to 140 grams. The prepared samples had a density of around 15 kg/m^3 compared to a typical bale density of 90 to 120 kg/m^3, as a lower density will reduce the time taken to reach equilibrium. The samples were placed in lightweight aluminium trays that were used to transport them from the laboratory oven to the environmental chamber and the electronic scales.

Fig.38 Samples of straw in the Environmental Chamber

Due to the size of the samples it proved difficult to set up a system whereby the samples could be weighed in the chamber without being moved; instead, the scales were placed on a stand immediately adjacent to the chamber allowing a simple combined process of opening the chamber door, removing the sample, closing the door, weighing the sample and returning to the chamber within 15 seconds.

A test was performed to confirm that the samples were large enough not to be adversely affected by this relatively short change in their environment: A sample was placed in the chamber to reach equilibrium at 90% RH. When the sample was removed from the chamber and placed on the electronic scales, the mass of the sample stabilised within 20 seconds and if left on the scales didn't change mass significantly for another 20 seconds, which represents the time taken to return it to the chamber. The frequent opening of the chamber door did effect the environment inside the chamber, but it would return to equilibrium within about 15 minutes, which was considered to have a minimal effect, as the measurements were performed at a minimum of 24-hour intervals. The consistency of the results shown in Fig.9, and the closeness of the readings for the different samples indicated that the deviation from the published methods was not adversely affecting the accuracy of the process.

6.2.1 Use of saturated salt solution

In order to establish an Isotherm, the sorption process was started at 30% RH and increased in steps of 10% at a time until 90% was reached. After this point the final two steps would be at 95% and 98%, which was the specified maximum RH that the chamber could sustain. Following the stipulation of BS EN ISO 12571, the RH of the chamber was being monitored with two different hygrometers, a TES 1365 and a Solamat, both of whom had been calibrated over saturated salt solutions to confirm their accuracy.

At a setting on the chamber of 30% the readings from the two hygrometers and the chamber were within 1% of each other, but as the RH levels increased discrepancies grew until, at the point where the chamber reached its theoretical maximum of 98%, the two hygrometers agreed that the chamber was under reading by 4.8% This gave the chamber a practical maximum of only 93.2%.

At a RH of 98% moisture content, straw reaches the limits of hygroscopic sorption and approaches its fibre saturation point so it is important to be able to replicate this as closely as possible in the laboratory. Having recalibrated the hygrometers to confirm that the environmental chamber could only condition at a maximum RH of 93.2%, the decision was made to continue the adsorption and desorption in the chamber as a continuous process, and wait till the desorption in the chamber had returned to 30% before taking one of the samples of wheat straw and placing it in a desiccator over a saturated salt solution of Potassium Sulphate (K_2SO_4) which will give an RH of 97.5% at 23ºC, and is the highest RH obtainable using this method (2000a).

Fig.39 Sample of straw in desiccator at 97.42% RH

6.3 Results of the sorption isotherms for wheat and oat straw

Fig.40 shows the sorption isotherms for three samples each of wheat and oat straw and the resulting sorption isotherms up to the highest levels of RH achieved in the chamber (93.2%). It can be seen that the results are very close for each of the straws with little deviation from the average. Compared to wheat the average moisture content for oat straw was very similar through the range up to 90%RH with a difference of only 0.3%, falling slightly at 93.2%RH with a lower value of 22.5% (1.9% lower than the wheat).

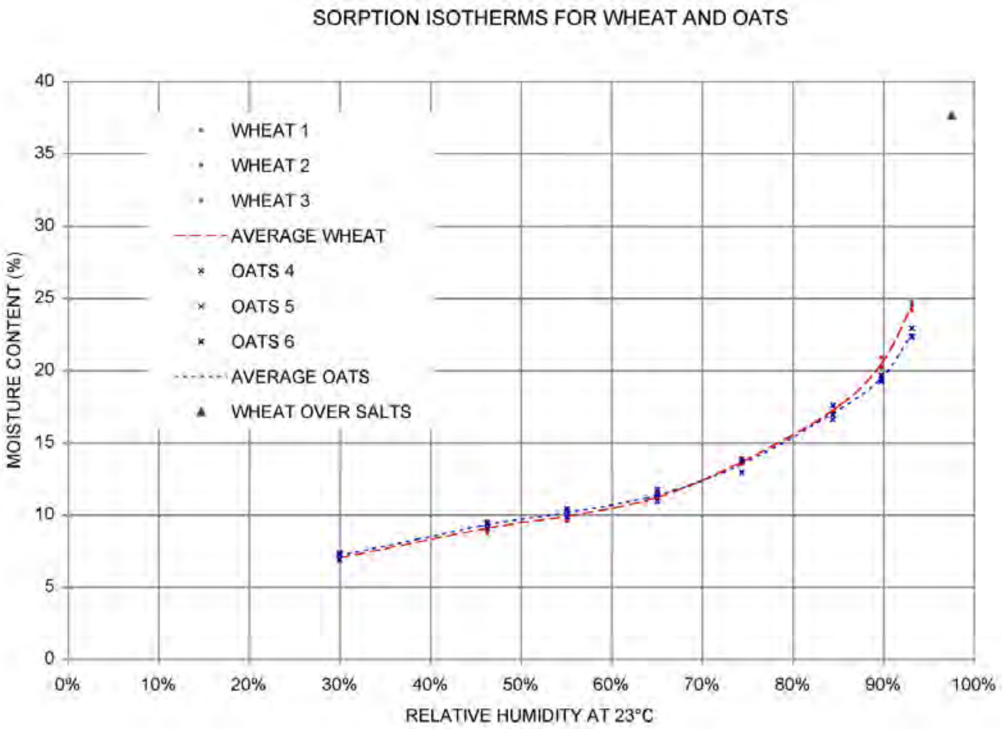


Fig.40 Sorption isotherms for all six samples of wheat and oat straw

6.3.1 Sorption and desorption for wheat straw

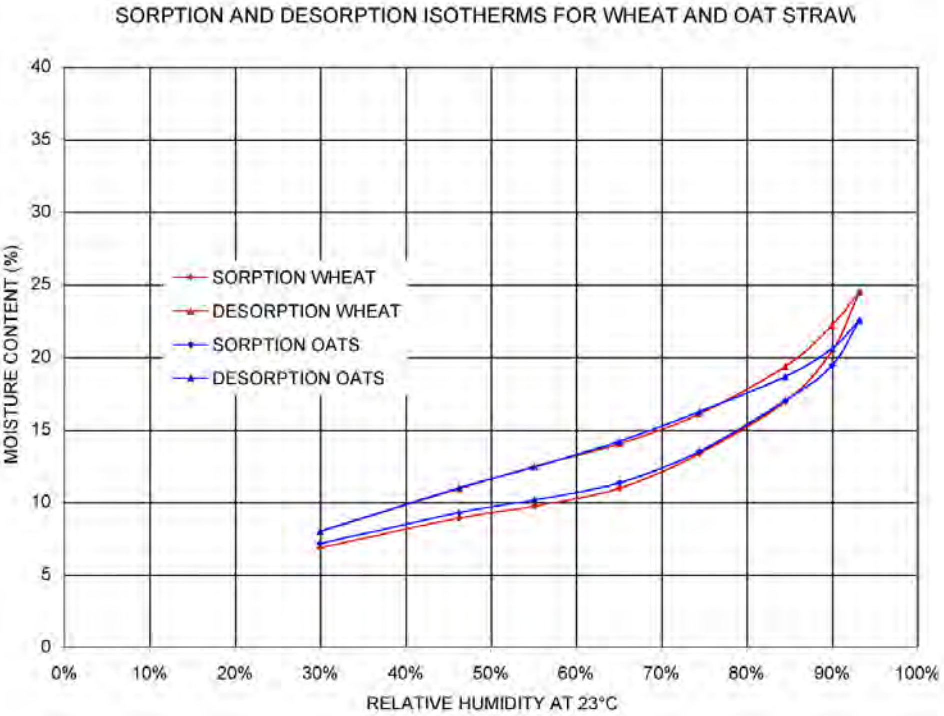


Fig.41 Sorption and desorption for wheat and oat straw

Fig.41 above shows both the averaged sorption and desorption results for wheat and oats.

The complete process of sorption and desorption took five months to complete. The isotherms for wheat straw from the chamber can be combined with the result from the sample of wheat straw kept over a saturated salt solution of K_2SO_4, which achieved a moisture content of 37.6% after nearly four months in the desiccator, to give the sorption and desorption isotherm shown below in Fig.42 . This gives a more complete view of the relationship between moisture content and RH, up to the theoretical fibre saturation point.

Fig.42 Complete sorption and desorption isotherm for wheat straw

6.4 Isotherms and hysteresis

The isotherms shown in Fig.41 and Fig.42 clearly illustrate the hysteresis effect. This was the reason why it was decided to use an environmental chamber to create the isotherms, as it was easier to run the sorption and desorption as a continuous process, as compared to moving the samples over different salt solutions.

The significance for this research is that any measurement of the moisture content of a sample of straw in a straw bale wall will be influenced by the moisture history of that straw. If the straw has had a higher moisture content in the past, then it will display a higher moisture content at the point of measurement than if it had previously contained less moisture.

6.5 Isotherms for different timber species

At the same time as the creation of a new set of sorption isotherms for straw, samples of pine, European oak and ramin, three distinctly different timber species, were placed in the environmental chamber alongside the straw samples to create isotherms for direct comparison with the straw. The three species were chosen for the following reasons; pine, because this was the timber used in the first Canadian probes, European oak as it was used in the original Goodhew probe first installed in the Totnes House and ramin, a hardwood from south-east Asia was chosen because it was firstly a relatively light and open pored hardwood, and the assumption was that these attributes would help make the timber more responsive to changes in RH. Secondly because ramin is used in the manufacture of broom handles and dowel sold by construction material suppliers that meant that round lengths of timber of the same diameter of the uPVC tube used for the body of the probe could be bought ‘off the shelf’. This made it much easier to form into the bullet shaped tip decided on for the improved probe.

6.5.1 Results of timber isotherms

Fig.43 compares the three timber species with wheat straw. Showing only the section of the sorption curves from 45% upward, it omits desorption to make it easier to compare the different traces.

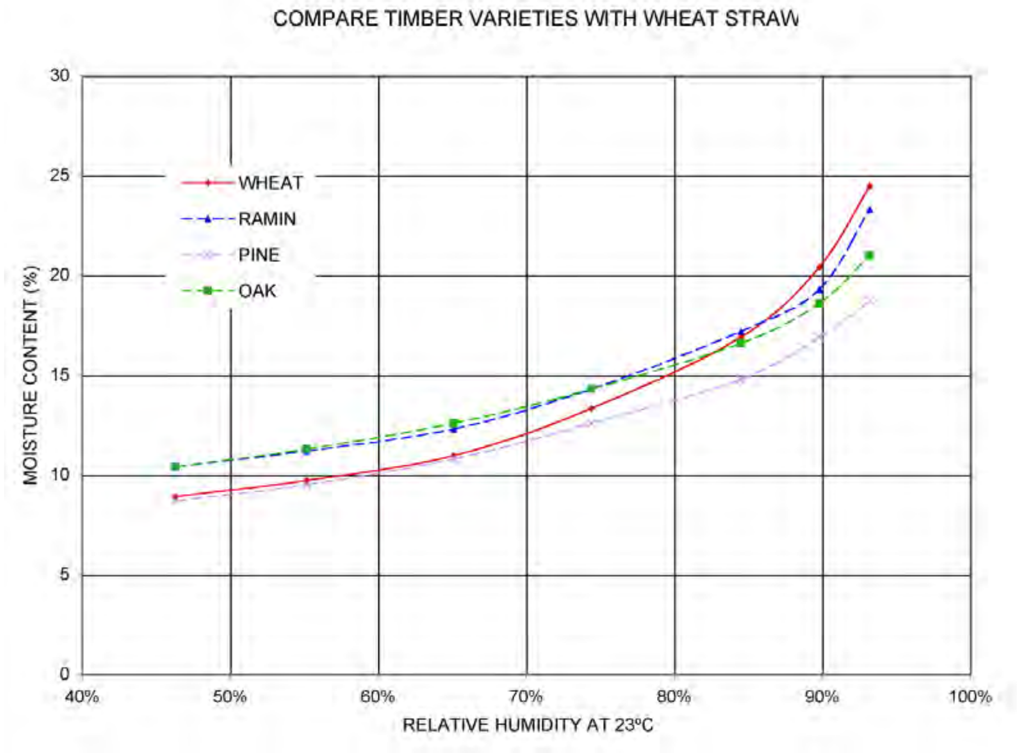


Fig.43 Section of sorption isotherms for three species of timber and wheat straw

By comparing the performance of the different timber species with the wheat straw it can be seen that none of the species has the same development as the straw, but because this research is more interested in the behaviour of the straw at RH values higher than 80%, it can be seen that ramin is the closest to the wheat. This is especially the case at the highest RH where the difference is 1.1% at 93.2%

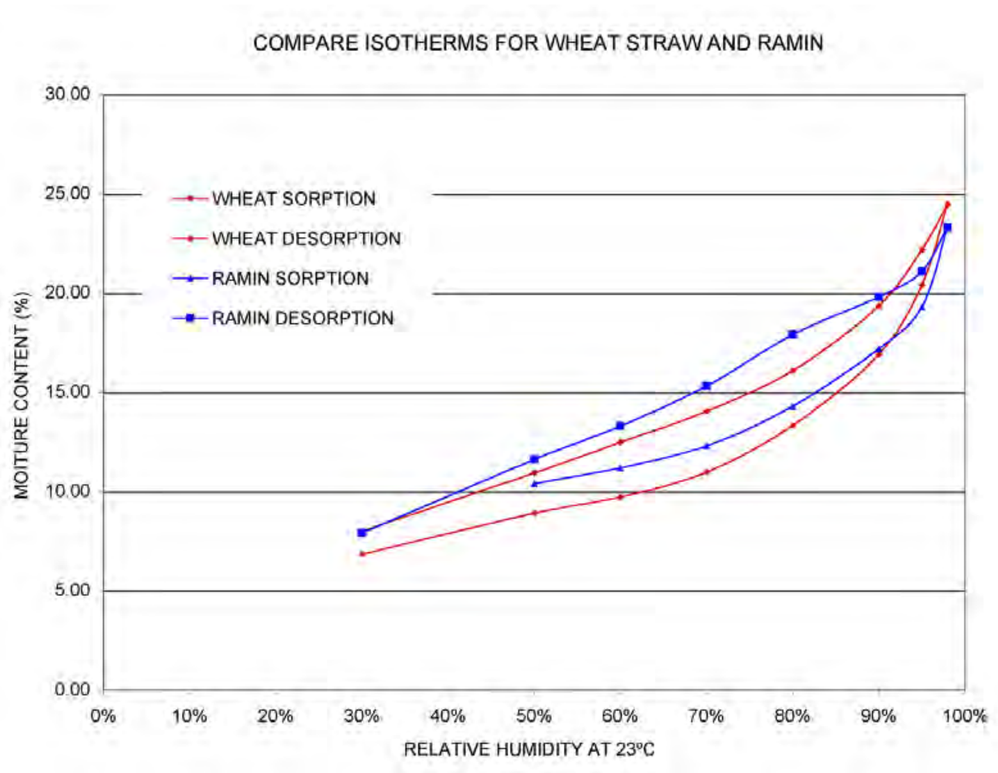


Fig.44 Adsorption and desorption isotherms for wheat straw and ramin

The isotherms for wheat straw and ramin do not coincide exactly. The greatest deviation is between 70% and 85% where the ramin shows a higher moisture content than the wheat. In practice this means that the finished probe will give a slightly higher moisture content reading at these levels of RH. In terms of providing a warning system for elevated moisture in the straw bale walls, this is better than if they gave a lower reading that the straw. The results in the crucial region where moisture content exceeds 20% are much closer.

These results were considered close enough to inform the choice of ramin to be used as the variety of timber in the new probe design that will go on to be tested in the walls of the Totnes House

6.6 The long term effects of continuous high RH levels on straw

6.6.1 Mould growth on straw at 97.6%

As has been discussed earlier in this chapter, in order to complete the sorption isotherms, a sample of wheat straw had been placed in a desiccator over a solution of Potassium Sulphate (K_2SO_4) in order to calculate the moisture content of the straw at a constant RH of 97.59% at 20˚C (EN ISO 12571, 2000b)

The straw had been in the desiccator from 21st of January until the 15th April 2008, a period of just under four months, before it reached its equilibrium moisture content of 37.62%. During the main part of this period the straw remained visually the same, no indications of microbial activity were observed until the end of March, and it was only during the last two weeks of the experiment that mould could be seen growing on the straw as shown in Fig.45 below.

Fig.45 Mould growing of straw after three months at 97.6% RH

During the process of surveying the different case study buildings (covered in later chapters), it was possible to visually inspect straw that had been at equivalent high moisture contents for prolonged periods of time whilst installed in walls protected by lime based renders. The high moisture content of the straw in all these cases could be traced to faults in the detailing of the buildings. Straw in a properly constructed lime rendered wall would not be expected to exhibit moisture levels above 20%. In none of the cases where the straw had been in a moist wall was there an obvious visual sign of microbial activity apart from discolouration, no visible moulds of the sort illustrated in fig.45 were recorded.

This prompted the question, to what extent is the lime in the render inhibiting mould growth? Microbial activity requires oxygen as well as moisture, and there is less oxygen available within a rendered wall, so the presence of lime would not be the only inhibitor to mould growth in the wall, but to try and asses the impact of lime alone a simple experiment was set up to observe the long term effects of moisture on selected samples of straw in different relationships to lime render

6.6.2 Desiccator experiment

This experiment was set up as an adjunct to the main research done in the laboratory, and was initially done out of general interest. There are no published standards for these tests, and only the single iteration of each set up was used. This may be insufficient for any firm conclusions to be drawn.

Three desiccators were used for this experiment. The first two desiccators contained three samples each:

1. The first sample was of straw from a fresh bale with no known history of excess moisture, and the straw was clean and golden in colour.
2. The second sample was from the straw that had previously been used in the isotherm experiment and had already displayed evidence of discolouration and mould growth. The sample had since dried back and

there was no longer any visible mould, but the straw had stayed slightly darker than the fresh straw.

3. The third item in the desiccator was a carefully constructed facsimile of a rendered straw bale wall. A section from the fresh bale of straw was cut out and restrung to retain density. It was covered in a coat of lime plaster (3 parts fine sand to 1 part lime putty) to a depth of 15 mm. The result was a rounded object measuring about 200 mm long by 100 mm diameter

The contents of one of the two desiccators can be seen in Fig.46 below

Fig.46 Desiccator containing two samples of straw with lump of plastered straw

The contents of the first of these two desiccators were suspended over a concentrated solution of sodium chloride (NaCl), to give a RH of 75.47% at 20˚C. This represents what would be an expected internal RH in a straw wall in this temperate maritime climate. The straw at equilibrium with this RH would have a moisture content of around 15%. It is possible that there would be greater evidence of mould growth at higher temperatures than 20˚C, but significantly higher temperatures are unlikely to be found in the walls of buildings in a temperate climate, and are therefore out of the scope of this thesis.

The second desiccator had a solution of potassium sulphate (K_2SO_4), to give a RH of 97.59% at 20˚C. This is the same solution used in the earlier isotherm experiment and represents the highest RH achievable with salt solutions at 20˚C, and the straw would have a moisture content of 37%. The photo below in fig.46 shows the desiccator with a RH meter indicating 97.3% at 24.7˚C, which is correct according to the charts in EN ISO 12571.

Fig.47 Straw samples in desiccator at 97.3% RH

The third desiccator contained the same two samples of straw, one clean, one previously mouldy, but this time without the lump of lime plastered straw. This desiccator was also at 97.3% RH. This desiccator would allow a comparison between straw on its own and straw in combination with lime at the same high RH.

The three desiccators and their contents are illustrated in fig.48 below.

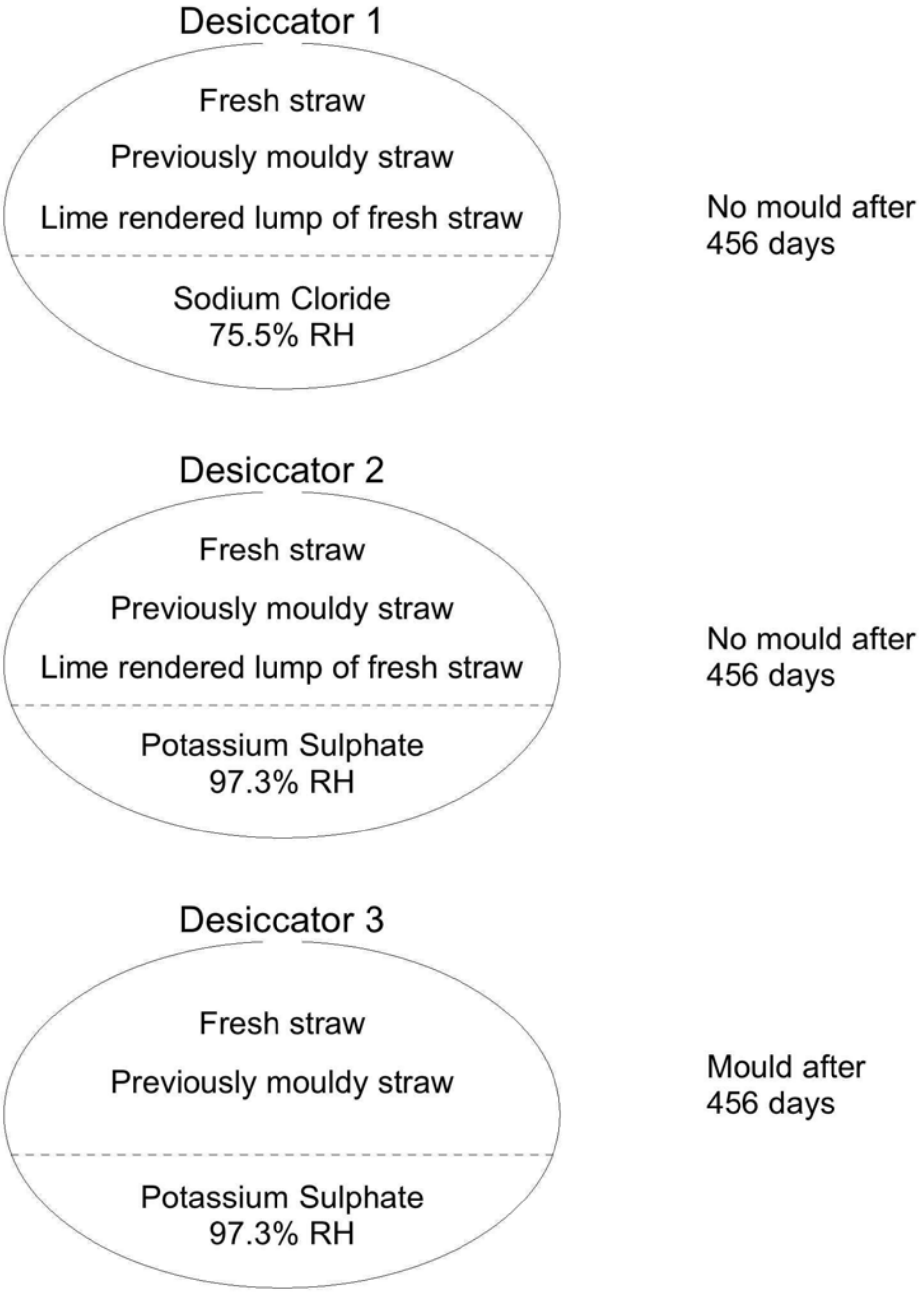


Fig.48 Diagram showing the contents of the three desiccators with their RH levels

The experiment started with the straw samples placed in the desiccators on 5th December 2008, and all three were left undisturbed (apart for visual checking) until the desiccators were opened on 19th March 2010, a period of 15 months. This time span was planned to allow enough time for microbial activity to commence, although it was assumed that this would occur sooner. In fact the experiment was only concluded when mould started to appear on the samples of straw in the desiccator without lime. These were the only samples to display obvious microbial activity

At the end of the experiment the two plastered lumps were broken open to examine the straw inside, see fig.49 below. In both cases the straw was still looking undamaged.

Fig.49 Plastered straw sample broken open

6.6.3 Visual results from the long term desiccator experiment

The three samples of straw shown in Fig.50, below were all from the two desiccators at 97.3% RH, and reading from the left they are:

1. Clean straw from desiccator with lime.
2. Previously mouldy straw from desiccator with lime.
3. Previously mouldy straw from desiccator without lime.

Fig.50 Three samples from desiccators at 97.3% RH

- Sample 1, the straw taken from a fresh bale shows no sign of deterioration despite having been at 97.3% RH for more than a year.

- Sample 2 had previously been growing mould, but there was no visual sign that the mould had been re-growing.

- Sample 3, which is from the desiccator without any lime, is from the previously mouldy straw and is the only sample to show clear signs of mould growth. There was also the beginning of mould growth on the sample of fresh straw from the desiccator without lime.

Fig.51 Straw from inside the lime plastered lumps

Fig.51 above, shows straw from the two lime plastered lumps:

- On the left is the straw that has been encased in a lime plaster and kept at 97.3% RH for 15 months
- On the right is the straw from the lime plastered lump that was kept at 75.5% for the same length of time

Neither of the two samples shows any visual sign of mould growth. The only apparent difference is that the sample from the higher RH is slightly darker, which would be commensurate with increased moisture content.

It is interesting to compare these pictures with an illustration from the desiccator experiments conducted by Lawrence (2009) shown in Fig.51 below, particularly sample no.3 on the right of Fig.51, which is from a desiccator on its own without the ameliorating effects of the lime.

Fig.52 Sample of straw from desiccator at 98% from Lawrence (2009)

The sample of straw shown above was also kept over a saturated solution of Potassium Sulphate (K_2SO_4), to give a RH of 97.59% at 20˚C, but shows a greater level of damage than all the samples from Plymouth. Lawrence states that the straw had swollen with moisture as well as growing mouldy. The sample looks as if it has been in contact with higher levels of RH than the Plymouth samples, but there is no record of this.

Due to the time taken for the experiment, it has not been possible to repeat the tests with other samples of straw, and although it may be difficult to draw conclusions from a single experiment it is notable that none of the samples of straw that were in contact with lime produced any visible mould, whereas both the samples that were on their own, with no contact with lime, showed signs of mould growth. This result was in accord with expectations, as it might be supposed that the presence of lime would inhibit microbial activity, as it is also used in household cleaners to kill and remove moulds from walls and surfaces.

6.7 Rate of change in the moisture content of straw

As a result of performing the sorption and desorption isotherms in a continuous sequence with the same samples of straw throughout, it is possible to get an idea of the speed with which straw reacts to changes in RH.

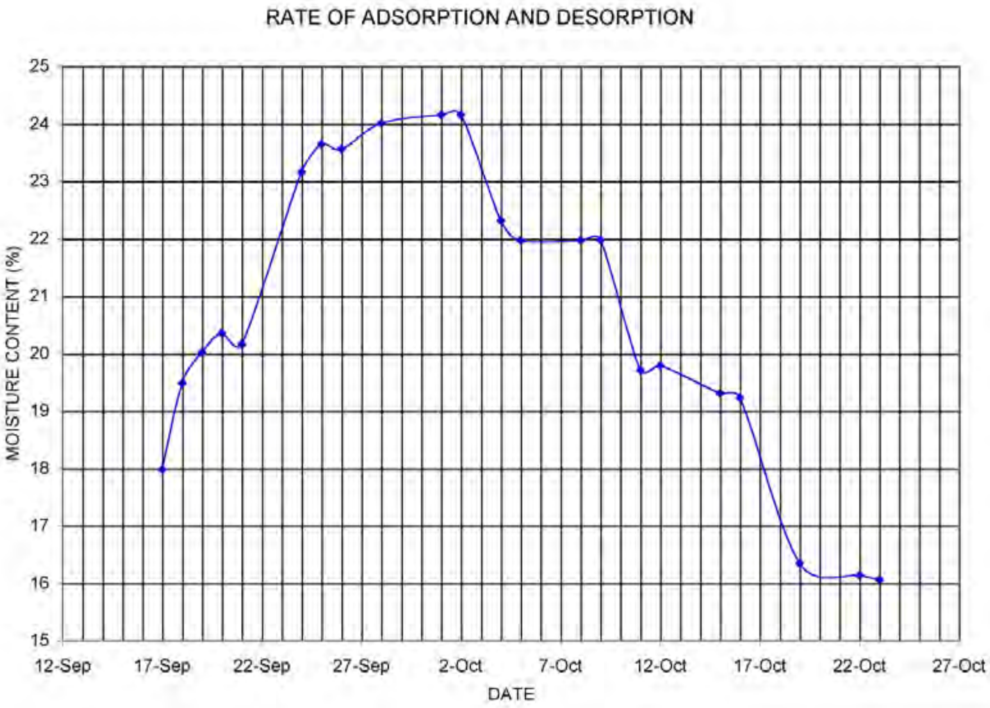


Fig.53 Rate of increase and decrease in straw moisture content. (Average of six samples in environmental chamber, RH not shown)

In Fig.53 above, the level of the moisture content of the straw is reacting to the step changes in RH made to plot the isotherms shown earlier in section 6.4.

The changes in RH are not plotted on the graph.

It is informative to look more closely at the period from 17th September to the 27th September. The changes in RH took place on the 17th when it went up from 85% to 90%, and then on the 21st it increased from 90% to 93%.

At each of these changes in RH, the straw is adsorbing moisture to increase its moisture content. Although this experiment wasn’t set up to track the speed of the changes, a clear pattern is shown, with the straw moisture content increasing more rapidly over the first 24 hours, then slowing as it reaches equilibrium. The pattern appears to be similar for desorption. An approximation of the rate of increase and decrease in moisture content could be said to be in the region of 1% per 24-hour period.

6.8 Hysteresis displayed in an isobar

In earlier sections of this chapter, the isotherms for straw have displayed hysteresis. In the isotherms the changes in RH at a constant temperature have produced results that show the straw retaining a higher moisture content for a given RH during the desorption phase than during sorption.

In this experiment, instead of changing RH at a constant temperature, the same samples of straw were subjected to an increase and decrease in temperature at a constant RH.

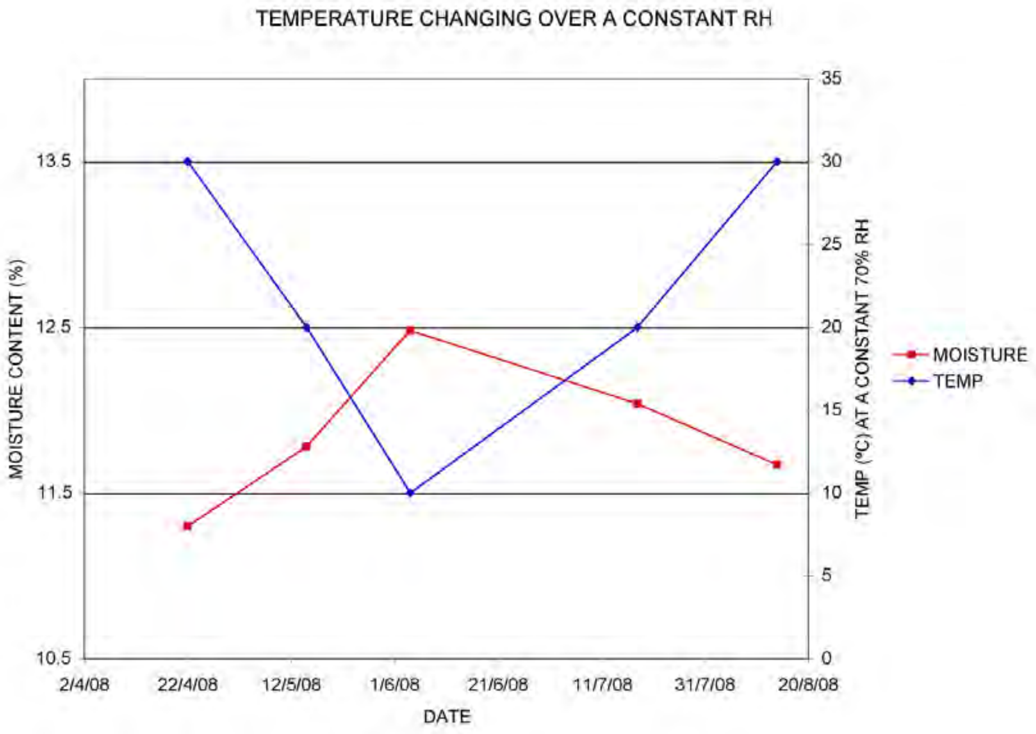


Fig.54 Hysteresis exhibited by straw after change in temperature at a constant RH.

The graph in Fig.54 above shows the effects of this change in temperature. The RH was kept at 70%, and the temperature, starting at 30ºC, was lowered to 20ºC and then 10ºC. The temperature was then returned to 20ºC and then 30ºC. The moisture content of the straw at each change in temperature has been allowed to reach equilibrium (note that the process took four months to complete).

Compared to the changes in moisture content due to changes in RH, the differences in moisture content are relatively small, being less than 1% for each 10ºC, but the moisture content clearly shows the effects of hysteresis, with the moisture content at the end of the cycle being 0.4% higher at the same temperature.

6.9 Analysis of laboratory results

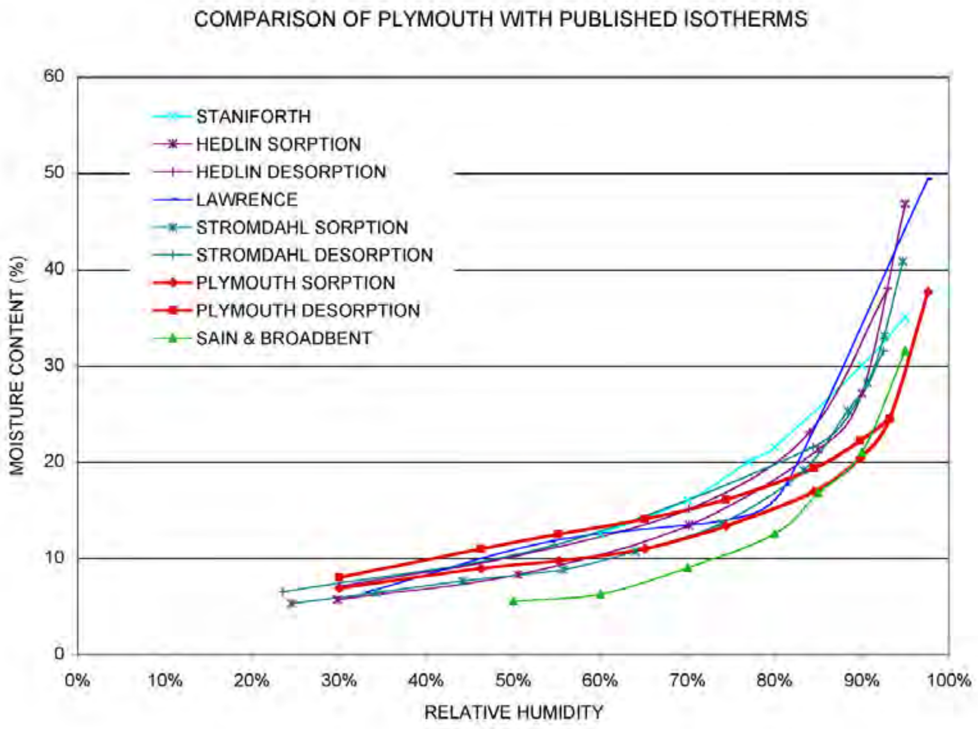


Fig.55 Plymouth results compared to all previously published isotherms

The graph shown above in Fig.55 compares the results from the isotherms created in the environmental chamber in Plymouth with all the previously published isotherms for wheat straw. Also included is the isotherm from Sain and Broadbent, which was for rice straw and therefore not directly comparable.

The isotherms all show a broadly similar development up to 60%, but after this point the results from Plymouth show a clear deviation from the others, with lower results for both sorption and desorption. The most pronounced difference is in the area between 90 and 93 % where the Plymouth isotherms are around 15% lower than the general trend, which results in a more pronounced ‘hockey stick’ curve.

No explanation is presented for this anomaly, but the differences between the Plymouth methodology and the previously published isotherms can be summarised as follows:

- The Plymouth isotherms were performed in a continuous sequence of sorption and desorption with the same samples throughout
- The Plymouth samples were larger, and the straws were left at 300mmm long. All the published isotherms involved cutting the straw into shorter lengths that would result in higher ratio of cut ends, which could affect sorption.

The isotherms published by Lawrence (2009) and Hedlin (1967) are the only previously published isotherms that have results above 95%, and both have a maximum moisture content higher than Plymouth. Lawrence gives a figure of 49.34% at 97.6% and Hedlin achieved 77% at 97.5% RH.

The maximum moisture content achieved at Plymouth was 37.4% at 97.5% RH. This represents the fibre saturation point of the straw, the point at which the capillaries and pores are full of water, but there is no free water in the straw. It is interesting to note that the ‘Balemaster’ probe has a similar maximum reading of 36.8%. It can be speculated that the manufacturers chose this upper limit as representing what they considered to be the fibre saturation point of wheat straw. Protimeter, the manufacturers of the ‘Balemaster, were a British company but are now part of GE Sensing, who are American. Communication with Protimeter failed to get an answer to this and other questions, the reason given that the original research and development material was lost during the move to GE Sensing.

6.10 Comparison of laboratory results with in-situ readings

In the development of the improved woodblock probes, readings from the woodblock probes were compared to readings from the 'Balemaster' probe at the same place in a straw bale wall. The Balemaster had previously been calibrated against a sample of the same straw, and was found to be accurate to within +/- 1.5%. The results showed a strong consistency between the readings from the woodblock probes and the 'Balemaster', shown in Fig.56 below.

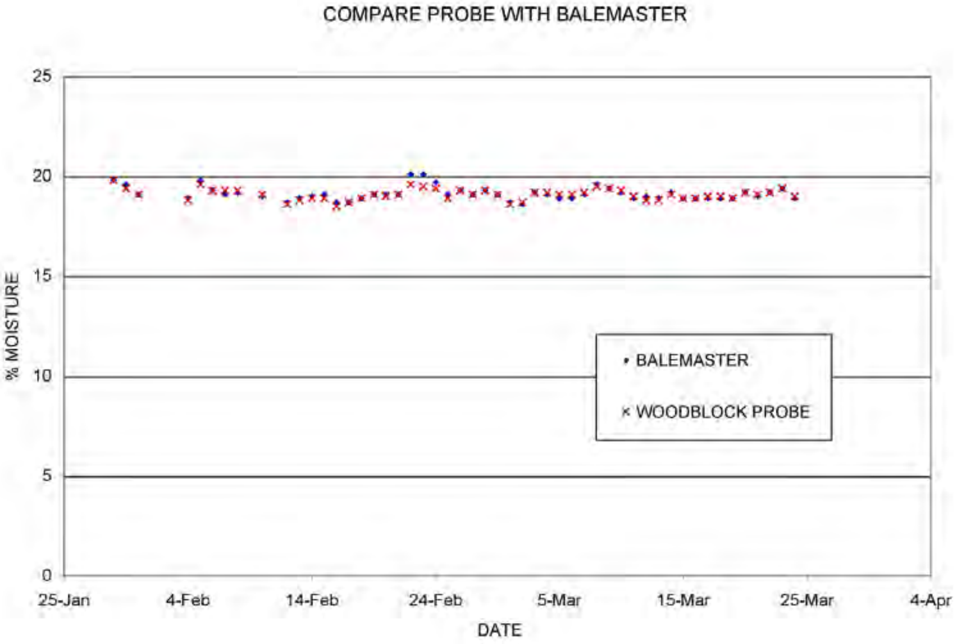


Fig.56 Comparison between readings from the woodblock probes and the 'Balemaster'

These results have helped to establish the consistency of the results from in-situ measurements by the different probes. What hasn't been shown is the relationship between the in-situ readings and the laboratory results

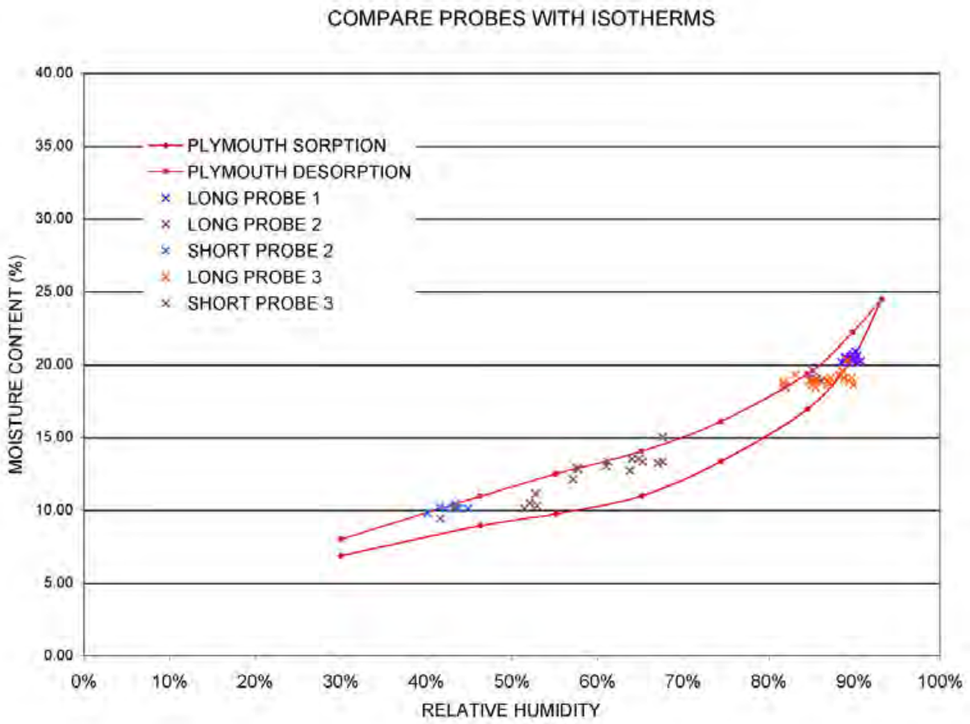


Fig.57 Results from wood block probes compared to Plymouth isotherms

The graph shown in Fig.57 above shows the results of readings from different wood block probes installed in the walls of the Totnes House. They have been plotted against the sorption and desorption isotherms created in the laboratory. The values for the long probes have been corrected for temperature variation according to the manufacturers guidance (Protimeter instructions say add .5% for every 5 degrees below 20ºC, and subtract.5% for every 5 degrees above (GE Sensing 2006))

The different probe readings were taken from the following sites:

The results for long probe 1 were taken in bedroom 1 between January and March 2008.

The results for long and short probe 2 were recorded in the master bedroom between 18th and 24th March 2010.

The results for the long and short probe 3 were recorded in the master bedroom between October 2009 and February 2010.

In the graph in Fig.57 it can be seen that virtually all the readings from the probes below 15% MC, and 70% RH fit well within the Plymouth isotherms. However at higher moisture contents some of the readings are slightly lower than the isotherm would indicate. If we add the isotherm for ramin, the timber species chosen for the wood block probes to the graph, then all the higher readings fall within that isotherm.

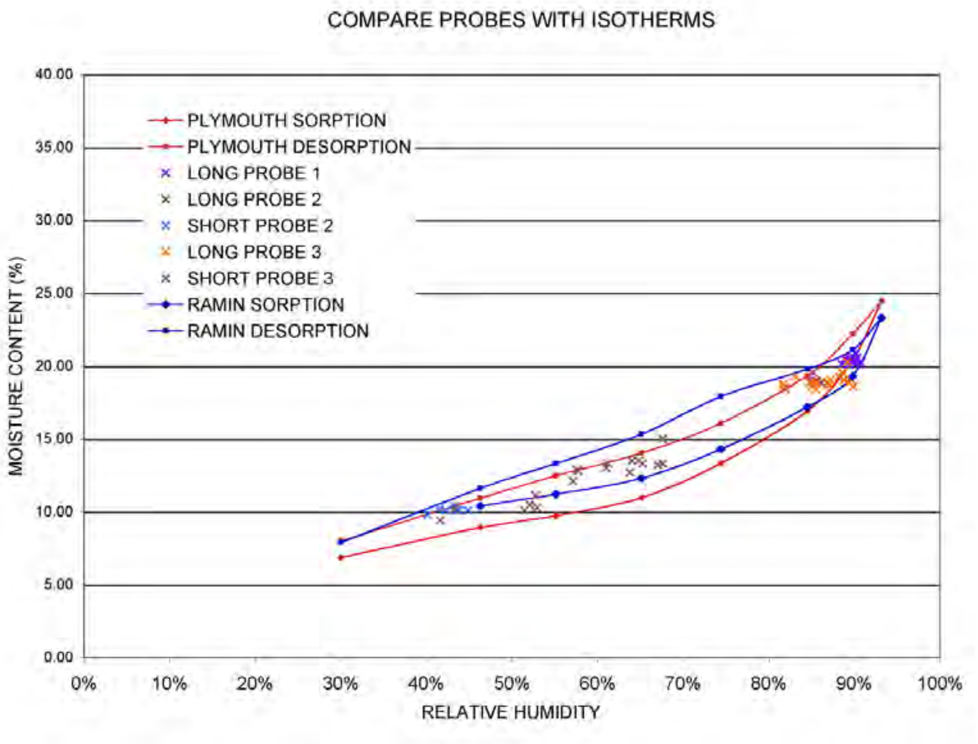


Fig.58 Results from wood block probes compared to Plymouth wheat straw isotherms, and the isotherms for ramin

It has already been noted that the Plymouth isotherm gives a generally lower set of values than other published isotherms above 60% RH. If the results from the in-situ woodblock probes are compared to a typical example of a published isotherm (Hedlin 1967), as in the graph in Fig.59 below, it can be seen that the fit is not as good as for the Plymouth isotherms.

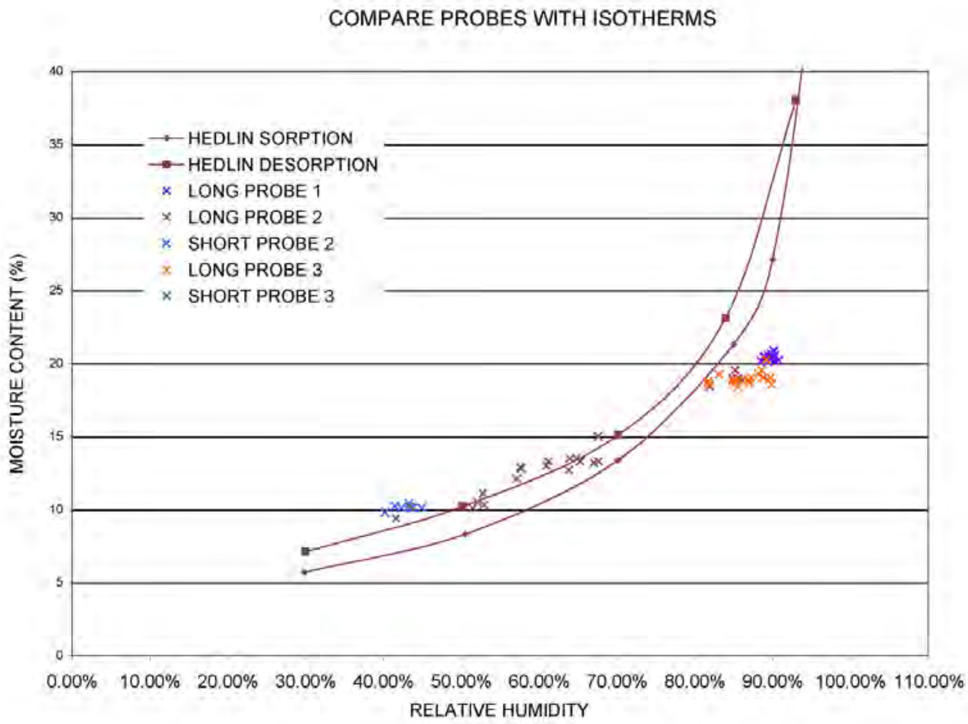


Fig.59 Results from wood block probes compared to Hedlin isotherms

6.11 Summary of chapter 6.

Chapter 6 has shown the process of creating a new set of sorption and desorption isotherms for straw in the laboratory. These results have been compared to isotherms for different timber species to allow an informed choice of timber for the new probes.

An experiment in which samples of straw were left at elevated RH levels for fifteen months has shown an unexpectedly low level of mould growth on the straw.

Moisture levels recorded by the new probes in a selection of straw bale walls have been found to be consistent with the results from the laboratory.

7. MOISTURE MONITORING OF THE TOTNES HOUSE

The principal case study is the Totnes House. The structure of the house is described in detail, and as it has been monitored continuously for the last three years, it establishes a reference for the other buildings.

The moisture performance of the straw bale walls of the Totnes house are described in detail. Particular attention is paid to the various sources of moisture, both from the interior and exterior of a straw bale wall and their effects on moisture gradient through the walls.

These measurements will provide a detailed picture of the moisture behaviour of the walls that will serve as a reference to compare with examples from the other case studies in chapter 8.

7.1 Description of the Totnes House

The Totnes House is a timber frame and straw bale house that the author designed and built in 2005. The house is situated in the south Devon market town of Totnes, in the south west of the United Kingdom. The Ordnance Survey grid reference is SX 801601, Latitude 50º 26’N, Longitude 3º 41’W.

Being the designer and builder of the house, as well as living in it, has made it central to the monitoring carried out as part of the research. Apart from a faulty drip detail that caused an ingress of water into one of the exterior walls (see section 6.1.4 ‘Long term drying of moisture in wall’) the house has been stable in terms of the moisture content of the walls, allowing it to be used as a control when compared to the other case studies.

The house sits on the northeast slope of a hill at 50m above mean sea level. The hill (called Windmill Down, see map below) behind the house protects it from the prevailing southwesterly weather systems. The corollary to this means that the house looks across the town to the northeast, and to make the most of the view it is this elevation that has the most glazing. This also produces a significant contribution to the thermal losses of the fabric of the house.

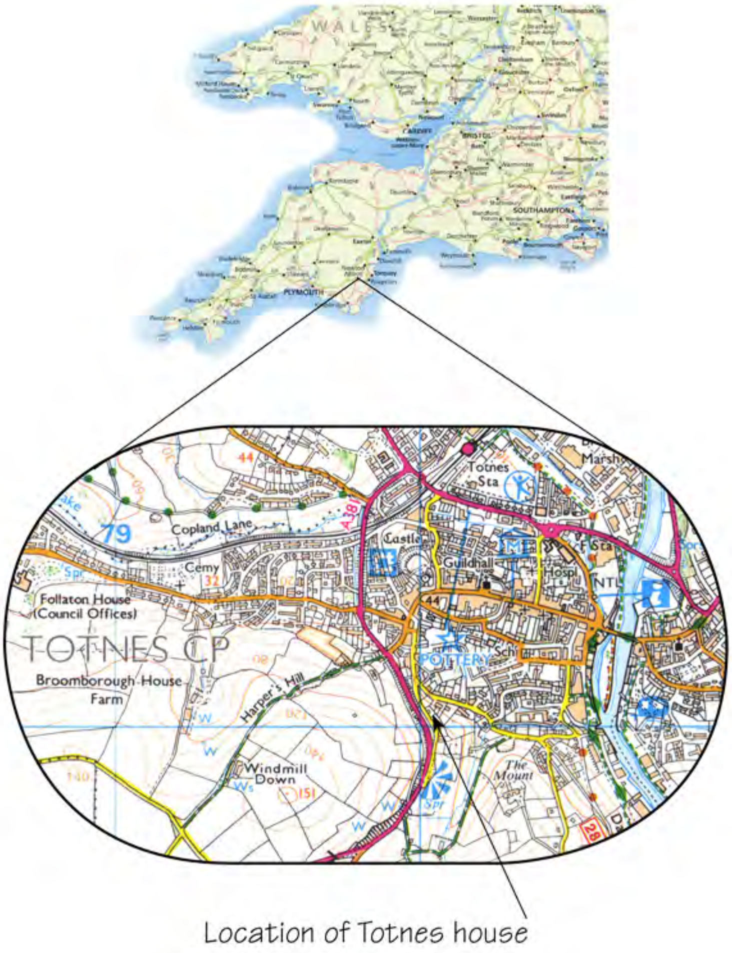


Fig.60 Map of the southwest of the UK, showing location of Totnes House

7.1.1 Layout and design of the Totnes House

The Totnes House is a four bedroom domestic dwelling. In order to fit the dwelling onto the sloping site the ground was dug out and a timber ‘Criblock’ retaining wall was built. The entrance from the road is on the high side of the site, which means that you enter on the first floor level that holds the living areas, and go downstairs to the bedrooms; a layout known as ‘upside down’.

Fig.61 Southeast and northeast elevations of Totnes House

The elevations show the original ground level (pale blue lines), and the general appearance of the house, with the ground floor being rendered with 30 mm of lime render, and the first floor protected by a rough sawn cedar cladding. The glazing on the northeast elevation is balanced by a south facing fully glazed conservatory/entrance as shown on the southeast elevation, and on the floor plans below.

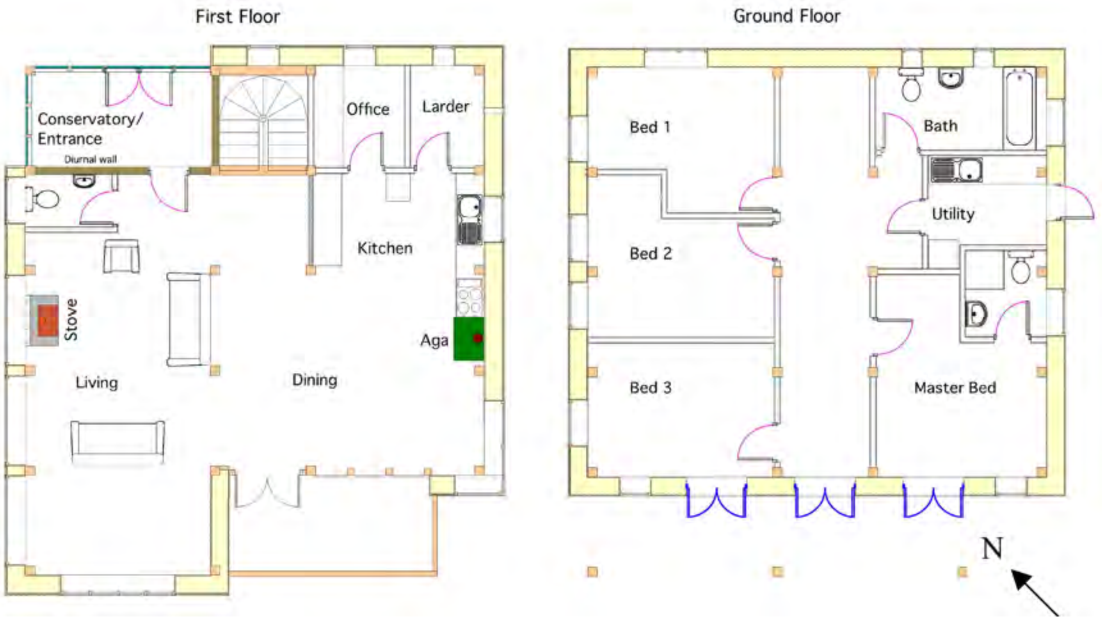


Fig.62 Floor plans of Totnes House

The position of the house, and the way in which it is cut into the existing bank means that there is a different environment in the area between the walls of the house and the retaining structure. There is little direct sunlight and less air movement, and it is noticeable that anything left in this area will start to turn green with algae, with mosses and ferns proliferating on the Criblock wall next to the house.

One of the decisions underpinning the design philosophy was to avoid the specification of construction materials with high embodied energy content, such as cement (Hammond and Jones 2008). This decision also influenced the sourcing of the chosen construction materials, attempting to obtain them as close as possible to the site in order to cut down on transport energy and potentially to support the local economy. It was therefore decided to use timber for the building’s structural frame, straw bales for the external walls, loose sheep’s wool for insulation and lime based renders for exterior and internal wall coverings.

The sections through the walls shown in Fig.63, below, illustrate some of the design features of the house. The main structure of the house is a large section post and beam timber frame made from Douglas fir. This kind of timber can be sourced locally as it is grown throughout the United Kingdom in managed plantations where the relatively fast growing trees are constantly replaced after felling. This is in contrast to the slower growing oak, the traditional material used for this type of house framing, the bulk of which has to be imported.

7.1.2 Construction and materials used in the Totnes House

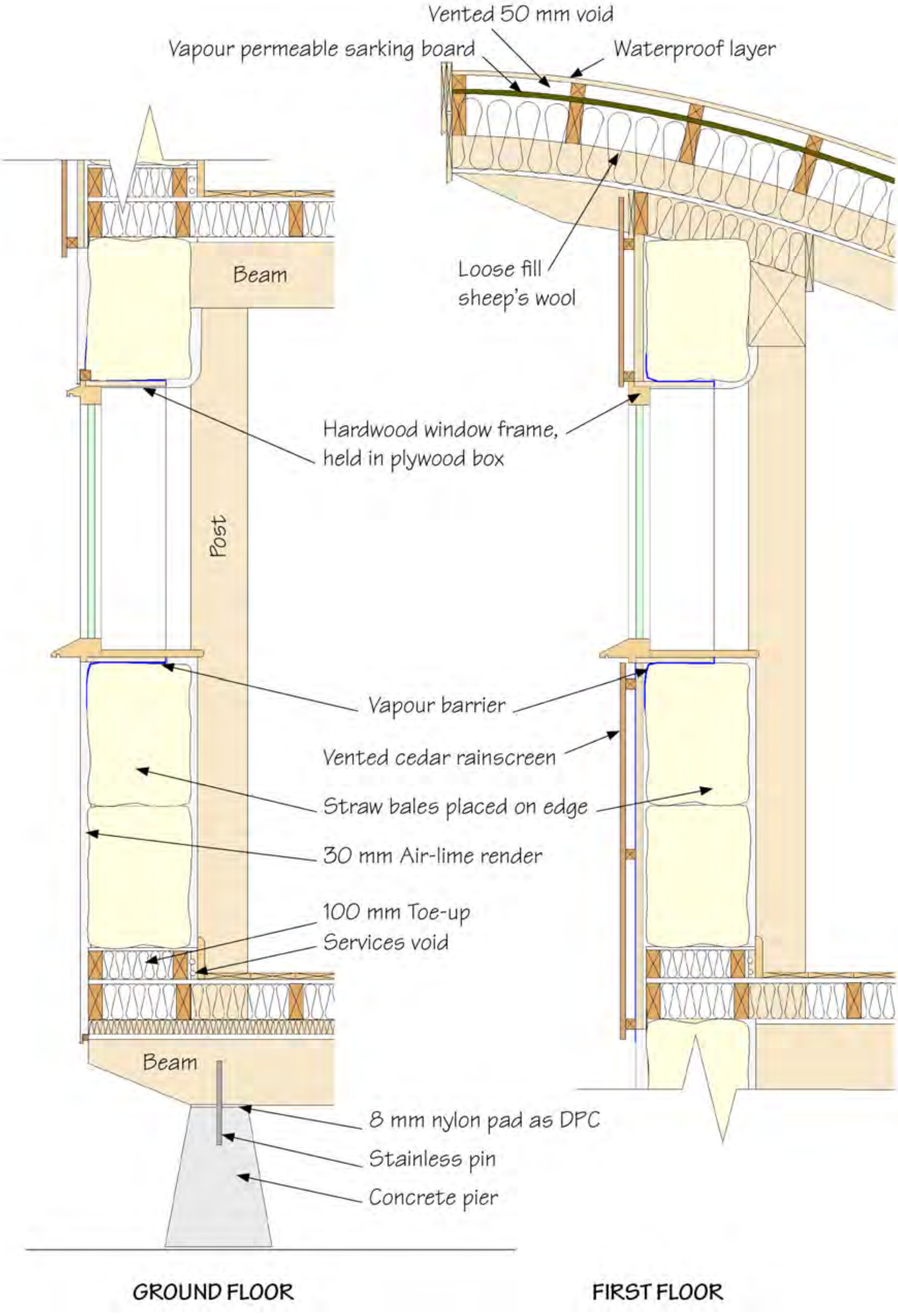


Fig.63 Typical wall sections from Totnes House

The structural frame is suspended from the ground on precast concrete piers that are resting on individual foundations, thus minimising the use of cement in the construction of the house. Once the frame was erected, the builders were able to construct the first layers of the roof. This enabled the rest of the build to proceed under cover – an important issue when using straw bales, which could be stored and worked on whilst being protected from the weather. The main floor joists are cantilevered out from the frame to support the straw bale wall that forms a continuous insulating blanket around the outside of the building’s structure. This minimises cold bridging and allows the traditionally jointed frame to be revealed inside the house.

Fig.64 First two courses of straw bale wall

The straw bale walls sit on a 100mm high, insulated toe up; this has two purposes, firstly it allows for a services void to run around the perimeter of the house without having to bury cables and pipes in the straw bale wall, secondly, it will protect the straw from any internal flooding. Clearly shown in Fig.64, (but omitted from the sectional drawings for clarity) is the horizontal ladder built into the wall. This helps to keep the wall straight, and provides a valuable fixing point both inside and outside the wall.

The ground floor walls are protected on both faces by a highly permeable 30mm layer of lime render, made up of 3.5 parts mixed sharp sand to one part lime putty. Fig.65 shows the application of the first of three 10mm layers using a compressed air render gun that forced the first coat at least 12mm into the surface of the well trimmed straw, ensuring a good bond between the disparate materials.

On the first floor, the external face of the wall has only 10mm of render, but further protection for these more exposed walls and additional shielding from driving rain comes from a vented rainscreen made from untreated cedar which is backed with a permeable vapour barrier.

The importance of these hygroscopic, vapour permeable finishes in the moisture performance of the building is explored elsewhere in this thesis. The use of a hygroscopic render also has a role to play in improving the inside air quality by moderating humidity and absorbing odours.

Fig.65 Using a compressed air render gun to apply the lime render

The insulation in the roof is made up of a 300mm thickness of loose sheep's wool, which was sourced locally from a company making sheepskin rugs. The

Wool, along with the straw bales, are by-products of an existing industry that might otherwise have to be disposed of by burning or landfill.

7.1.3 Sourcing the straw

The straw used in the construction of the Totnes House was sourced from a farm 10 miles to the south. This was the nearest farm to the site that still used a baler of the sort that produces the small square bales typically used in construction. It was possible to adjust the baling machine to give the bale a width of 500 mm as opposed to the standard width of 450 mm (Jones 2007; New-Holland 2009). This was done to simplify the coursing of the bales (coursing is a term used in construction to describe the lines of bricks or blocks in a wall). With the bales placed on edge, the width of 500 mm gives the desired ceiling height of 2500 mm with five courses of bales.

7.1.4 Bales laid on edge

As has been discussed in earlier chapters, the conventional orientation for bales in a wall is for them to be laid on their flat side. This is the only way to build a self supporting wall of the sort needed for a load bearing straw bale structure. However, in the Totnes House, the structure of the building is in the timber frame and the straw bale walls only have to support themselves. Tying the bales back to the frame with polypropylene strapping, as shown in fig.66 below, combined with the use of the horizontal ladder shown in fig.64 made it possible to use the bales on edge without loss of structural integrity. The main advantage to using the bales on edge is that the same U-value (see chapter 3) can be achieved for the wall as for one made from bales on their flat, but with a 28% reduction in width of the wall, and the same reduction in the total number of bales used.

Fig.66 Bale laid on edge, held against post with polypropylene strapping.

7.2 Results of Long term monitoring of the Totnes House

In section 5.2 the installation of the Goodhew probes (Goodhew *et al.* 2004) was discussed with reference to the belief that the readings were lower than expected, especially when compared to the 'Balemaster' probe. The first use of the 'Balemaster' was when one was borrowed from the University of Bath for a one off comparison with the Goodhew probes on 24th May 2007. This was when the readings shown in Fig.22 were taken.

On 5th June 2007 another 'Balemaster' was acquired to form a permanent part of this research, and this has been used to monitor the Totnes House almost continuously since that date. Regular measurements have been taken over three years from 2007 to 2010. The 'Balemaster' was also used to conduct 'one off' moisture surveys of the different case study buildings

7.2.1 Moisture profile of a typical straw bale wall

The experience of recording the moisture content of the Totnes House, and the other case study buildings, has given a clear picture of the range of moisture content that can be found in different straw bale walls.

The moisture readings taken at the Totnes House show a range of moisture contents, but if the examples where poor detailing or construction defects have allowed the ingress of moisture are ignored, then a picture of a typical straw bale wall can be established that can be used as a reference for comparison with other straw bale walls.

A measurement of the moisture content of the external wall of Bedroom 2 from January 2007 can be selected as an example of a 'typical' wall. Using the 'Balemaster' to record a series of measurements through the wall (see section 5.2.4), the results can be illustrated in a simple table.

DEPTH THROUGH WALL	100	150	200	250	300	350
MOISTURE CONTENT	8.52	10.24	11.64	12.77	14.51	16.24

These results can then be plotted on a graph to give a graphic representation of the moisture gradient through the wall.

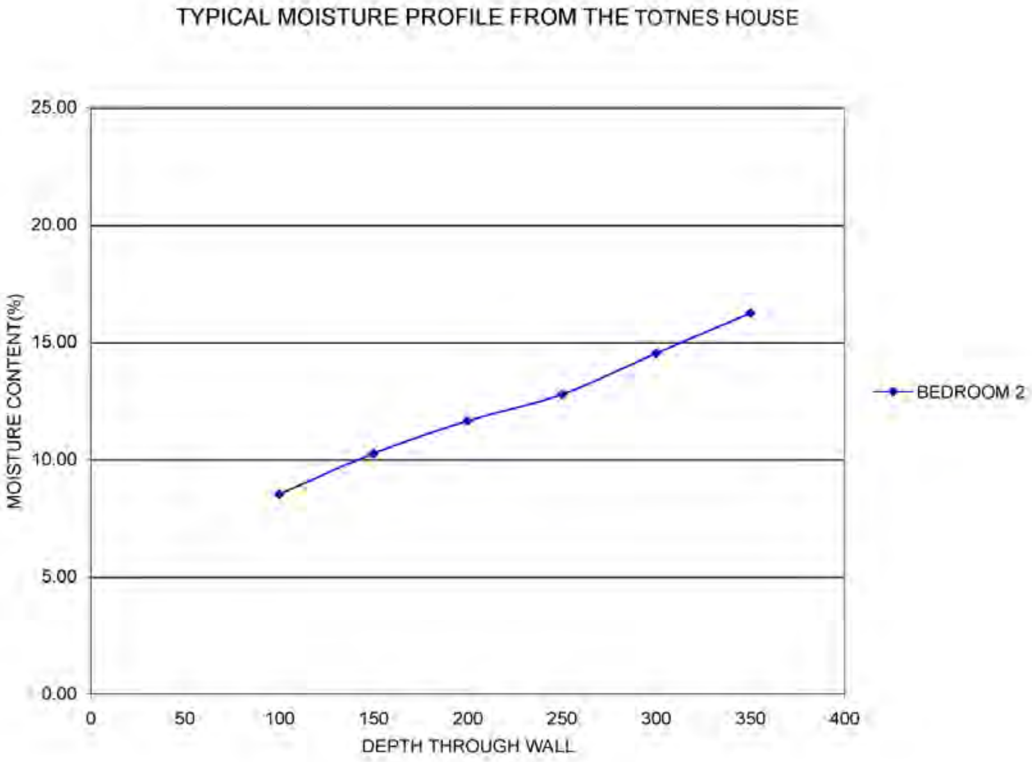
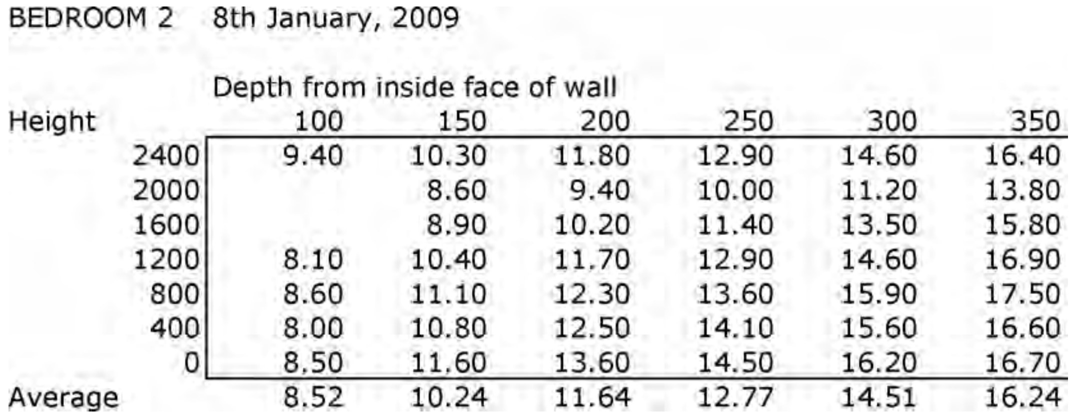


Fig.67 Example of typical moisture profile

This profile is interesting in that it demonstrates through actual measurements the theoretically straight moisture gradient through a homogenous substance

7.2.2 Detailed picture of moisture in a typical straw bale wall

The readings presented in the previous section show a simple one-dimensional moisture profile. By increasing the number of measuring points in a wall a more detailed picture of the pattern of moisture in a single wall can be produced. With the ‘Balemaster’ being inserted into the wall at seven heights, and each insertion recorded at 50 mm intervals, the 42 readings can be plotted in a table, charting the moisture content for a section through the wall.



BEDROOM 2 8th January, 2009

	Depth from inside face of wall					
Height	100	150	200	250	300	350
2400	9.40	10.30	11.80	12.90	14.60	16.40
2000		8.60	9.40	10.00	11.20	13.80
1600		8.90	10.20	11.40	13.50	15.80
1200	8.10	10.40	11.70	12.90	14.60	16.90
800	8.60	11.10	12.30	13.60	15.90	17.50
400	8.00	10.80	12.50	14.10	15.60	16.60
0	8.50	11.60	13.60	14.50	16.20	16.70
Average	8.52	10.24	11.64	12.77	14.51	16.24

Table.8 Readings using ‘Balemaster’ in the wall of Bedroom 2

The readings shown above in Table 8 are interesting in that they show a consistency of moisture content both through the depth of the wall and from top to bottom, apart from the lower moisture shown in the readings at the heights of 1600 and 2000 from the bottom of the wall. The probable explanation for the difference is the presence of a window opening in the straw wall that exactly coincides with these two points, with a sill height of 1600, and a head height of 2000. The window is set at the outside of the wall, and is 300 mm to the right of the monitoring points which therefore increases the surface area of rendered internal wall, lowering the moisture content of the adjacent straw.

In an article in ‘The Last Straw’, Clark Sanders describes using a Delmhorst moisture meter to monitor the walls of a straw bale house (Sanders 1994). The Delmhorst meter is of a similar type to the ‘‘Balemaster’’ used in this research, but had a 10” (250 mm) probe as compared to the 600 mm available with the ‘Balemaster’. Using this shorter probe he measured the walls of the building at three heights (defined as top – 1800mm middle – 1200mm and low – 300mm). The probe was inserted to three depths, 50mm, 100mm and 175mm. From these readings, Sanders produced the following drawings, shown in Fig.68

below, which were later reproduced in the book ‘Serious Straw Bale’ (Lacinski and Bergeron 2000).

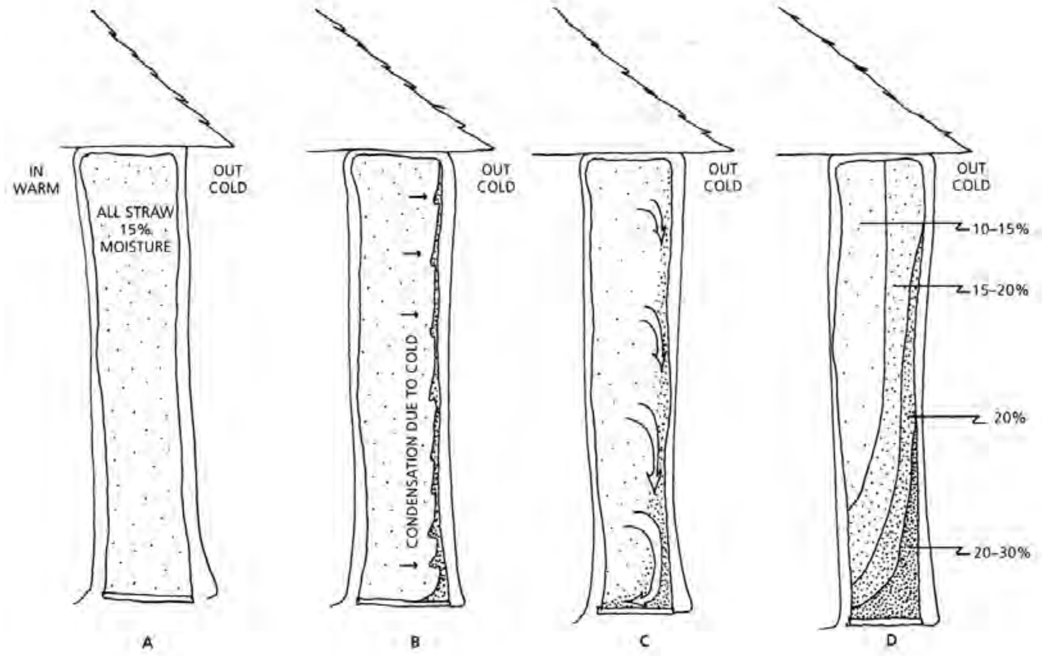


Fig.68 Sanders illustration of moisture patterns in a straw wall
From (Lacinski and Bergeron 2000).

The building that Sanders was monitoring had a cement render on the walls, which has a lower permeability than the lime render used on the Totnes House, and illustrates the moisture being held against the exterior wall. This shows a build up of moisture to levels of up to 30% towards the outside bottom edge of the walls. Sanders(1994) also states that ‘If moisture content is less than 15%, it tends not to migrate and stabilizes in the whole wall’

To compare with the Sanders illustration, the readings from table.8 above can also be presented by drawing the lines defining the changes in moisture levels on a representation of a section of wall, thus providing a coloured map of the pattern of moisture through the wall.
The resulting moisture map is shown in Fig.69 below.

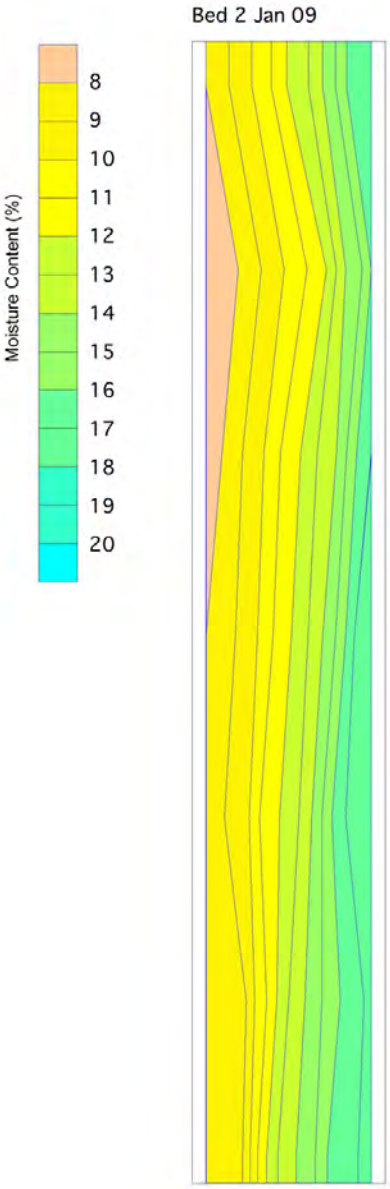


Fig.69 Moisture map of the wall of bedroom 2
(Interior of the house on the left)

The moisture map is drawn on an accurate scale section of rendered wall with a height of 2.5 m and a depth of 420 mm (comprising of 360 mm of straw with 30 mm of render on each side). The different levels of moisture are illustrated by using graduated bands of colour and shows an even spread of moisture through the wall. The area where the proximity of the window opening has resulted in lower moisture levels can be clearly seen towards the top of the wall.

In comparison with the Sanders assertion that moisture at 15% or below will stabilise through the wall, this map shows an even distribution of moisture from just above 8% on the inside to a maximum of 17.5% on the outside.

It is interesting to note that a clear measured moisture gradient is shown, with a uniform increase through the wall. This indicates that the actual moisture content is behaving in a way that relates to theoretical vapour pressure gradients (Szokolay 2004).

The moisture profile in Fig.67 can be augmented with moisture content readings from timber found adjacent to the interior and exterior surfaces of the wall to extend the moisture gradient. The measurements were made on one day in September 2008, when the interior temperature was 20ºC and the exterior was 5ºC. The internal RH was 45% and the external RH was 90%.

Combined with the calculated temperature and dew point gradients they give an illustration of the relationship between moisture and temperature and are shown in Fig.70 below. The gradients through the wall show the influence of a vapour permeable render on keeping the dew point below the temperature gradient, avoiding the potential for interstitial condensation

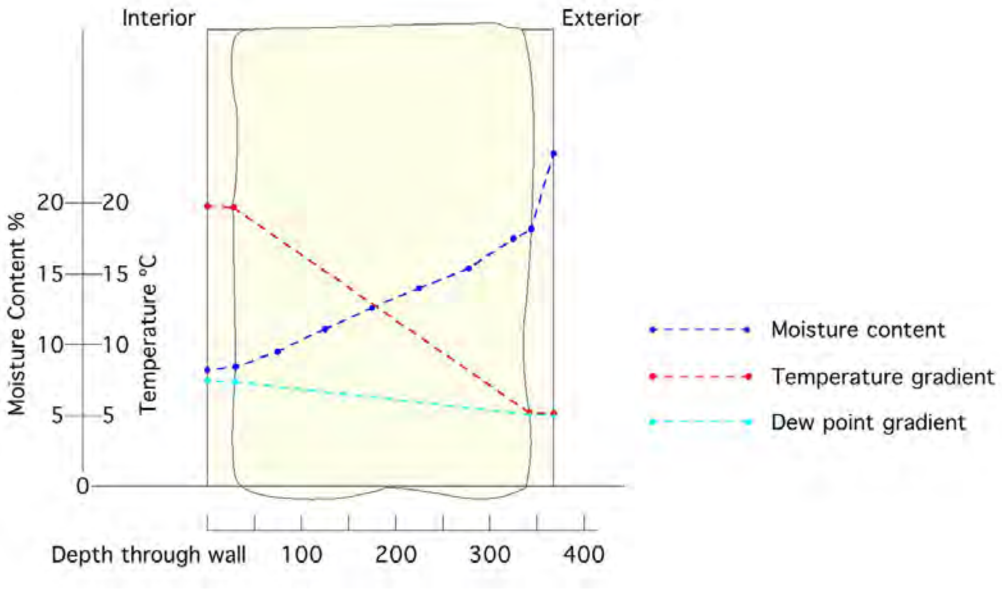


Fig.70 Moisture, Temperature and Dew point gradients

If the render used was less permeable than the lime, then the dew point gradient would cross the temperature gradient at the outer edge of the wall (as shown in Fig.19 in section 3.2.1). If this was the case, then the moisture levels in the straw close to the exterior render could be expected to be significantly higher.

7.2.3 Higher levels of moisture in a wall

Despite having stated earlier that the walls of the Totnes House had provided stable moisture measurements, there was one opportunity to record the results of a high build up of moisture in the walls of this building.

The southeast corner of the ground floor (Bedroom 1) is under the glazed entrance lobby and a parapet capping protects the ground floor walls. This corner of the house is shaded by the retaining walls and the proximity of the outside steps. The air is still and therefore has a feeling of dampness, with a lot of green lichen growing on the surrounding walls. After the finish coat of render had been applied in July 2005 it was noticed that this area of the external walls looked darker for longer than the rest of the house

In 2007, measurements taken with the ‘‘Balemaster’’ showed that one corner of bedroom 1 of the house was giving readings approaching 37%, where the bedroom next door had a maximum of 18%. The problem was traced to a badly executed drip detail on the parapet capping of a section of the straw bale wall. The final coat of lime render had mistakenly been built up to fill the space behind a preformed drip and the wall surface behind it, creating a route for surface rainwater to penetrate into the interior of the wall. The defect was immediately fixed with the addition of a gutter around the parapet.

Fig.71 Location of faulty drip detail above bedroom 1

After the drip had been remedied, a series of detailed readings were taken at different heights and depths through the affected wall section. These readings confirmed significantly elevated moisture levels in the straw throughout the wall. A section of render was removed from close to the bottom of the interior side of the wall, as can be seen in section 7.6, and a sample of straw was removed for gravimetric analysis and visual inspection.

A moisture map comparing the moisture in the two adjacent bedrooms can be seen below in Fig.72.

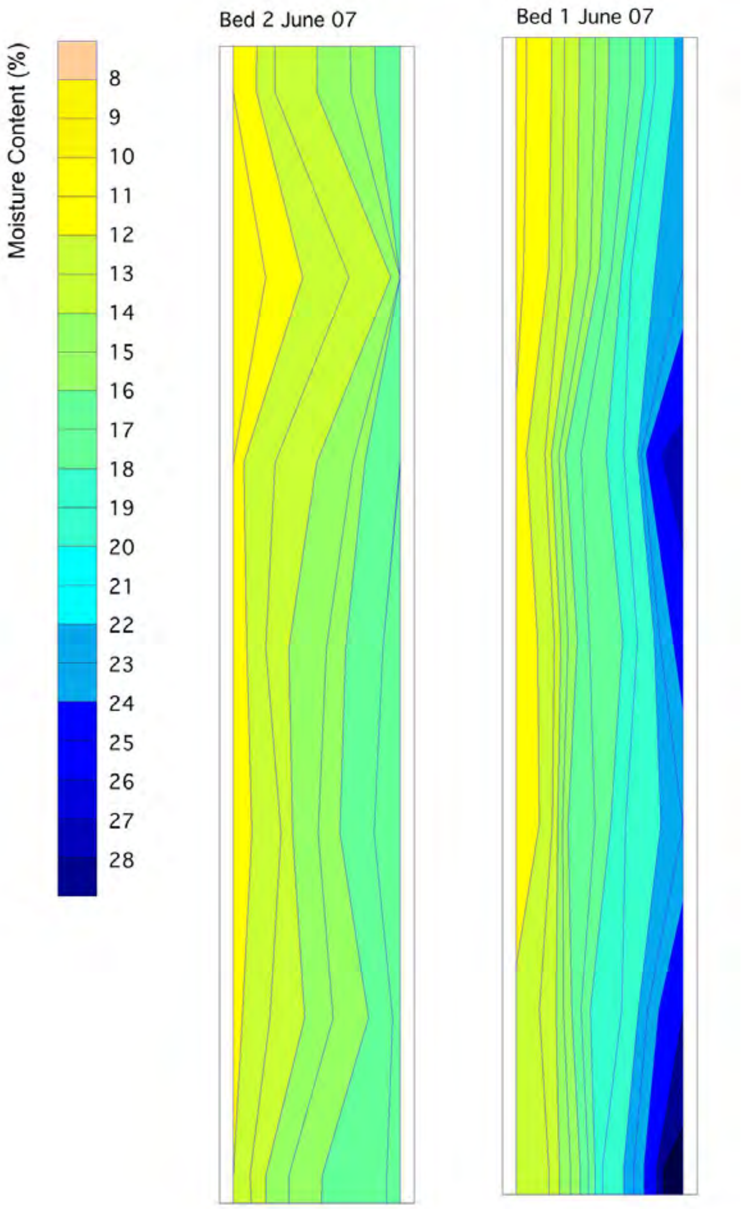


Fig.72 Moisture map of Bedrooms1 and 2 after water ingress to Bed 1 (Interior of the house on the left)

The moisture maps show that the two walls display a similar level of moisture on the interior side, with bedroom 2 showing an expected maximum of 17 – 18% on the exterior. The map moisture map from bedroom 1 was from a vertical array of holes drilled at a distance of 1200 mm from the point of maximum water ingress. The map shows much higher levels of moisture on the exterior with a maximum reading of 28% towards the bottom of the wall.

Comparing this map with Sanders illustration (Fig.67) shows a more even distribution of moisture with the apparent tendency for higher moisture to migrate towards the outer edge of the wall rather than towards the bottom.

7.2.4 External influences on the moisture level in walls

The moisture levels of the walls discussed in the previous section displayed differences that could be put down to structural variations, or failures in the building fabric. The two moisture maps of the wall to bedroom 2 that show similar levels of moisture, with the one from January 2009 in Fig.69 showing slightly lower moisture levels on the interior than the same wall in June 2007. This is probably due to the whole house drying out over time. The elevated moisture in the wall of bedroom 1 is an exception with a known cause. This raises the question of how much the moisture levels in walls can vary just due to normal environmental differences.

If we look at each of the external walls of the Totnes House on a single day, we find that each exhibits a different moisture profile, and gives an indication of the effects of environmental variations, as shown in Fig.73 below.

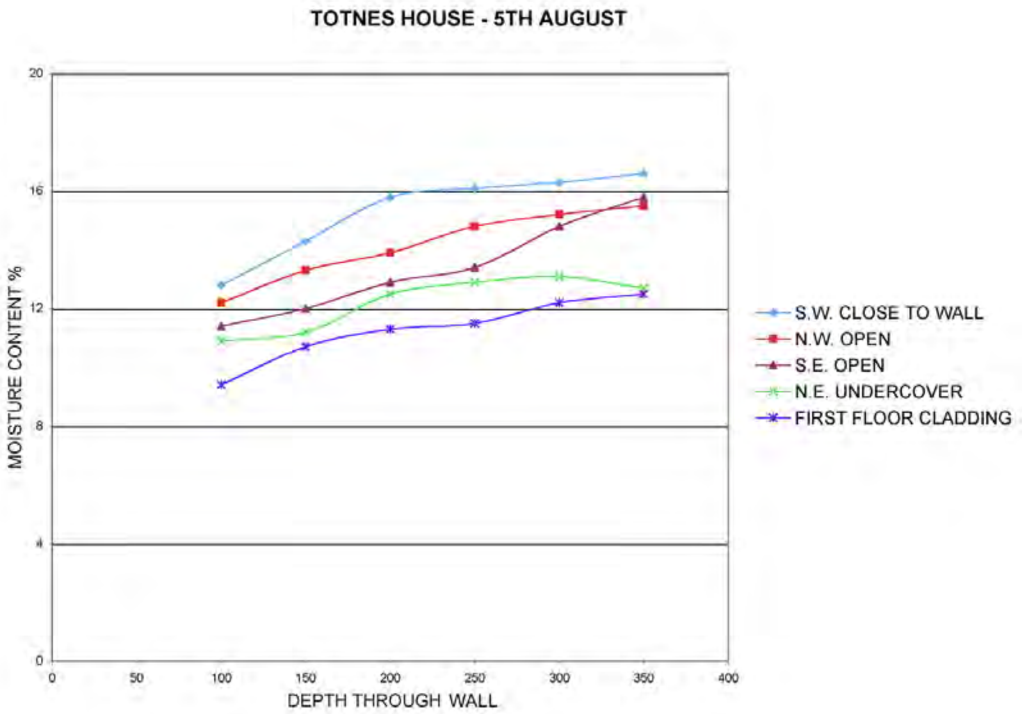


Fig.73 Readings from different walls of the Totnes House taken on the 5th August 2010

The graph in Fig.73 above shows the readings from the ‘Balemaster’ inserted into five different sites around the Totnes House within the space of 30 minutes on the same day. The graph provides a series of readings taken through each wall at 50 mm intervals.

The sites were all at the same height from the bottom of the rendered ground floor walls, one on each side of the house except the last one, which is from a first floor wall that has an additional cedar rainscreen.

Each side of the house has a different microclimate. This has not been fully recorded, but is observable, and there are relevant features that can be assumed to effect the immediate environment of each wall.

The following is a description of the environment around each wall, and the implications for the moisture levels at each location. (The floor plans for the house are illustrated in Fig.62 in section 7.2.1 above)

- S.W. CLOSE TO WALL. The southwest wall is the wall closest to the retaining wall at the back of the house where there is less air movement, and mosses and ferns proliferate. It is also the wall that faces the prevailing weather. These two factors combined would probably explain why this wall has the highest moisture levels.
- N.W. OPEN. The northwest wall is more exposed to the weather than the southwest wall, but has a more open aspect with greater airflow.
- S.E. OPEN. The southeast wall has the same open aspect as the northwest wall, but receives less of the prevailing weather.
- N.E. UNDERCOVER. This wall is fully protected by a first floor balcony, which means it never receives any direct precipitation. This would explain why it has a significantly lower moisture content than the other ground floor walls.
- FIRST FLOOR CLADDING The orientation of this wall is less important, as all the first floor walls behind the cedar cladding display similar low levels of moisture due to their full protection from the weather. The role of a rainscreen in the protection of straw bale walls will be explored later in the next chapter.

7.2.5 Internal influences on the moisture level in walls

One of the expected factors that will influence the internal moisture levels is the increased RH in rooms such as kitchens and bathrooms where steam from hot water can be expected to permeate the walls through the valour permeable internal render.

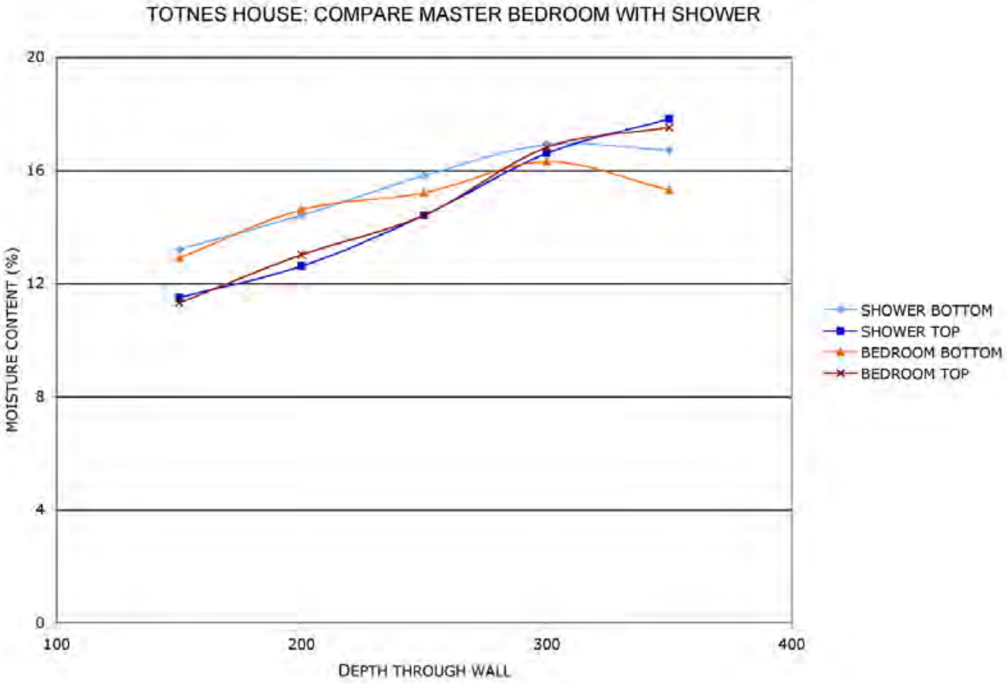


Fig.74 Comparing bedroom with adjacent shower room on the same day. 26th Oct. 2007

The graph shown in Fig.74 above shows readings with the ‘Balemaster’ performed in a similar way to the readings in the previous graph, with readings taken at 50 mm intervals through the adjacent external walls of the shower room and master bedroom. This time the readings were taken at two heights, from the top, (at a height of 2400 mm) and bottom, (at a height of100 mm) of each wall. As could be expected from previous readings, the top of each wall displays less moisture than the bottom through the bulk of the wall, but in both cases there is a lower moisture reading at the outside of the bottom of each wall.

One explanation for this could be the presence of the rainscreen on the first floor that terminates just above where the reading for the top of each wall was taken. This may have the effect of precipitating additional water running off the rainscreen onto the top of the lower wall at this point.

The moisture levels in the bedroom and shower room don’t however show any increase in moisture due to the average of two showers a day (taken in the shower room). This unexpected result was consistent across readings taken on different occasions, and can be compared to a set of readings taken at the bottom of the walls of the first floor.

The first floor of the Totnes House is a largely open plan area with distinct areas for dining, sitting and eating. This allows a comparison to be made between areas which generate higher levels of RH, as will be found in the Kitchen, with areas such as the sitting room where no additional water vapour is created.

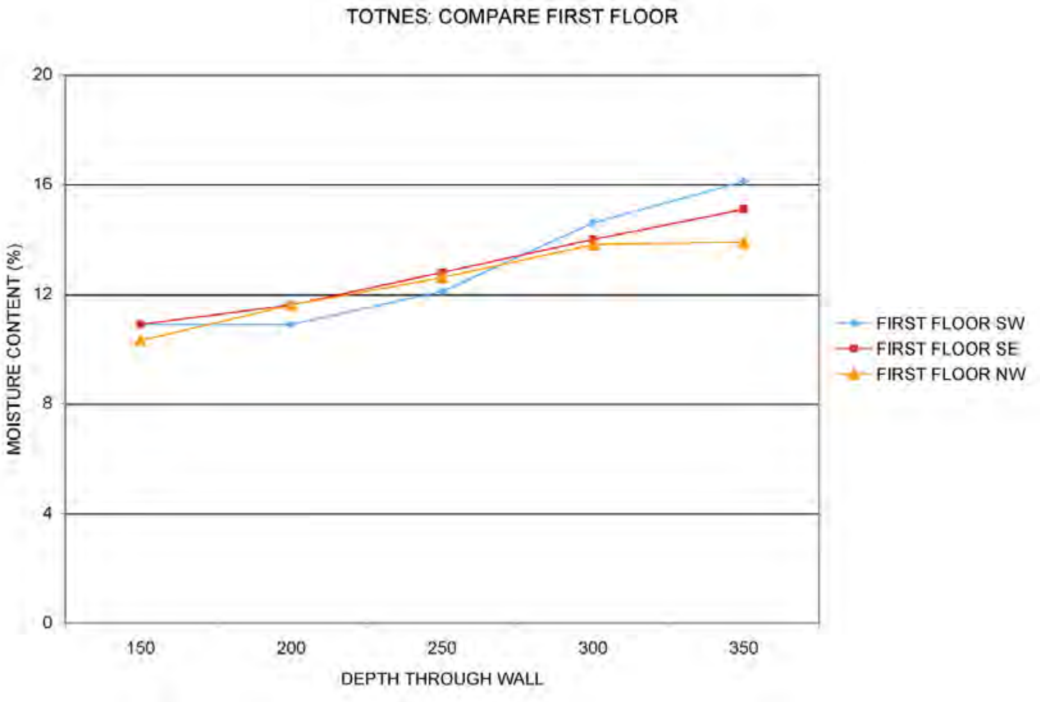


Fig.75 Readings from different walls of the first floor of the Totnes House 25th Jan. 2010

The readings shown in Fig.75 above are were all taken from the bottom of the walls. Unlike the ground floor walls, an additional cedar rainscreen cladding protects all these walls

- FIRST FLOOR SW is the weather wall and the prevailing wind, despite the cladding, may be affecting the moisture levels to give a slightly higher reading than the other first floor walls.
- FIRST FLOOR SE is the wall to the sitting area, and shows a very similar moisture profile to:-

- FIRST FLOOR NW. This is the wall to the kitchen, which is in regular use but has no dedicated extractor fan. Because of the greater amount of warm, moist air created by the culinary activities taking place every day, this wall might be expected to show a higher moisture content yet it has a slightly lower reading than the other walls.

The readings from the shower room and the kitchen both show an unexpected result in that it could be expected that the more concentrated vapour levels produced from cooking and bathing would result in higher moisture levels in the straw. However, there is no indication that this is happening, and an explanation may be that these periods of increased moisture are of short enough duration that the 30mm of lime render on the interior is enough to adsorb and ameliorate the effect of these regular, short-lived, moisture episodes.

As with the readings taken in the shower room (Fig.74), it is surprising that the patterns of occupancy with their changes in moisture being produced (showers, kitchens), should have such an apparently negligible effect on the moisture in the walls

Closer comparison with the readings from the different walls on the first floor in Fig.74 show that the presence of the rainscreen cladding that covers all the first floor walls is producing similar moisture levels in all the walls, compared with the greater variation on the ground floor shown in Fig.73. The effects of using a ventilated rainscreen cladding on the exterior of a straw bale wall are explored in the next chapter.

7.2.6 Variations in moisture levels over time

All the preceding graphs and illustrations in this section have been snapshots of the moisture levels in a wall at a single moment in time. As readings have been collected over three years, it is also possible to look at changes in moisture level in the same walls over time.

The graph in Fig.76 (below), shows all the readings collected from the wall of bedroom 1. During the first year, readings were collected regularly, on a fortnightly basis. Over the following two years readings were still collected from the walls, but on a less regular basis, with more focus given to individual areas, and the testing of the new wood block probes. This makes the following graph less useful, but it can still give an indication of moisture levels in the wall over a longer period of time.

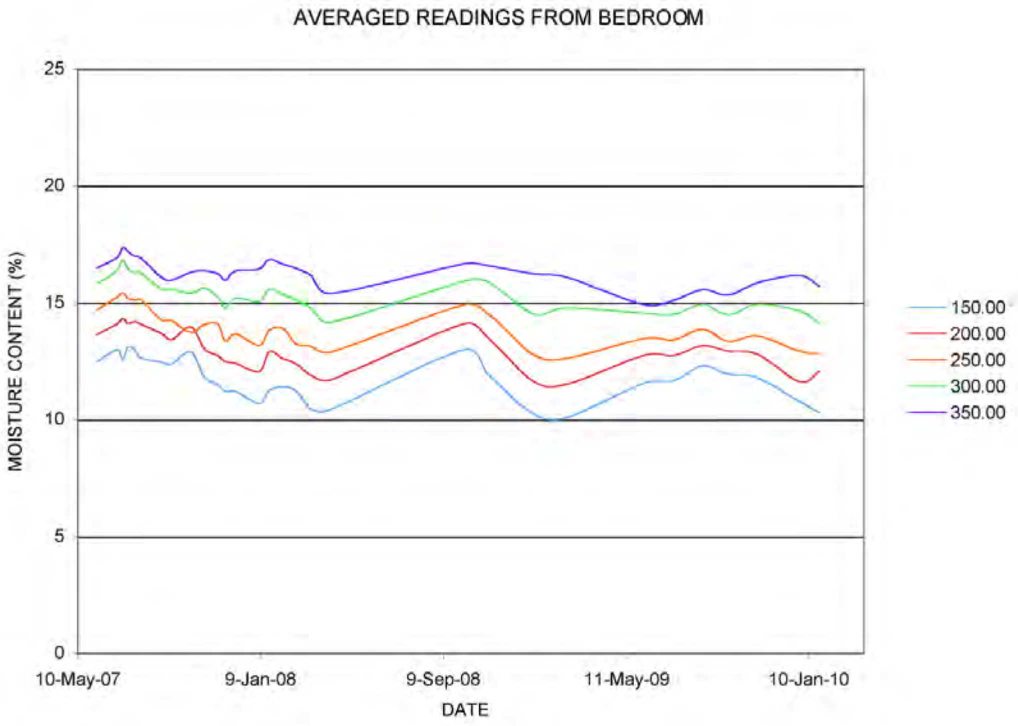


Fig.76 Graph showing the averaged readings through the depth of the wall of bedroom 1, from May 2007 to January 2010

(The different coloured traces are for the different depths through the wall, the smoother sections are from periods where fewer readings were taken)

The graph above in Fig.76 shows the readings at increasing depths through the wall, but each trace is an average of all the readings at the different heights. There is probably insufficient data to draw definite conclusions about the moisture behaviour over three years, but the following observations can be made:

- It can be seen that the moisture gradient stays fairly consistent from 150 mm into the wall to the outside edge at 350 mm.
- Interestingly, the 3% variation in moisture content on the interior of the wall, with a maximum reading of 13.1% and a lowest of 10.1%, is greater than the 2.25% difference between the highest (17.35) and lowest (15.10) reading at the exterior.
- It is possible to see a seasonal pattern to the readings, especially on the interior of the wall. The winter months show lower moisture levels than the summer, which is may be the result of the interior being heated, which has the effect of lowering the internal RH.

7.2.7 Reaction of a straw bale wall to weather patterns.

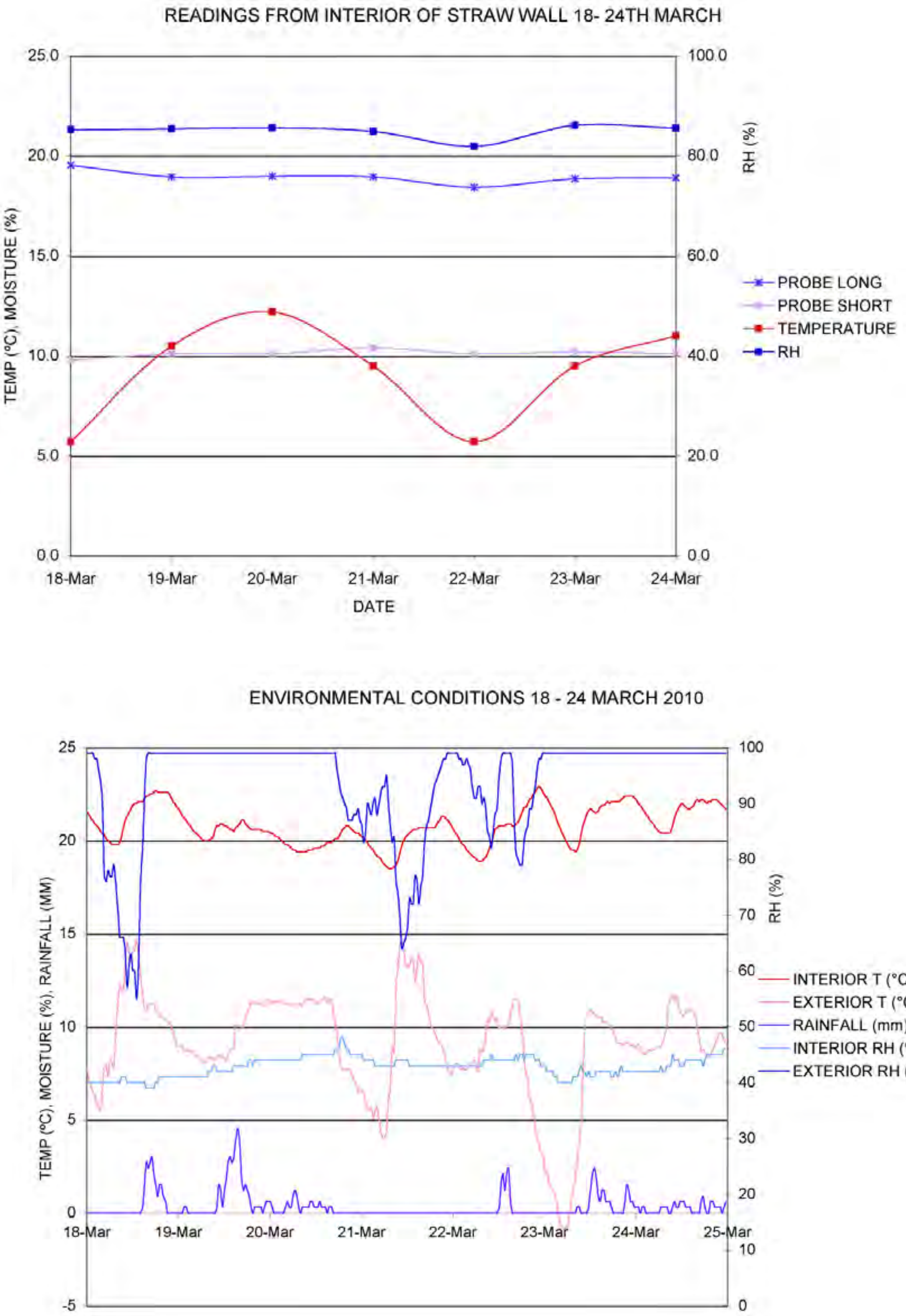


Fig.77 Moisture levels inside a wall compared to environmental conditions on the interior and exterior of the Totnes House recorded over a week

In Fig.77 above, a week's worth of readings from inside the wall of the master bedroom of the Totnes House are detailed in the upper graph. These can be compared with the readings shown in the lower graph that depict the environmental conditions that will impact on the conditions inside the wall. This week was chosen because it showed a relatively wide range of weather conditions to compare with the state of the straw in the wall.

The moisture content of the wall remained fairly constant to within plus or minus 1.1%. The RH, measured at the same depth as the long probe, 350 mm into the wall from the interior, was also steady. The only significant change within the wall was the temperature, again measured 350 mm into the wall, which showed a swing from 5.7ºC to 12.2ºC.

Comparing the readings from within the wall of the Totnes House to the environmental conditions on either side of the wall over the same period indicates that the changes in the external environment are greater than the interior, as could be expected in a heated domestic dwelling. There was some rain, and the external RH changes from below 60% to 100% while the rain was falling. The widest range of changes occur in the temperature, which during the day of the 21st reaches a high of 14.7ºC, but during the night of the 23rd dropped to 0.9ºC below freezing. This does not coincide directly with the changes of temperature in the wall, but as discussed in chapter 2, a thermal lag can be expected which could explain this disparity.

What is illustrated by Fig.77 above, is the low level of reaction in the moisture content of straw in the wall in comparison to the environment inside and outside the wall.

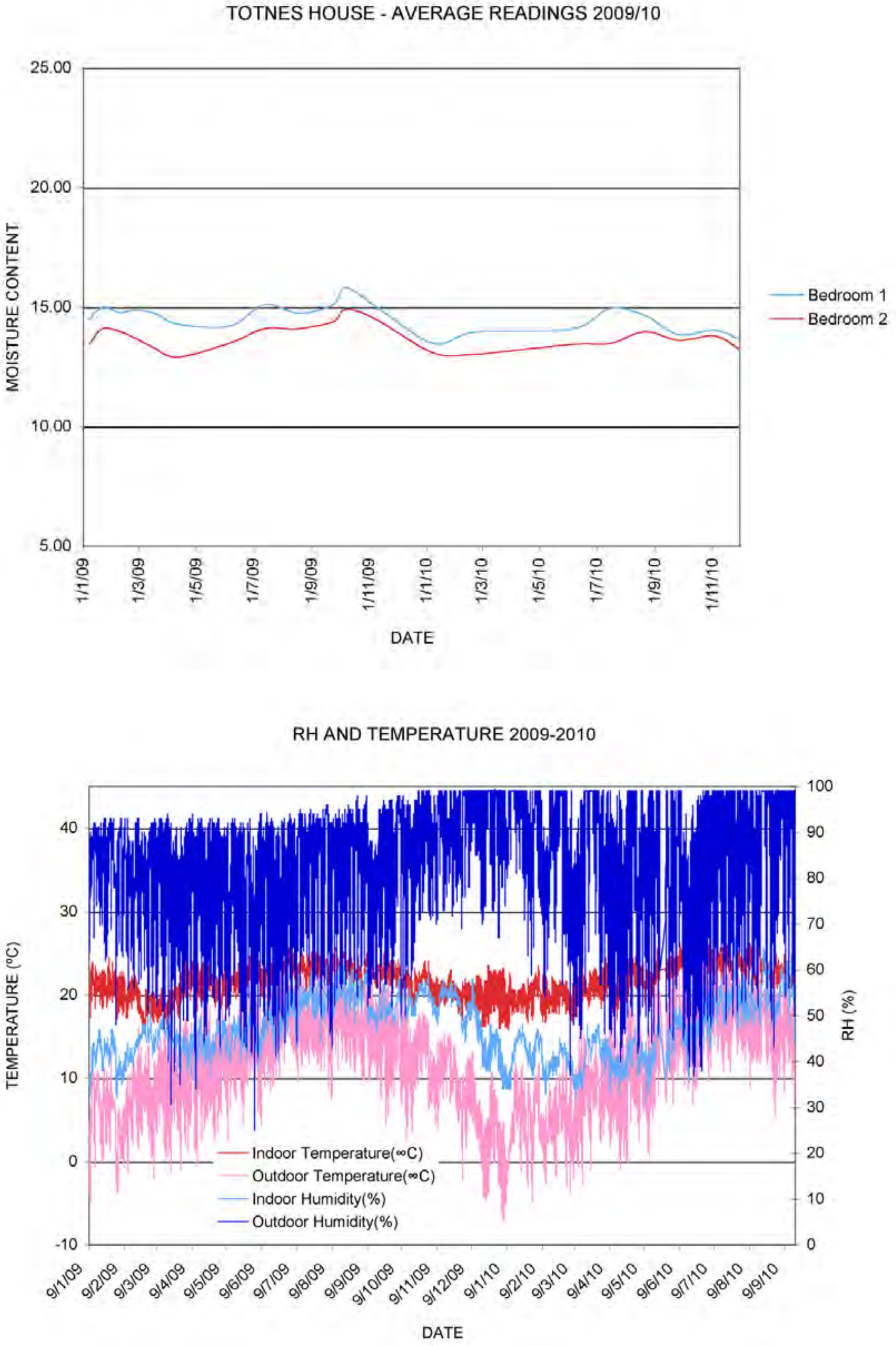


Fig.78 Average moisture content of the straw in the walls of the Totnes House compared to the environmental conditions inside and outside the house over a 21 month period.

In Fig.78 above, a similar comparison was made between the average moisture content of two of the bedrooms in the Totnes House and their immediate environment, but this time over a longer period of nearly two years. There seems to be a discernable pattern emerging with moisture in the walls increasing gradually through the summer months to reach a peak at the beginning of October 2009, and descending through the winter to reach a minimum moisture content in February. The lack of regular data collection through the whole period makes conclusions difficult, but a similar pattern can be seen in the data from the weather station shown in the lower graph, especially in temperature.

7.3 Comparison of Totnes house with the case study buildings

Having looked at the moisture performance of the Totnes house, the results can be compared to a series of additional case study buildings.

This chapter describes the selection and methodology used for the in-situ monitoring of the case study buildings.

7.3.1 The case study buildings

This research has visited and surveyed a variety of buildings and structures that use straw bales, and in order to simplify the findings they are outlined in the two tables below. A more detailed description, and some further results are to be found in appendix A

The first table is of buildings that have been visited and surveyed with the 'Balemaster' probe, which gives a detailed snapshot of the state of the walls at the time of the visit. The exception to this was the Liskeard panel project. These panels were being continuously monitored for RH and temperature as part of a joint research project with the University of Bath.

The second table lists the buildings that have also been surveyed with the 'Balemaster'. In addition, these buildings have subsequently had the new probes installed for continuous monitoring of the moisture content of the straw in the walls.

BUILDING SURVEYED	DESCRIPTION	CONSTRUCTION	TYPICAL MOISTURE
	The Straw Bale Theatre at the Centre for Alternative Technology (CAT) in mid Wales. Built in 1999 by members of staff and volunteers on courses supervised by professionals.	Internal post and beam timber frame structure with straw bale walls wrapping around the outside. Concrete footings and slab over compressed slate. Hydrated lime render.	Most walls showing slightly higher than average moisture content than the norm (typically 12% to 19%). Wall at rear of building had previously had items leaning on it, and the render showed a damp patch - moisture at exterior of this wall had reached 33.7%.
	Garage and workshop in garden of private house in Exmouth, Devon. Built in 2007 by owner with volunteer assistance.	Load-bearing straw walls on rammed earth tyre footings. Concrete slab. Air lime render.	Moisture in the walls well within the norm, with average moisture typically 13% to 16.5%.
	Grange Farm. Converted agricultural buildings on exposed site in Somerset. Designed by White Design (Architects).	Large (2.1m x 1m x 1m) bales used with flat parapet roofs. Straw walls used as additional cladding around existing buildings.	Dangerously high moisture levels in two of the walls measured, with moisture levels over 36.8%. Roof details since changed.

	Panel at the University of the West of England (UWE), Bristol. An early ‘ModCell’ panel erected on its own as example of similar panels used in main structure of new building adjacent (2003).	‘ModCell’ is a pre-fabricated structural straw bale panel system. An engineered timber box frame is filled with straw bales and finished with a proprietary lime render that contains some cement.	The display panel didn’t have a proper roof, and the render was also cracked. Moisture content had reached high levels, with an overall average of 24%. Panels in building had slightly elevated levels (10.5% to 19%).
	Set of test panels built in a field in Liskeard, Cornwall. Constructed in 2007 to test the permeability of different render finishes.	Constructed as the ‘ModCell’ panels above, the last panel on the right had a timber rainscreen added to compare its performance with the rendered panels.	The rainscreen panel showed an average moisture content of 13.6% compared to 16.8% for the rendered panels, an improvement of 3.2%.
	Hedgerow House in Leitrim, Eire. Designed by architect Dominic Stevens and built in 2007.	Construction features a separate external timber frame forming a rectilinear structure with curved, load bearing, straw bale walls forming the living spaces within it. The whole structure is suspended off the ground.	Poor design detailing and substandard execution have resulted in a building with many problems, including an average moisture content of over 24%.

	Greyfield Sawmill. Large double height industrial building in south Devon. Constructed in 2008, and since dismantled.	Timber frame with glulam beams using straw bale infill and a straw bale roof. Straw used for acoustic as well as thermal insulation.	Straw used in construction had been stored for some time, and had a grey appearance. Moisture levels between 11.7% and 19.7%.
	Meeting house at the Ecology Building Society HQ, Silsden, West Yorkshire. Built in 2006.	Circular load bearing building. Straw bale walls on random stone footings. Lime render showing some cracking.	Moisture levels show slightly elevated moisture content towards the outside edge of the straw where the render has cracked. Maximum moisture content 23.3%.

Table.5 Buildings surveyed with 'Balemaster" probe

BUILDINGS WITH PROBES INSTALLED	DESCRIPTION	CONSTRUCTION	TYPICAL MOISTURE
	Holiday cottage built by Carol Atkinson on her farm in Goole, West Yorkshire. Visited during construction in early 2009.	Timber frame suspended off the ground with straw bale infill. Mixture of lime and earthen renders. Some walls made from hemp-lime.	Some of the straw had suffered water damage during construction phase. Most of the walls were within the norm, but dangerously elevated moisture content (36%) was found in one wall.
	The Footprint. The National Trust's eco-base at St Catherine's Woods near Windermere in the Lake District National Park. Built in 2006.	Traditionally jointed oak frame suspended on concrete piers, straw bale infill walls finished with lime render.	Moisture levels were within safe levels (below 25%), but showed higher levels than the norm, especially at the base of the walls. Monitoring has shown a reduction over time.
	Studio built into the slope at the bottom of a garden in Bristol by Rik Lander in 2007. Single large room with glazed end elevation.	Load bearing straw walls built on rammed earth tyre retaining walls. Straw walls finished with earthen render. Gently sloping green roof.	Despite concerns over the weathering of the earth render, all walls display moisture levels within the norm. Monitoring of the walls has shown very little change over time.

	Cuckoo Farm, near Modbury, Devon. Two-story farmhouse built to look like a vernacular building in 2007. Visitors assume that it's an old cob house.	Traditional oak frame on conventional concrete slab, with straw bale walls wrapping around the outside. Thatched roof.	Problems with the render produced large cracks, and in some areas sections of the render had fallen off. Repairs have since reduced the moisture levels in the walls. This building is an example of the resilience of straw in less than ideal conditions.
	Classroom at Occombe Organic Farm visitors centre. Torbay, Devon. Built by students of South Devon College in 2008.	Load bearing straw walls on rammed earth tyre footings, supported on rubble trenches. Lime render on walls. Timber roof.	A mistake during the construction phase resulted in significant moisture damage to the straw in the walls. Long term monitoring has shown gradual drying of the walls.
	The Totnes House. Designed and built by the author in 2005.	Suspended traditional timber frame with straw bale walls wrapping around the outside. Lime render on ground floor external walls, timber rainscreen protects first floor walls.	Continuous monitoring of walls in a stable condition over three years has produced reference moisture levels to compare with the other buildings.

Table.6 Buildings surveyed with 'Balemaster' probe, and subsequently installed with the new wood block probe

7.3.2 Moisture performance of the case study buildings

The previous chapter described using the ‘Balemaster’ to record a moisture profile through the wall of the Totnes house. In the figure below the same method is used to record a typical moisture profile from a range of the case study buildings to provide an overview of the different moisture performances.

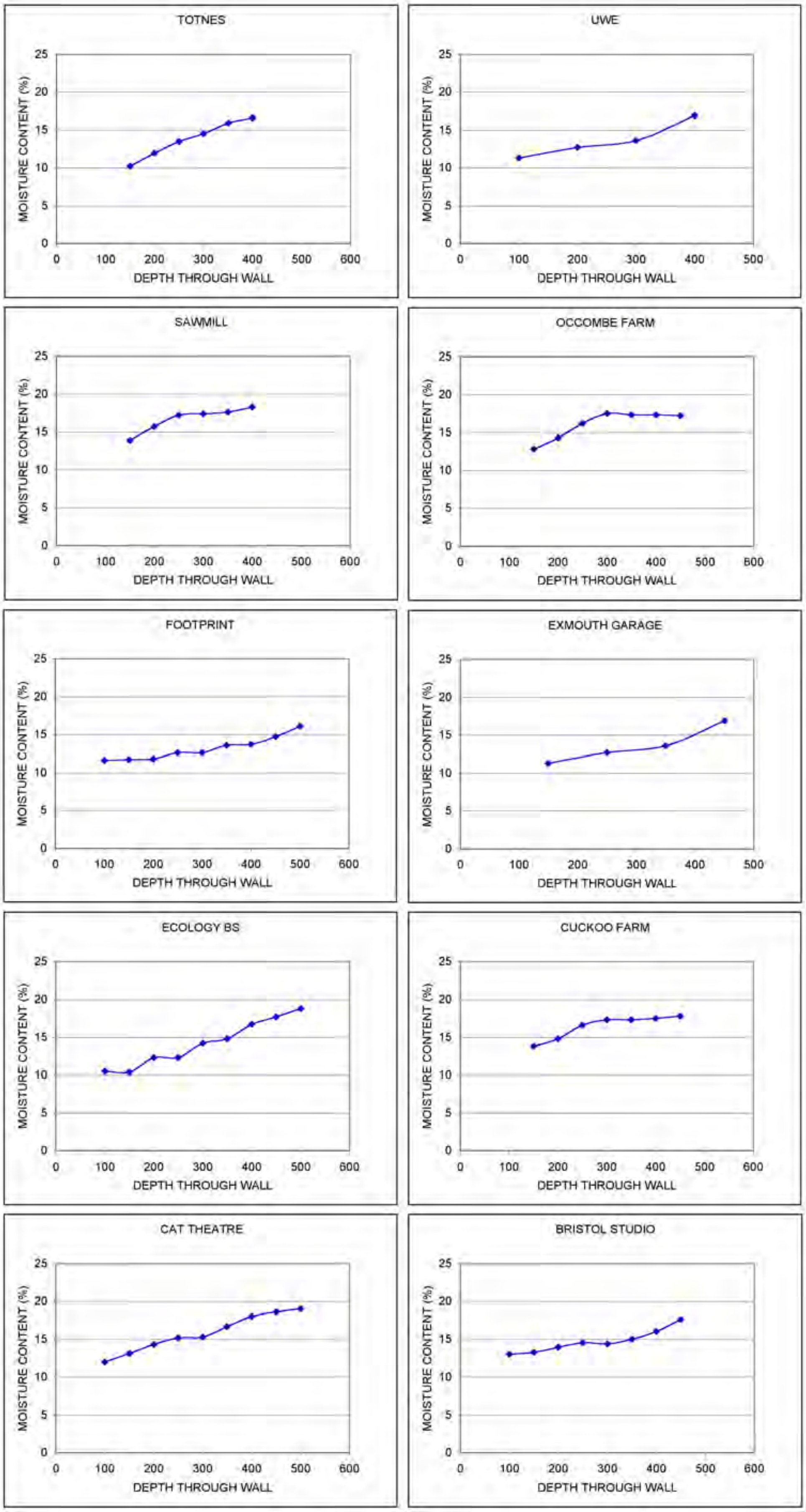


Fig.79 Comparative moisture profiles from a range of case study buildings

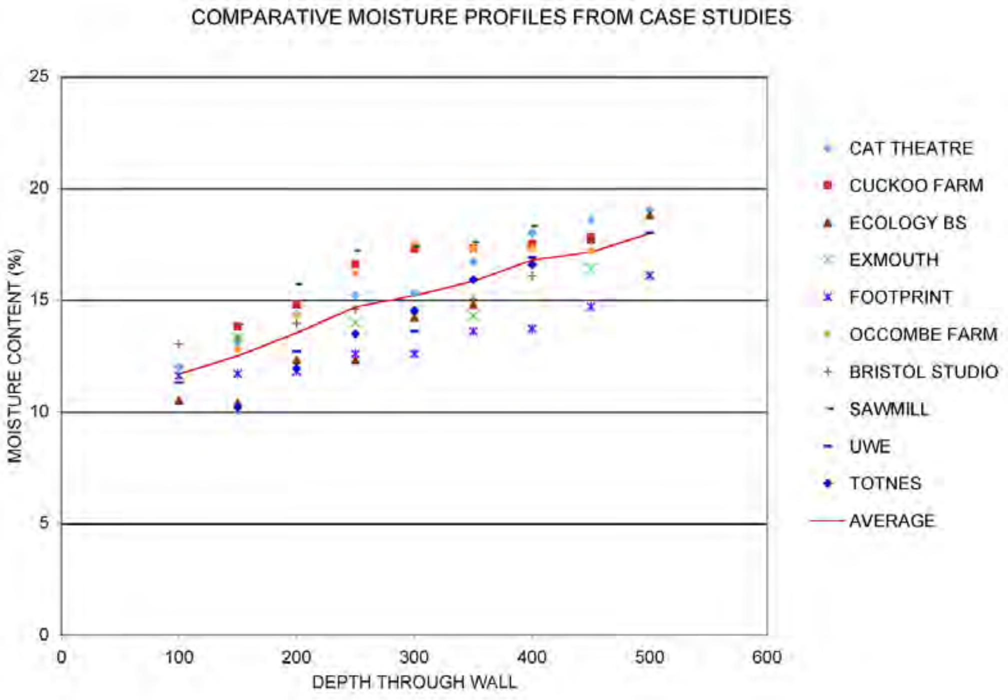


Fig.80 Comparative moisture profiles from all the case studies presented on one graph

The two figures above show a range of moisture profiles through a typical wall of the Totnes House and selected walls of the other case study buildings. At each case study building a series of readings at different heights and locations were made with the 'Balemaster', the profiles shown in the Fig.79 & Fig.80 (above) were chosen because they were seen to be representative of that particular building.

It is interesting to note that the variations found in the readings from a single building shown earlier in Fig.73 cover a similar range of moisture content to all the case study buildings shown in Fig.80.

All the profiles come from walls that were on the exterior of a building and therefore the moisture profiles are from the inside to the outside of each building. The moisture profiles show the effect of the different environments on each side of the wall. Although all the profiles display different moisture levels, there are similarities, and Fig.80 shows a common pattern and gradient, especially in the average of the readings shown by the red line.

	INSIDE (%)	CENTRE (%)	OUTSIDE (%)	DIFFERENCE (%)
HIGHEST	13.3	17.5	19.3	6
LOWEST	10.5	12.6	16.4	5.9
AVERAGE	12.5	15.2	17.9	5.4
SPREAD	2.8	4.9	2.9	

Table.7 Summary of values from the moisture profiles of selected case studies. The columns show the readings from nearest the inside edge of the wall, the middle of the wall, and the outside edge of the wall. The last column shows the difference between the inside and outside readings.

The summary of the results in the table above shows that there is an even spread of moisture levels through the different walls, with the readings from the inside and outside separated by less than 3%, and a greater spread in the middle of just under 5%. The increase in moisture from inside to outside is also consistent at around 6%. The average of the readings in the middle of the walls is 15.2%, which is very similar to the figure of 15%, which is the overall average of all the readings from the selected walls.

These case studies are not shown for the following reasons:

- Grange Farm, and Hedgerow House, as they both had suffered from water ingress and were therefore untypical.
- The panels at Liskeard and UWE, as they were freestanding in the outside with no interior or exterior.
- The holiday cottage built by Carol Atkinson was excluded because it was in the process of construction, and therefore also untypical.

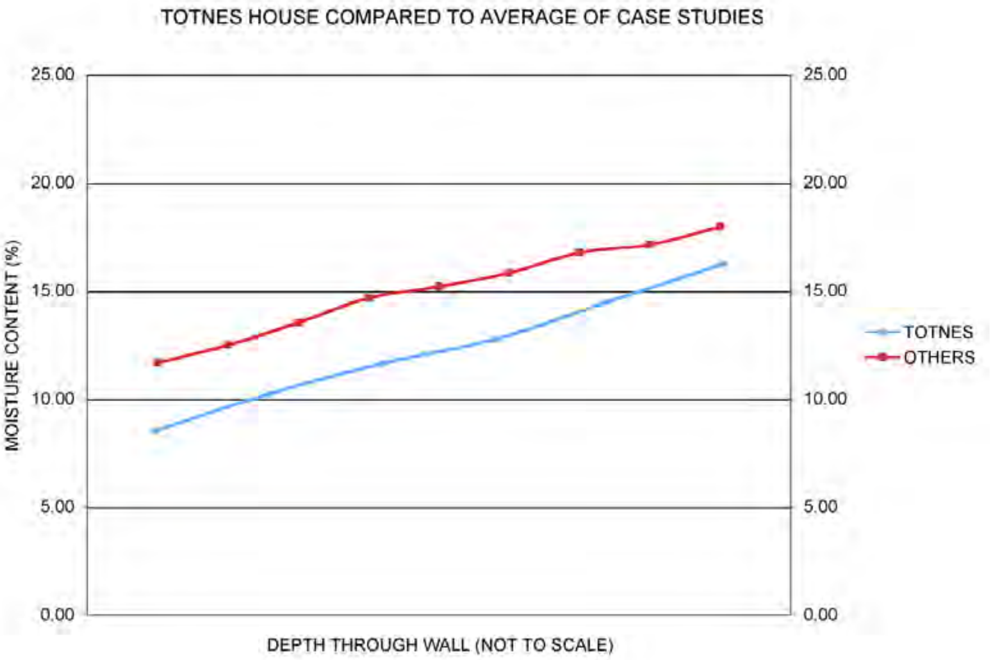


Fig.81 Average moisture content of bedroom 2 in the Totnes House compared to the averaged moisture profile of all the other case study buildings.

Because the bales in the walls of the Totnes house are laid on their edge, the depth of the wall is less than any of the other case study buildings. In order to get a comparison between the readings from the Totnes House and the others, the scale of the 'x' axis (Depth through wall) in each case has been changed to show the inside and outside of the walls in the same plane.

The graph shown above in Fig.81 (above) shows that this wall of the Totnes House follows a similar gradient but has a lower overall moisture content. The lower moisture content could be explained by the fact that apart from Cuckoo Farm, the Totnes house is the only building in this research that is a fully occupied domestic dwelling. This means that the internal temperatures will be higher, and RH will generally be lower during the heating months of October to March.

In section 7.2.3 Two moisture maps from the Totnes House where shown to compare the patterns of moisture in a wall where higher levels of moisture had been recorded.

These can be compared with a moisture map of a first floor wall at Cuckoo Farm (Fig.82, below).

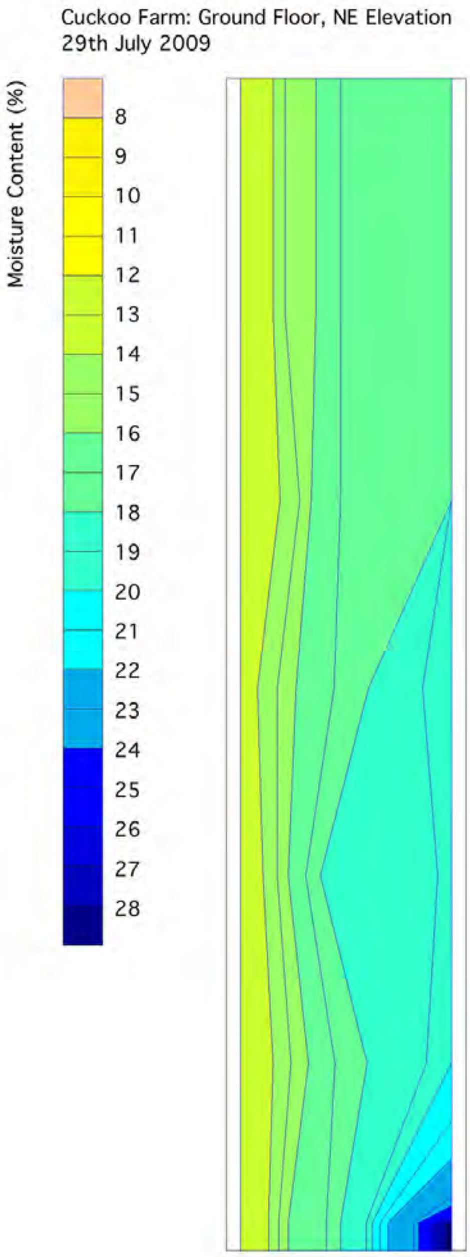


Fig.82 Moisture map of wall at Cuckoo Farm
(Interior of the house on the left)

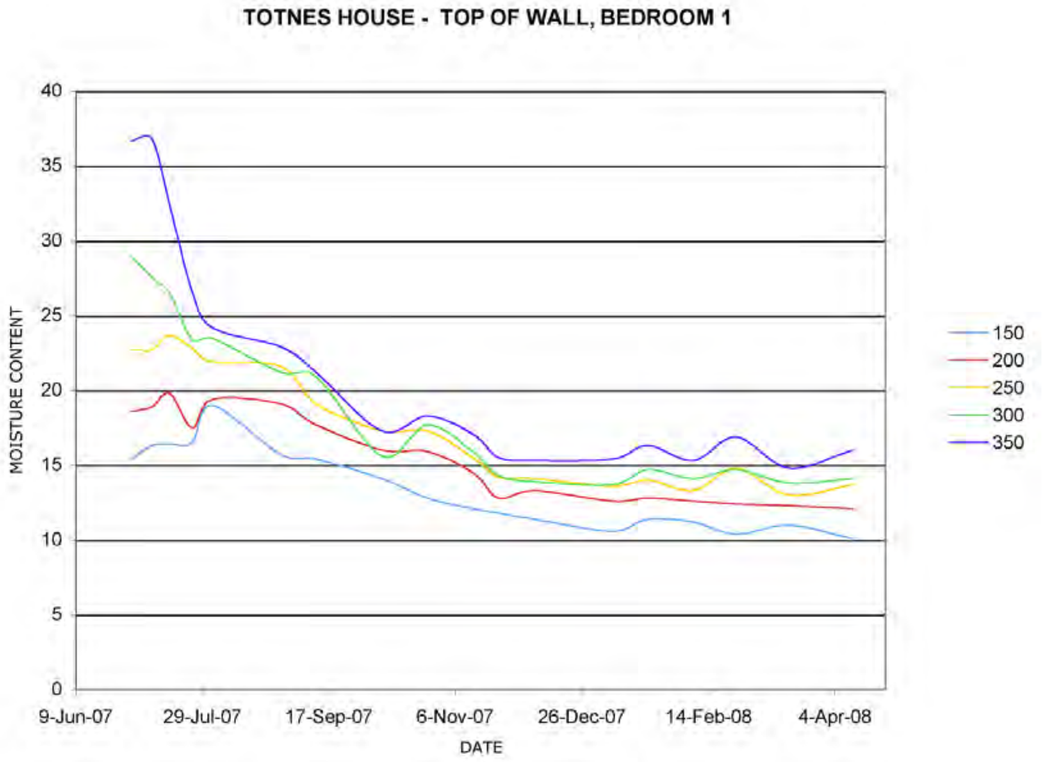
The moisture map of the wall at Cuckoo Farm shows a higher level of moisture (average 14.3%) on the interior side of the wall than the walls of the Totnes House (average 8.52%). Apart from presumed differences in heating regime and internal RH levels, an explanation for this could be that the interior walls of this building had not been rendered, and the surface of the straw is open to the atmosphere. The fact that a lime render has a lower vapour resistance than straw might be an explanation as to why the straw behind the render of an interior wall has a lower moisture content than uncovered straw. The role of a hygroscopic render in the moisture performance of straw is discussed elsewhere in this thesis

The exterior of the wall is also showing a higher than average moisture content as compared to the Totnes House, but not by as high a margin as was seen for the interior. The readings were 18.06% for Cuckoo Farm and 16.24% for the Totnes house.
This wall at Cuckoo Farm faces north, so is not the weather wall, but there have been problems with the render, which has cracked and been repaired. This could explain the generally higher moisture levels.

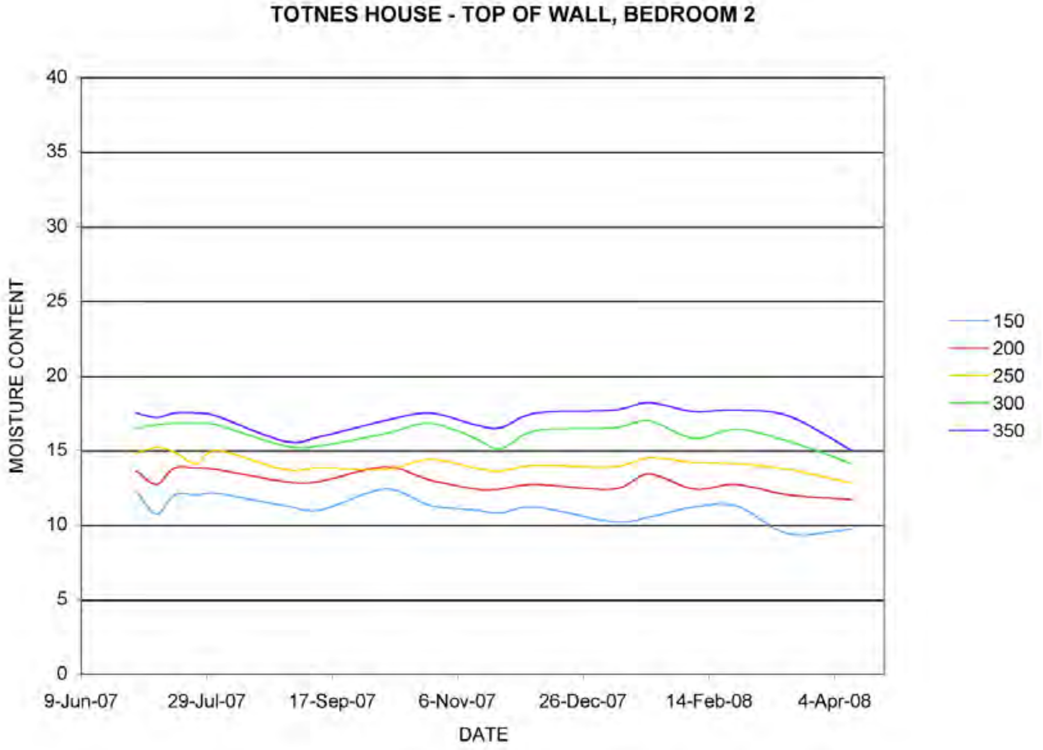
The other marked difference between this wall and the walls of the Totnes House is the sudden increase in moisture at the outside bottom edge of the wall. The moisture behaviour in this section is more like the walls illustrated in the Sanders diagrams in Fig.68 (section 7.2.1). However, the increase in moisture isn't gradual and the more localised nature of the high moisture levels might also be explained by the dark stain at the bottom of the render. This stain could have
resulted from the habit of the owners of piling up objects against the wall, thus creating a path for moisture to enter the wall at this point.

7.3.3Long term drying of moisture in straw bale walls

A wall from the Totnes house that had suffered from water ingress has been discussed in the previous chapter, and a moisture map shown in fig.72. In the moisture map, the level of moisture in the wall is illustrated at the point that it was discovered The graph, below, in Fig.83 shows the pattern of moisture in the wall as it dries back over an 11 month period. This is shown with the readings from the adjacent bedroom over the same period.



TOTNES HOUSE - TOP OF WALL, BEDROOM 1



TOTNES HOUSE - TOP OF WALL, BEDROOM 2

Fig.83 Comparative readings from the bottom of the wet and dry walls. June 2007 to April 2008

The graphs in Fig.83 show comparative moisture measurements of the exterior walls of the two adjacent rooms during the drying out of the wet wall between June 2007 and April 2008. The measurements were taken at 50mm intervals

through the wall from a depth of 150mm to 350mm, starting from the inside face. The drying process went through two distinct phases:
During the first five weeks the outside of the wall (the dark trace on the graph at 350mm) dried back fairly rapidly, while at the same time the trace nearest the interior of the wall shows the opposite trend. There are perhaps two conclusions to be drawn from this:

- First, the apparent movement of moisture from the outside of the wall to the inside seems to indicate that the vapour pressure is equalising across the whole wall causing the excess moisture to spread itself more evenly through the wall.
- Second, that in order for this phenomenon to be visible, it seems likely that the moisture ingress had only started shortly before it was discovered and stopped, or it might have spread further through the wall.

The second phase went through to November 2007, and shows the whole depth of the wall drying out at a similar rate until it reached a level of moisture content comparable to the dry wall shown below. The level achieved is indicative of the expected levels in a lime rendered wall, with the spread of moisture going from 12% on the inside to 16.0% on the outside. The graph of the dry wall, although appearing almost flat compared to the wet wall, showed that whilst the outside of the wall stays at around 16.5%, the inside of the wall, even eighteen months after the house was completed, is still gradually drying back from 13.0% to 11.5%.

At Occombe Farm, one of the case study buildings, there was an ingress of water during the construction phase. While the roof covering was being installed, a sudden downpour caused water to run into the tops of the walls, and down the tensioning straps that were being used to compress the walls (this is a technique used to pre-compress the straw of a load-bearing wall to avoid differential movement when the roof load is added).

Fig.84 Water damaged straw has been removed from wall of Occombe Farm

The fully saturated straw surrounding the blue tensioning straps turned black and started to compost within 48 hours of the downpour. The owner of the building had the blackened straw removed and decided not to replace the rest of the straw in the walls, despite the advice given at the time. The remaining straw, although not fully saturated with water had a high moisture content with sections of the straw reading over the ‘Balemaster’ limit of 36.8%. The photograph in Fig.84 above, shows the wall with most of the blackened straw removed, but the water damage is still evident.

Regular monitoring of the walls at Occombe Farm commenced a week after the water ingress, and the results from measuring the moisture at the top, middle and bottom of one of the walls are shown in fig.85 below

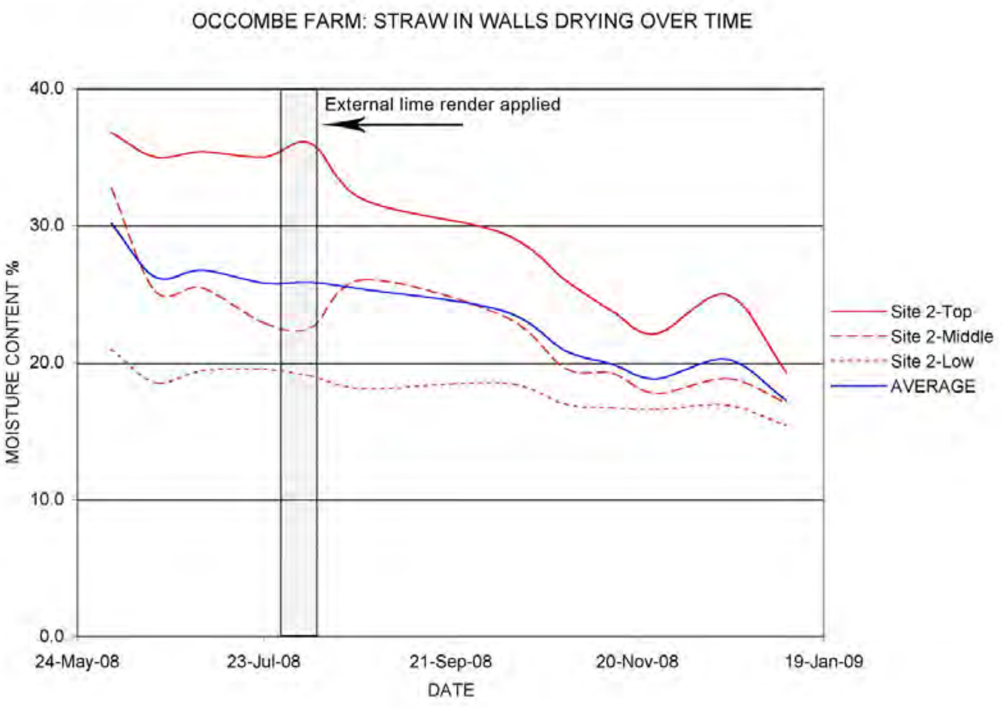


Fig.85 Pattern of moisture in straw bale wall at Occombe Farm The grey rectangle shown after 23-Jul-08 represents the application of the external render.

Looking at the graph shown in Fig.85 the data seems to suggest that the application of the external lime render is having an effect on the drying of the wall. The patterns of moisture at the top and middle of the wall do change at the time of the rendering, with the moisture in the middle of the wall increasing at the same time that the moisture at the top is decreasing by a similar amount. The average moisture content isn’t affected which indicates that the render may be influencing the redistribution of moisture in the wall. Overall, the moisture in this wall has taken 9 months to fall back to an acceptable level, with a maximum moisture content below 20%, at a rate of 1.4% per month.

Comparing the results from Occombe with the wall of the Totnes house shown in Fig.83 the rate of drying at Totnes was faster with a drop of 1.81% per month. In the case of the Totnes house, the moisture levels didn't start as high, and finished lower, with a maximum of just over 15%. As previously stated, the Totnes house is also a heated domestic dwelling and at the time of the drying of the Occombe wall, the building was largely unoccupied.

Another building that has shown a distinct pattern of moisture behaviour is the holiday cottage built by Carol Atkinson in Yorkshire shown in Fig.86 below. In this example the results are from the new wood block probes that were installed in the building during the construction phase. The initial steep rise in the moisture content, displayed by the probes, is the effect of the probes adjusting to the actual moisture in the wall. By the time of the third reading, 16 days after installation, the probes were showing the same levels of moisture as the 'Balemaster' recorded at the same place. For the next six months the average moisture levels stayed at a relatively high rate, displaying their highest average moisture content of 22.6% in September 2009, 7 months after installation. Over the next 4 months the average moisture level fell to 18.9%, a drop of 3.7%. This is slower than the overall rate of change at either Occombe or Totnes, but can be compared to the second phase of drying at the Totnes House.

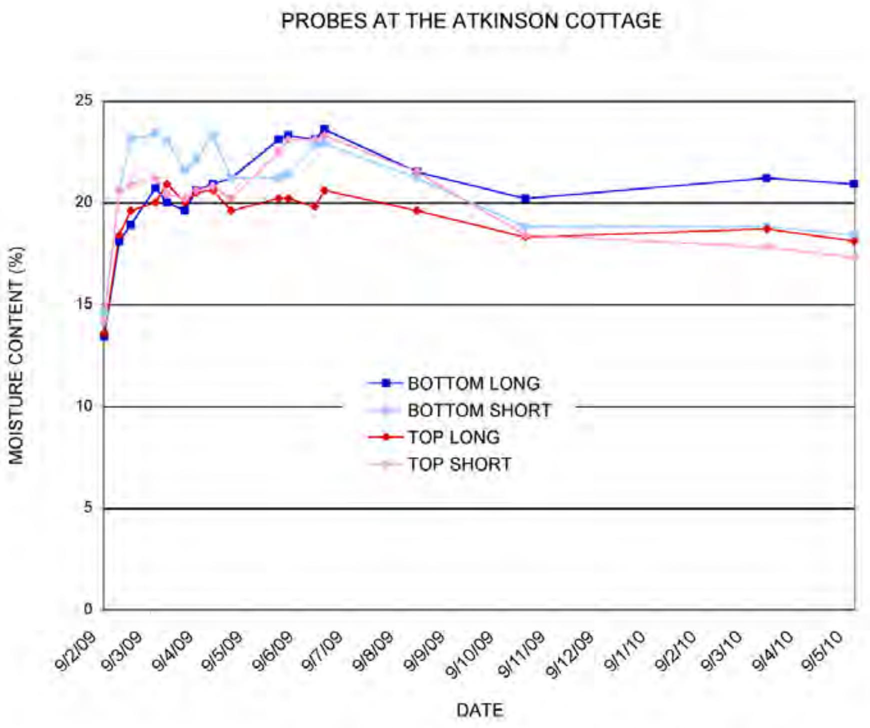


Fig.86 Patterns of moisture recorded from the probes in the walls of the Atkinson cottage

7.3.4 Analysis of the relative rates of change in a straw bale wall.

In the laboratory research that created the isotherms for straw it was possible to measure the reaction time of loose straw to changes in the RH of its immediate environment. As discussed in section 6.7 the experiment found that the straw in the environmental chamber adsorbed and desorbed moisture at a rate of approximately 1% per 24hr period. The rate of change in a stable rendered straw bale wall is more difficult to measure. This is because the changes are slow, and the monitoring of the case studies was not set up to gauge the time that a finished straw able wall will take to adsorb or desorb moisture. This specific task would be a difficult to contrive, as it would presumably involve deliberately introducing moisture into a wall in order to gauge the response. However, it has been possible to look at changes in walls that have suffered from more extreme moisture episodes.

In the section above the drying out of the wall of Bedroom 1 from the Totnes House was illustrated in Fig.83 Looking at the purple trace that shows the moisture levels at the outside edge of the wall (350 mm from the inside), the highest recorded rate of change in a finished wall with excess moisture was between the 9th of July and the 25th July when the moisture content fell by 10.2% over 16 days, a rate of 0.6% per 24hr period. The difference in the rate of change in the straw in the Laboratory, compared to straw in a wall, may be due to the greater density of the bales in the wall and the buffering effect of the render.

The graph in Fig.87 below, shows the readings from the wood block probes installed at the Footprint Project at lake Windermere. The pattern here is not the same as in Fig.86, but a similar general rise in moisture levels through the summer months is displayed.

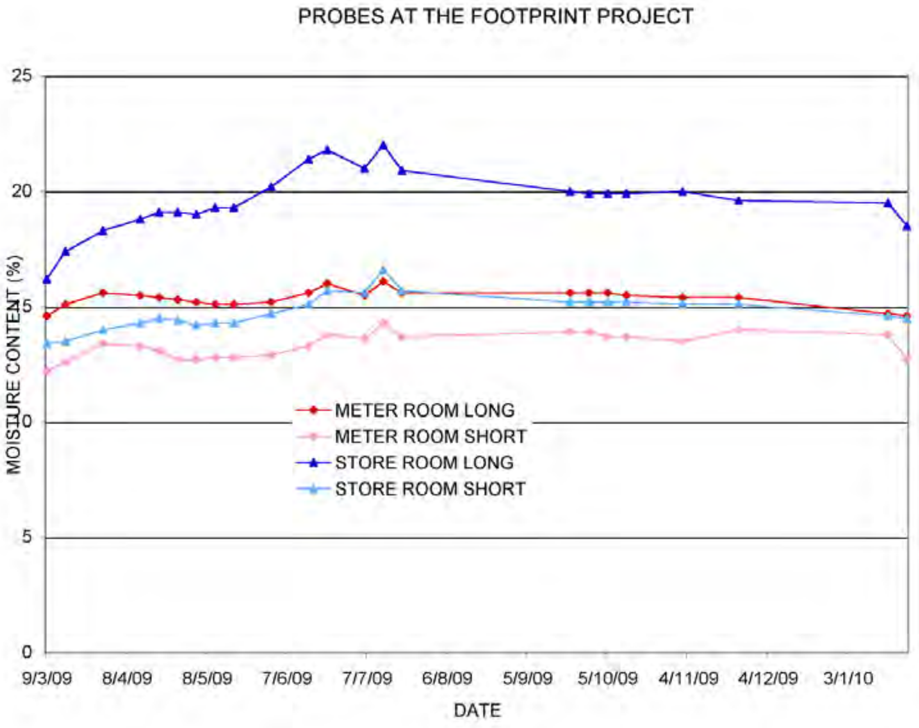


Fig.87 Readings from the new wood block probes installed at the Footprint Project

7.3.5 Effects of more extreme weather

Three coats of lime render protect the ground floor walls of the Totnes House. This form of render was chosen for its greater permeance to water vapour, as described in chapter 3.

The problem with such a hygroscopic material is that there is the potential for moisture from driving rain to enter the wall, and although it would normally evaporate from the wall surface, if the rain is constant then there can be a dangerous build up of moisture in the straw. An example of such moisture build up can be seen in the moisture profile through a wall on the southwest elevation of Cuckoo Farm, compared to a wall on the same elevation of the Totnes House (Fig.88, below). For both these houses the prevailing wind is from the southwest, so it is the elevation that receives the most rain. In the case of Cuckoo Farm the moisture has reached a level of 26.8% at the exterior edge of the straw.

The wall at Cuckoo Farm was built with the bales on their flat side, and so the depth of the wall is 100 mm thicker than that of the Totnes House, so the moisture profiles in the graph have been adjusted so the finish in plane with each other.

The differences between these southwest walls of Cuckoo Farm and the Totnes House that might be effecting the moisture levels are:

Cuckoo Farm is in an exposed position on a hill at a height of 110 m (Totnes House is at 50 m)

Cuckoo Farm is nearer the coast, with no high ground between it and the sea and so can be assumed to have higher levels of precipitation.

There are only two coats of render on the walls of Cuckoo Farm, with a depth of 20 mm (Totnes House has 30 mm). The render was also of a poor quality and in some places had cracked badly as shown in the picture in Fig.86 below.

Fig.88 Poor quality of render on NE wall at Cuckoo Farm

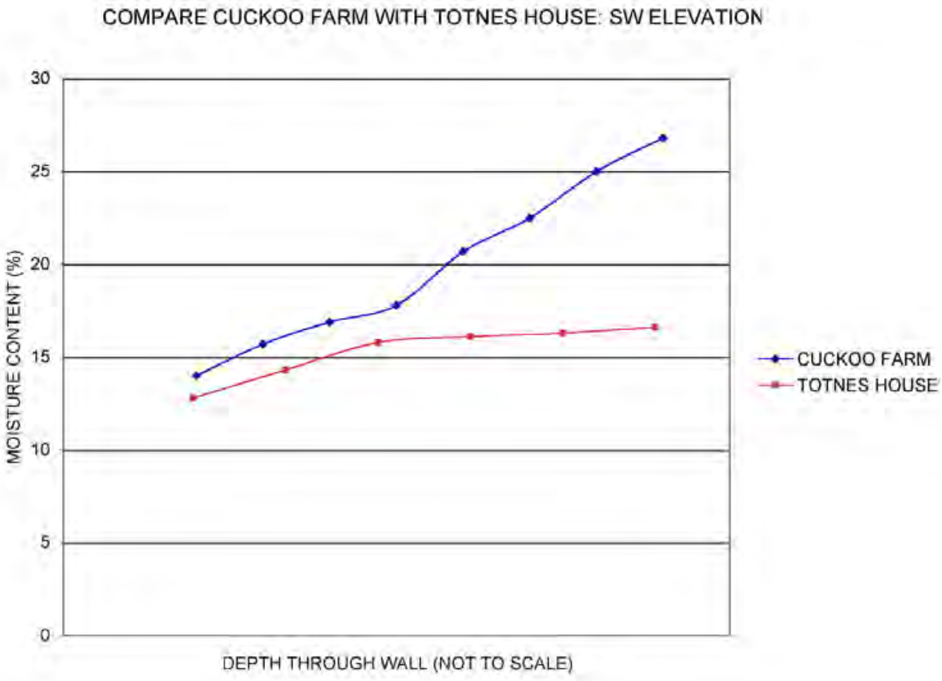


Fig.89 Comparing the moisture levels in the weather walls of the Totnes House and Cuckoo Farm.

Because the bales in the walls of the Totnes house are laid on their edge, the depth of the wall is less than any of the other case study buildings. In order to get a comparison between the readings from the Totnes House and the others, the scale of the 'x' axis (Depth through wall) in each case has been changed to show the inside and outside of the walls in the same plane.

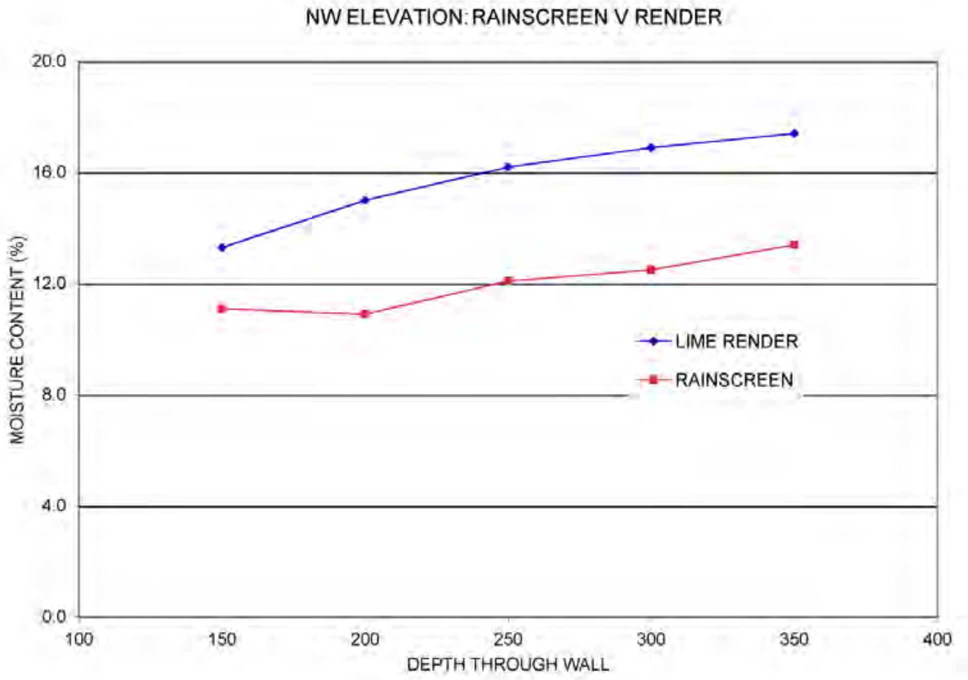
These measurements were taken at Cuckoo Farm in July 2009. More recently (Mid 2010) remedial work has been done on the wall, with much of the render replaced with a better, thicker application of hydraulic lime. The moisture level at the outside edge of the straw on 29th November 2010 was at 23.5%. This is still a high reading, but there are encouraging signs of a reduction over time.

7.4 Role of rainscreen in protecting straw bale walls

If plain rendered walls in exposed positions are vulnerable to increased moisture, then a potential solution is to add a further layer of protection in the form of a pressure equalised rainscreen (PER) (Straube 2001). This could take the form of a vented impervious layer on the outside of the building. In natural buildings such as those made with straw bales, the rainscreen is commonly made from timber.

7.4.1 Results from Totnes House

In the moisture measurements taken at the Totnes House on the same day, and shown in fig.73 (section 7.2.4), it can be seen that the wall with the lowest moisture content was the first floor wall protected by a timber rainscreen. Simultaneous measurements had also been taken from two elevations of the Totnes House on an earlier occasion. Taken on the same day, the 8th November 2008, these readings directly compare the ground floor (30 mm lime render) with the first floor (timber rainscreen). On two of the elevations, Northwest and Southeast, moisture readings were taken in the same position on both floors, allowing a comparison to be made (Fig.88, below). All the exterior walls are constructed with straw bales on their edge, with a thickness of 390mm, including three coats of ‘fat’ lime render on the inside. The outside of the straw bale wall on the first floor has a single 10mm coat of render, an air gap of 25 mm, a breather membrane, another air gap of 25 mm and finally the cedar rainscreen which is 18 mm thick; leading to an overall exterior wall thickness of 468mm. On the ground floor the straw is finished with the same three coats of fat lime render on both sides.



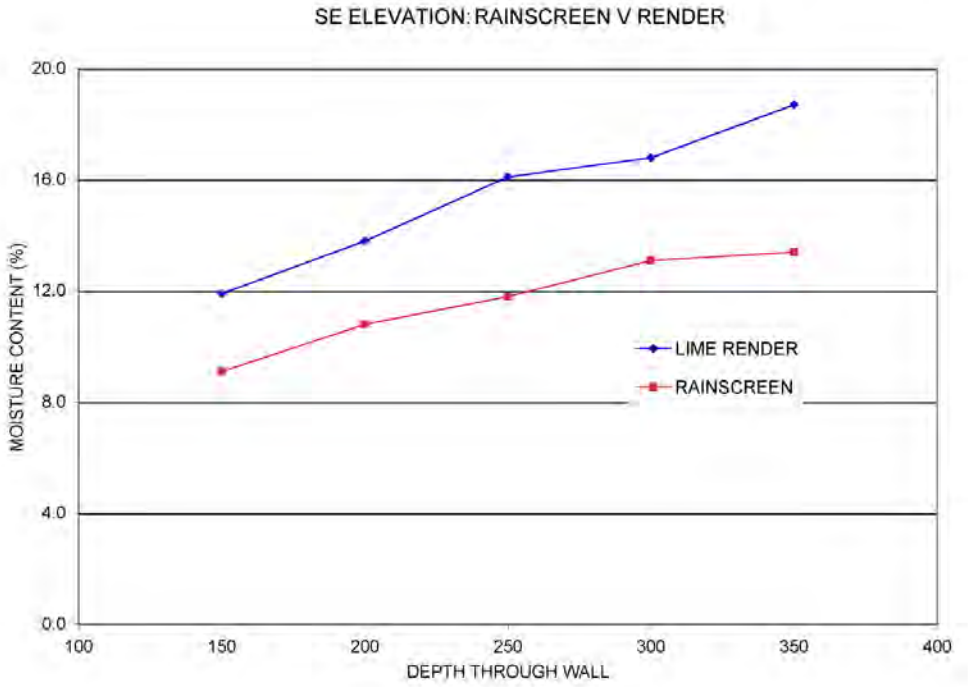


Fig.90 Comparing the moisture content of walls protected by a rainscreen with plain rendered walls.

The graphs in Fig.90 above show similarities, with the average difference in moisture content between the render and the rainscreen cladding being 3.8% on both elevations. There are other factors influencing the readings, such as distance from the ground, and the fact that the water running off the rainscreen cladding is likely to be falling on the render below. This research indicates that these results provide a fair representation of the reduction in moisture afforded by the use of rainscreen cladding.

7.4.2 Results from Liskeard

The readings from the Totnes House can be compared with the results of an experiment set up by the University of Bath, to compare the efficacy of different mixtures of lime render on a series of straw bale filled panels, constructed in a field near Liskeard, Cornwall in 2007. It was decided to add timber rainscreen cladding to one of the panels, allowing a comparison to be made between two of the panels that were the same in all respects apart from the addition of the rainscreen cladding to one of them, see Fig.91 below.

Fig.91 Panel at Liskeard with timber cladding

The method used to measure the moisture content of the straw bale panels at Liskeard differs from that used at the Totnes House. In this case the moisture content was recorded by using relative humidity sensors, placed at various locations in each panel. The graph in Figure 90 below shows a combined average reading from the same four sensors placed at the bottom front and middle, middle front and middle of the middle in both the rendered and rainscreen panels.

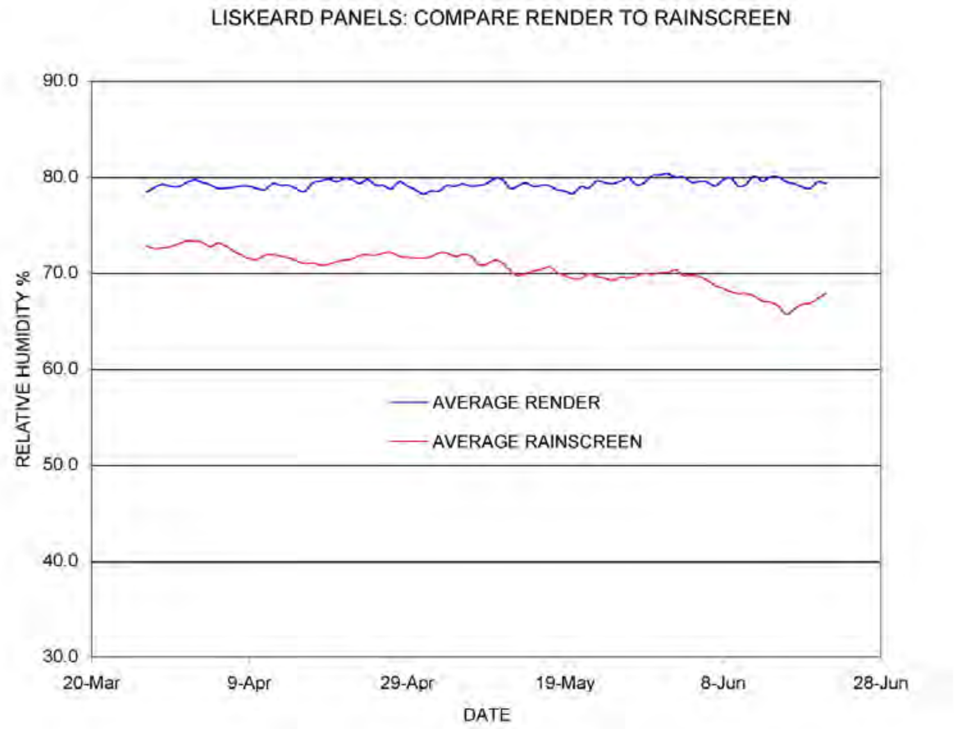


Fig.92 Averaged RH readings from two of the Liskeard panels, one with a rendered finish, the other protected by a rainscreen.

The other difference is that the Liskeard graph in Fig.92 above shows a series of readings taken over three months, rather than a snapshot of a single day, as in the Totnes House graphs in Fig.90 above. It can be seen that the rendered panel has remained fairly constant at around 80% relative humidity (RH), while the rainscreen cladding protected panel is gradually drying out.

Using the sorption isotherms discussed in chapter 6, it is possible to translate the RH values into moisture content (written as a percentage of the weight of water to the dry weight of straw). When observing the RH of the two panels at the end of the time period, it can be seen that the rendered panel has an average of 79.5% compared to the rainscreen cladding panel at 65.7%. This translates to moisture contents respectively of 16.8% and 13.6% with a difference of 3.2%. At the Totnes House the difference was 3.8%, showing that a rainscreen cladding panel has had a consistent effect in these different applications.

7.5 Buildings that exhibit evidence of high levels of moisture

In Chapter 6 an experiment was conducted to look at the long term effects of elevated moisture on straw in the laboratory. The results of this experiment with straw in desiccators can be compared with observations from different examples of the straw bale case study buildings that have experienced problems with high levels of moisture or water ingress.

Fig.93 Bottom of damp wall at the Totnes House

The first example is of a straw wall with higher than normal moisture levels, but no recorded water saturation. Due to a problem with a drip detail at the Totnes House (see chapter 6), water ingress had been occurring for an unknown period of time, but not in large enough quantities to saturate the straw. The readings at the base of the wall showed an average moisture content of 25.7%, with a maximum of 34% which is above the recommended maximum safe level of 25%(Summers 2006), but below the fibre saturation point (Lawrence *et al.* 2009). When a section of the lime render was removed to investigate the condition of the straw in the wall (as shown in fig.93 above), the straw appeared in good condition but felt damp to the touch. The straw looked darker than fresh straw, but when it had dried in the room it resumed the same colour as fresh straw, as shown in fig.94 below

Fig.94 Straw from the damp wall at the Totnes House, after drying

The next case is from Hedgerow House in Leitrim, Ireland. This house had many problems with its construction, and there was excess moisture in the parts of its walls that were exposed to the weather, but like the Totnes House, it did not appear to be saturated. Two samples of straw were photographed at the site and are shown in fig.95 below

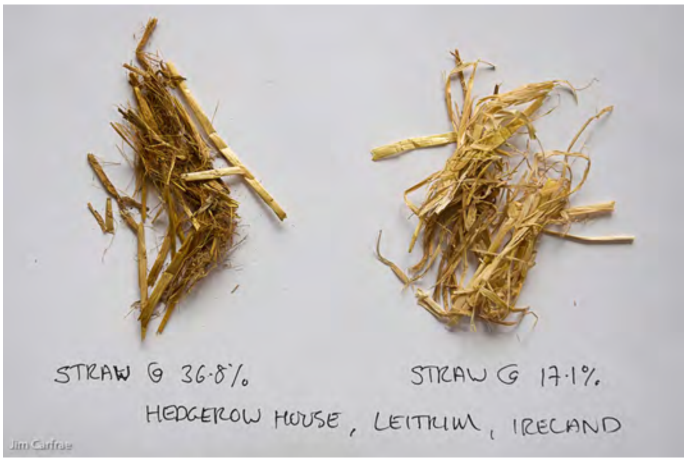


Fig.95 Samples of straw from Hedgerow House

The sample on the left is from an exposed wall where the maximum reading was 36.8%. This sample is both darker than the sample on the right, which is from a point in the same wall where the moisture was lower, but also shows some small black dots, which might indicate microbial activity.

The damp straw from the Irish house still had structural integrity; the stalks resisted being pulled apart and felt the same as the dry straw from the same wall. This apparent durability was unlike the water damaged straw from the load bearing building at Occombe Farm pictured below in fig.96

Fig.96 Water damaged straw at Occombe Farm

The photograph taken at Occombe Farm, above, shows a section of wall where water had been allowed to enter the top of the wall during the construction phase. The water ingress occurred only once, but in large quantities at regularly spaced intervals along the length of the walls. This water ingress meant that specific areas became saturated beyond the fibre saturation point and free water was present in the wall. The straw at these points went black and started to break down. The rotten straw was removed and the cause of the water ingress was fixed. Closing off the water allowing the remaining straw to dry out. Where the straw had achieved high moisture levels, but had not become saturated, the straw was discoloured but still retained its structural integrity.

The level of damage at Cuckoo farm was similar to Occombe. In this case there had been a significant failure of the render after application, and water ingress had followed. Like Occombe, saturated sections of straw quickly turned black and rotten, but again, where the straw just had high moisture levels, it still appears robust. See fig.97 below.

Fig.97 Corner of a wall at Cuckoo farm, where the render has failed.

The final example of a structure that has suffered with water ingress comes from a single ModCell display panel at the University of the West of England (UWE).

ModCell is a proprietary pre-fabricated straw filled panel system that has been successfully used in a variety buildings (ModCell 2010a), but this single panel had been erected on its own without an adequate weatherproof capping, which along with cracks in the external render, had allowed water ingress from the top over some time.

Fig.98 Section taken from bottom of ModCell panel at UWE

Readings taken from the panel revealed moisture contents in excess of 36.8% in some areas (The maximum value recorded by the ‘Balemaster’ probe), and the average of all the readings across the panel was 24.2%.

Despite the relatively high moisture readings, the straw retained its fresh golden colour apart from the first 30mm or so of straw at the bottom, which was wet to the touch and had a dark discolouration.

The straw was sitting on a plastic DPC and therefore unable to drain any of the water that might have entered the panel from the top.

7.6 Summary of Chapter 7

The monitoring of the case study buildings has shown that where there is a difference in interior and exterior environments, the moisture in a typical straw bale wall will form an even gradient from the interior to the exterior.

In the buildings monitored in this temperate maritime climate it was unusual to find moisture levels above 20% in the straw of a wall made from rendered straw bales. Where the moisture was higher than 20% there was generally an observable cause of the moisture ingress.

The moisture content of the straw in walls that had not been subjected to abnormal water ingress proved remarkably consistent, and showed small degrees of change over time.

The common observation from these case studies is that if the straw has a moisture content above 25%, but below the fibre saturation point of 37%, then it is unlikely to have sustained permanent damage if the cause of the elevated moisture is identified and the straw is allowed to dry back.

It is equally clear that straw subjected to free water, particularly where the water is prevented from escaping, will deteriorate quickly. In all cases where straw was left saturated it had started to break down and needed to be replaced.

8. SUMMARY OF FINDINGS, FURTHER WORK AND CONCLUSION

This chapter summarises the findings of the research and the role of straw bale in the future of low carbon building.

It also provides suggestions for further work, including the viability of using data logging with the newly developed probe. Questions are raised over the consistency of the wood species used.

8.1 Specific objectives

In the opening chapter a set of objectives for this research were laid out as follows:

- To provide an overview of straw used as a construction material, particularly as used for domestic housing in temperate maritime climates.
- Investigate the problems caused by moisture in straw when used as a construction material.
- Establish a methodology to monitor moisture content in straw when used as a construction material.
- Explore the development of a wood block probe as a means of testing moisture content in straw when used as a construction material.
- Establish hygrothermal measurements for straw in the laboratory
- Analyse the results of monitoring the moisture content in a number of case study buildings, where straw is used as a construction material.
- Formulate a series of recommendations to help avoid the potential for high levels of moisture in the design of low energy housing using straw as a construction material.

A summary of how these objectives have been answered is detailed below:

1. To provide an overview of straw used as a construction material, particularly as used for domestic housing in temperate maritime climates:

There were fears expressed in the literature that straw bale construction might not be suitable in a climate distinguished by high levels of precipitation and elevated levels of environmental RH, such as is found in a temperate maritime climate.

Earlier research carried out on straw bale buildings in the more arid regions of the world found moisture levels that seldom rose above 15%, unless there was a problem with the building that allowed water ingress. The review of the literature also established a gap in the knowledge with regard to what sort of moisture levels could be expected in a predominately cool, humid, environment.

This research helps to address this gap in the knowledge by investigating buildings in a temperate maritime climate. The buildings detailed and monitored by this research have shown moisture levels that seldom rise above 20% in normal circumstances, and have an average of 17.5% moisture content at the outside edge of the wall, well within the accepted maximum safe level of 25%

2. Investigate the problems caused by moisture in straw when used as a construction material:

There are two related problems that have been identified by this research, and caused by excessive levels of moisture in straw. Both will impact on the longevity of the straw, and consequently the building it has been used in. The first problem occurs when the straw has accidentally become saturated with water. This is more likely to happen in the construction phase, and will result in the straw starting to rot and turn black as it breaks down.

The second problem was found to arise if the straw had been subjected to elevated moisture levels even without becoming saturated. In this case the danger is from mould growths on the straw that break the straw down gradually, also presenting a health risk to humans if the spores are released into the atmosphere.

The difference is that once the straw has started to rot and turn black there is nothing that can be done except replace it. If the straw has started to grow mould but isn’t saturated, in a lot of cases, it can be dried out and reused, or left in-situ if the cause of moisture ingress can be identified and stopped.

3. Establish a methodology to monitor moisture content in straw when used as a construction material:

The different methods available for measuring the moisture content of straw have been examined and tested. Gravimetric analysis was used as part of the laboratory procedures, but is impractical for use with existing straw bale structures unless a substantial amount of straw can be safely removed.
RH and temperature measurements were integral to the research, but the use of RH probes for in-situ monitoring was discounted on the grounds of excessive cost, along with uncertainty over their ability to accurately reflect the moisture of straw once hysteresis was taken into account.

The use of the “Balemaster’ agricultural straw moisture probe proved effective and accurate for surveying straw bale buildings, but cannot be left in-situ for continuous monitoring.
The principle of embedding a block of timber in the straw, on the assumption that its hygrothermal performance will closely mimic the surrounding straw, has been found to best suit the long term monitoring of straw bale walls and was therefore used for this research.

4. Explore the development of a wood block probe as a means of testing moisture content in straw when used as a construction material:

This research has developed a new probe that has improved on a method of monitoring the moisture content of straw bale walls by using wood to mimic the moisture content of the straw. Different prototype designs were tested in-situ while the moisture performance of a selection of timber species were compared to straw in the laboratory. These two strands were brought together in a design that was then calibrated in the laboratory to within +/- 1%. The new probes were installed in the walls of a straw bale house and compared to the readings from an agricultural straw probe, as well as RH and temperature probes concurrently. The results of these tests show that the new wood block probes display a level of accuracy that confirms the laboratory results, and is within +/- 1%.

5. Establish hygrothermal measurements for straw in the laboratory:

A full set of sorption and desorption isotherms for both wheat and oat straw have been created in the laboratory. Isotherms for three species of timber were created at the same time, allowing for an informed decision on the choice of timber for the wood block probe.

The isotherms for straw and timber both demonstrate similar levels of hysteresis, but show lower levels of moisture at high RH than previously published isotherms. Comparative in-situ measurements with the ‘Balemaster’, an RH and temperature probe, and wood block probes installed in the same walls gave results that indicated that the new isotherms were indeed accurate in this context.

6. Analyse the results of monitoring the moisture content in a number of case study buildings, where straw is used as a construction material:

The monitoring of the case study buildings showed that in a temperate maritime climate, the maximum moisture content found in an suitably detailed straw bale wall, is likely to be 20%. The walls of the case study buildings showed broadly similar moisture profiles through the wall from inside to outside, which is in accordance with the theory of moisture transport through a hygroscopic structure.

Where there was a moisture content in excess of 20%, an external cause for it was normally found. Such high levels of moisture could be traced to either a fault in the construction of the wall, or unusually high levels of precipitation from driving rain. This research also indicated that the effects of elevated moisture, caused by driving rain, can be mitigated by the use of a ventilated timber rainscreen. This was shown to reduce the moisture in a straw bale wall by over 3%.

While the level of moisture found in the walls of the case study buildings was generally higher than the moisture levels in the walls monitored for the published studies from more arid climates, the increased moisture content was not high enough to cause long term problems for the structural integrity, longevity of the wall, or to provide a health risk to those in occupancy.

7. Formulate a series of recommendations to help avoid the potential for high levels of moisture in the design of low energy housing using straw as a construction material:

Recommendations to help avoid the potential for high levels of moisture in the design of low energy housing using straw as a construction material are as follows:

- Ensure that the render on the straw bale walls, or any other form of cladding, is vapour permeable.
- To mitigate against water ingress, it is important to pay attention to drip details and sills.
- If the design of the building calls for a shallow or flush eaves detail, then it would be wise to use a ventilated rainscreen to protect the walls below the eaves.
- A ventilated rainscreen is also recommended for additional protection on walls that face the prevailing weather patterns, and buildings in exposed situations.

- If using a lime render as a vapour permeable finish, then pay particular attention to the proper procedures for the mixing, applying and curing of the material, in order to avoid the cracking that was seen on some of the case study buildings.
- Contrary to some predictions, there were no examples of elevated moisture levels in the walls of rooms that had high levels of internally generated water vapour such as bathrooms and kitchens.

8.2 Inter-relationship of Laboratory results and In-situ measurements

The results in the preceding sections show a close relationship between the readings from the various probes and the laboratory work. This confirms a level of accuracy that makes the new woodblock probes viable as a means of measuring the moisture content. This is an important contribution to the knowledge in this area of straw bale monitoring. It is relatively unusual for the different strands of research to come together so closely and to find the results from the laboratory supported by results from the field and vice versa.

8.3 Limitations of the results and suggestions for further work

On the surface, the description of the new wood block probes seems simple. They are composed of a small number of relatively cheap and easy to source materials. A piece of ramin cut from the end of a broomstick is attached to the end of a length of uPVC overflow pipe. Then two lengths of wire are attached to a pair of stainless steel screws in the ramin, and the finished probe is ready to be inserted into the straw bale wall.

These probes have been specifically designed for the builder of a straw bale house to be able to manufacture and install the probes for themselves. In practice they are not as simple to construct without the facilities found in a workshop. The ramin bullet needs to be turned on a lathe to produce the pointed tip, and to be reduced in diameter to fit in the uPVC tube. Inserting the stainless steel screws is difficult without the use of a pillar drill, and a soldering iron is needed to attach the wires. Having said that, none of the above procedures are any more difficult than the building of a straw bale house.

8.3.1 Development of data logging probe

Although this research has indicated that changes in the moisture content of the straw in a rendered wall will change relatively slowly from day to day, it would be of interest to compare hourly readings of the moisture content from the wood block probe to the levels of the RH and temperature in a wall taken in the same place and at the same frequency.

The monitoring of straw bale walls using the new wood block probe used in this research did not allow for readings more frequent than once every 24 hours, and the process of physically moving from probe to probe in order to record the moisture content manually is time consuming. An obvious development of the wood block probe would be to incorporate some form of remote data logging facility.

Unfortunately the wood block probe in its current form does not lend itself to use with a data logger. Bigland-Pritchard (2005) states that

“The enormous variation of timber conductivity with moisture content demands high resolution over multiple orders of magnitude of resistance”.

This means that the moisture content cannot be measured with a standard multimeter, which precludes the use of a conventional data logger. A method of using a block of wood for measuring moisture that could be used with a data logger would be an area for future development.

8.3.2 Consistency of ramin samples

Further work will need to be done on the consistency of different samples of ramin, which was the timber species chosen for the wood block probes. During the production of the 48 sets of probes to be used in the long term monitoring project, two different sets of the dowel used to make the ramin tips of the probes were acquired from separate suppliers. During calibration it was found that one set of probes were giving slightly different readings to the rest and this was traced to a particular sample of dowel. All the dowel was described as being made from ramin, and all looked similar, but it appeared that there were variations in the timber used. The readings from the samples that conformed with each other were within =/- 1% moisture content at 90% RH, whereas the rogue samples were all reading -2.5%.

The calibration process was used to identify and reject the rogue sample of ramin, but this will be difficult for the individual constructor to do without the use of sophisticated equipment such as the environmental chamber. This does not mean that the new probe is unusable without calibration, but rather that the high levels of accuracy established by this research will be difficult to achieve in the real world. It should however be noted that even with the variations in ramin samples, the new probes are still more accurate than the original Canadian designed probe.

8.4 Concluding statement.

This research has produced a new design for a wood block probe that can be manufactured for a relatively low cost. This makes it available to people constructing straw bale buildings. They could afford to install a number of these probes in their walls to monitor the moisture content with a degree of accuracy not previously achievable.

The results of the monitoring of the case study buildings has shown that as long as there is proper attention paid to the construction and detailing, there is no reason why a straw bale building should not last at least as long as any comparable timber building in a temperate maritime climate.

APENDICES

APPENDIX A. THE CASE STUDY BUILDINGS

Selection

Fourteen structures built using straw bales were selected for this research.

The straw bale buildings are listed in chapter 7 of this thesis. They were chosen as they represent a range of different forms of building, and use a variety of construction techniques. Two of them were experimental panels, standing on their own without being part of a building.

The buildings are described in more detail in the following sections. In the case of the studies where large amounts of data were collected, additional results can be found on the DATA CD ROM attached to this thesis

Methodology

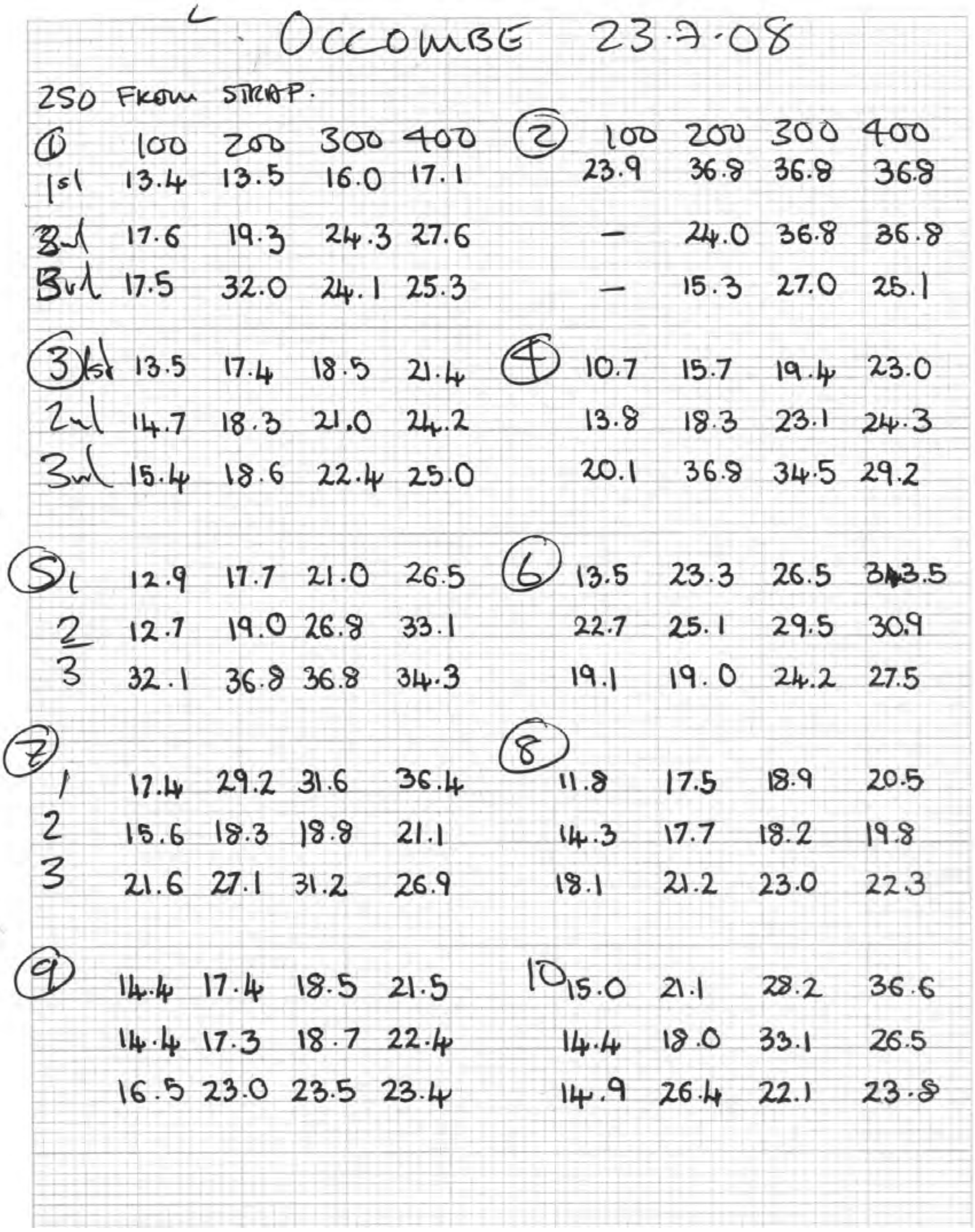
On the initial visit each of the buildings was photographed and then either a plan of the building was acquired, or a sketch plan was made.

Having received the owner’s permission to drill the required holes through the wall covering, a visual survey was performed. Looking around the building, an informed decision could be made for a selection of sites to insert the ‘Balemaster’ for a moisture survey. The choice of where to use the ‘Balemaster’ was based on looking for sites that indicated potential moisture problems. These might include areas with observable weaknesses such as faulty detailing, damp showing on the wall or a reported problem with the construction.

These could be compared with readings from a site that didn't appear to have problems.

Depending on the accessibility of the building, and the results of the moisture survey, a decision could be made as to the suitability of the building for further surveys. These would initially be carried out with the 'Balemaster' until the new wood block probes were ready to be installed. In the case of buildings that were too distant for regular visits the wood block probes were installed and instructions left on how to take regular readings.

The readings were taken from ten sites around the same building at Occombe farm. At each site the 'Balemaster' was inserted at four increasing depths through the straw bale wall, at three different heights. In the case of Occombe, this process was repeated twice a month for three months until the building was ready for occupation. After this point the measuring was limited to two sites and continued for another nine months.

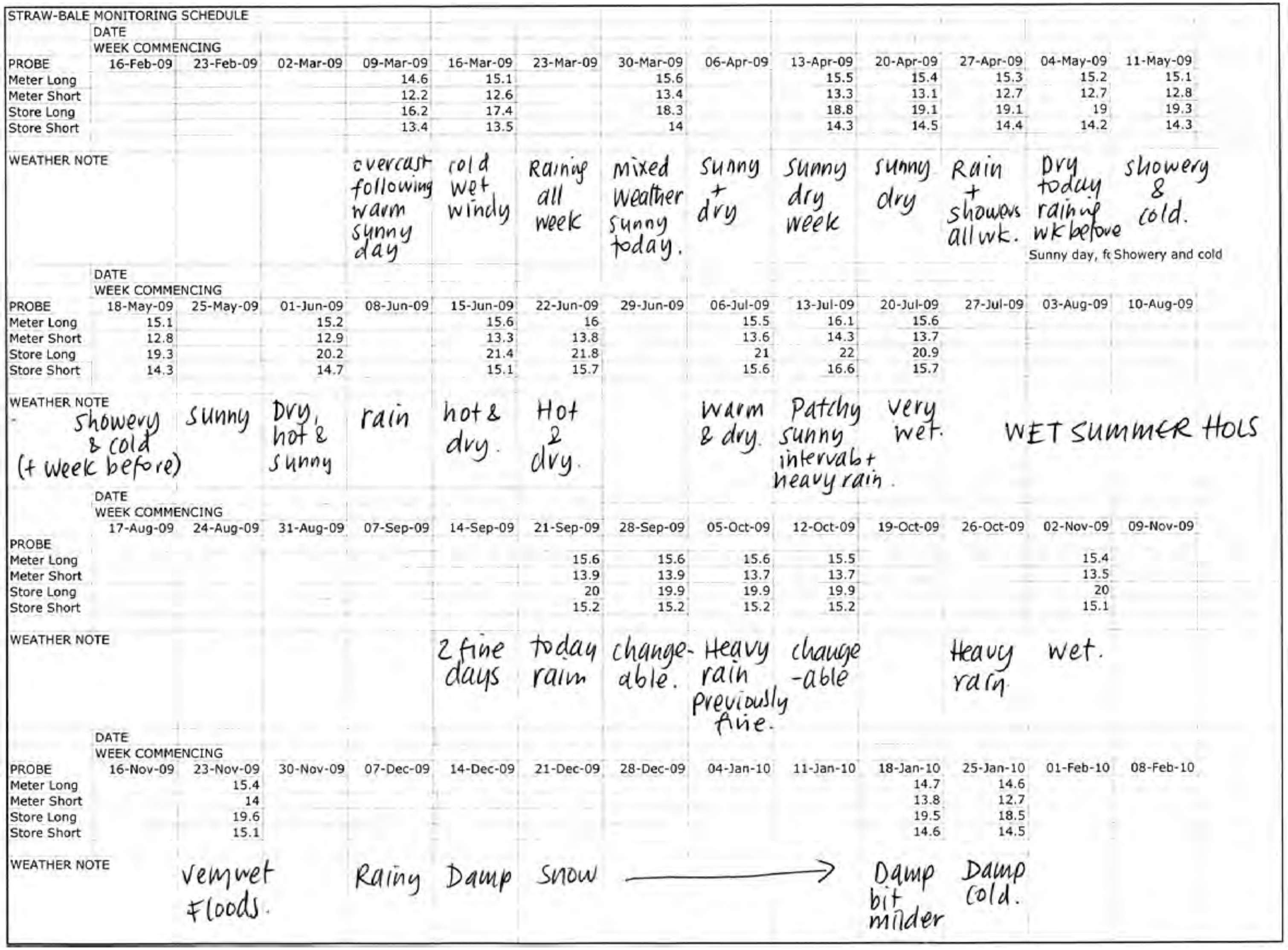


OCCOMBE 23.7.08

250 FROM STRAP.

①	100	200	300	400	②	100	200	300	400
1st	13.4	13.5	16.0	17.1		23.9	36.8	36.8	36.8
2nd	17.6	19.3	24.3	27.6		–	24.0	36.8	36.8
3rd	17.5	32.0	24.1	25.3		–	15.3	27.0	25.1
③ 1st	13.5	17.4	18.5	21.4	④	10.7	15.7	19.4	23.0
2nd	14.7	18.3	21.0	24.2		13.8	18.3	23.1	24.3
3rd	15.4	18.6	22.4	25.0		20.1	36.8	34.5	29.2
⑤ 1	12.9	17.7	21.0	26.5	⑥	13.5	23.3	26.5	343.5
2	12.7	19.0	26.8	33.1		22.7	25.1	29.5	30.9
3	32.1	36.8	36.8	34.3		19.1	19.0	24.2	27.5
⑦ 1	17.4	29.2	31.6	36.4	⑧	11.8	17.5	18.9	20.5
2	15.6	18.3	18.8	21.1		14.3	17.7	18.2	19.8
3	21.6	27.1	31.2	26.9		18.1	21.2	23.0	22.3
⑨	14.4	17.4	18.5	21.5	10	15.0	21.1	28.2	36.6
	14.4	17.3	18.7	22.4		14.4	18.0	33.1	26.5
	16.5	23.0	23.5	23.4		14.9	26.4	22.1	23.8

Fig.A1 An example sheet of readings taken with the 'Balemaster'.



STRAW-BALE MONITORING SCHEDULE

PROBE	16-Feb-09	23-Feb-09	02-Mar-09	09-Mar-09	16-Mar-09	23-Mar-09	30-Mar-09	06-Apr-09	13-Apr-09	20-Apr-09	27-Apr-09	04-May-09	11-May-09
DATE WEEK COMMENCING	16-Feb-09	23-Feb-09	02-Mar-09	09-Mar-09	16-Mar-09	23-Mar-09	30-Mar-09	06-Apr-09	13-Apr-09	20-Apr-09	27-Apr-09	04-May-09	11-May-09
Meter Long				14.6	15.1		15.6		15.5	15.4	15.3	15.2	15.1
Meter Short				12.2	12.6		13.4		13.3	13.1	12.7	12.7	12.8
Store Long				16.2	17.4		18.3		18.8	19.1	19.1	19	19.3
Store Short				13.4	13.5		14		14.3	14.5	14.4	14.2	14.3
WEATHER NOTE				overcast following warm sunny day	cold wet windy	Raining all week	mixed weather sunny today.	Sunny + dry	Sunny dry week	sunny dry	Rain + showers all wk.	Dry today raining wk before Sunny day, fc	showery & cold. Showery and cold
DATE WEEK COMMENCING	18-May-09	25-May-09	01-Jun-09	08-Jun-09	15-Jun-09	22-Jun-09	29-Jun-09	06-Jul-09	13-Jul-09	20-Jul-09	27-Jul-09	03-Aug-09	10-Aug-09
Meter Long	15.1		15.2		15.6	16		15.5	16.1	15.6			
Meter Short	12.8		12.9		13.3	13.8		13.6	14.3	13.7			
Store Long	19.3		20.2		21.4	21.8		21	22	20.9			
Store Short	14.3		14.7		15.1	15.7		15.6	16.6	15.7			
WEATHER NOTE	Showery & cold (+ week before)	sunny	Dry, hot & sunny	rain	hot & dry.	Hot & dry.		warm & dry.	Patchy sunny intervals + heavy rain.	very wet.	WET SUMMER HOLS		
DATE WEEK COMMENCING	17-Aug-09	24-Aug-09	31-Aug-09	07-Sep-09	14-Sep-09	21-Sep-09	28-Sep-09	05-Oct-09	12-Oct-09	19-Oct-09	26-Oct-09	02-Nov-09	09-Nov-09
Meter Long						15.6	15.6	15.6	15.5			15.4	
Meter Short						13.9	13.9	13.7	13.7			13.5	
Store Long						20	19.9	19.9	19.9			20	
Store Short						15.2	15.2	15.2	15.2			15.1	
WEATHER NOTE					2 fine days	today rain	change-able.	Heavy rain previously fine.	change -able		Heavy rain.	wet.	
DATE WEEK COMMENCING	16-Nov-09	23-Nov-09	30-Nov-09	07-Dec-09	14-Dec-09	21-Dec-09	28-Dec-09	04-Jan-10	11-Jan-10	18-Jan-10	25-Jan-10	01-Feb-10	08-Feb-10
Meter Long		15.4								14.7	14.6		
Meter Short		14								13.8	12.7		
Store Long		19.6								19.5	18.5		
Store Short		15.1								14.6	14.5		
WEATHER NOTE		very wet Floods.		Raining	Damp	Snow	⟶			Damp bit milder	Damp cold.		

Fig.A2 An example of the sheet given to the owner of a building in order to record the results of the wood block probe monitoring

Not all the buildings visited as part of this research were suitable for inclusion in this research. The following pages provide more details of the structures that were included as case study buildings.

The following buildings were surveyed with the ‘Balemaster’, but didn’t have the wood block probes installed:

1. The Theatre at the Centre for Alternative Technology (CAT).

This building was one of the first to be surveyed, but due to the distances involved, was not revisited for further measurements.

Following a survey with the ‘Balemaster’, two pairs of an early version of the revised wood block probes were installed in the walls of the building. Instructions on how to use the probes were left along with the timber moisture meter needed to take the moisture measurements. Unfortunately no results have ever been sent back to form part of this research.

The results of the initial visit and moisture survey were published in the form of an informal report to the owners. The data is also on the DATA CD ROM included with this thesis.

The report is reproduced at the end of this thesis as it contains a useful summary of the building and the observations made at the time.

2. A garage on a residential property in Exmouth, Devon UK.

Description

Fig.A3 Garage at Exmouth

A simple rectangular structure forming a garage and storeroom, built by the owner with volunteer assistance.

Fig.A4 Straw supported on tyre wall.

The structure is built on a limecrete slab. A dwarf wall of rammed earth tyres supports the load bearing straw bale walls. At this point the internal rendering has not been completed

Fig.A5 Exterior of garage

The external lime render was applied by hand on the slightly unevenly laid straw bales.

Readings.

Balemaster readings were taken at the top and bottom of each of the walls at four locations around the building, as well as under the sills of both the windows. The results are shown in the table below.

	DEPTH THROUGH WALL			
POSITION	100	200	300	400
1 LOW	11.7	12.9	14.1	14.5
1 HIGH	12.8	12.3	13	14.6
2 LOW	13.3	14	14.3	16.4
2 HIGH	13.5	14.5	14.6	15.9
3 LOW	13.4	13.9	14.7	17.6
3 HIGH	12.1	12.3	13.1	14.5
4 LOW	14.2	15.9	16	15.9
4 HIGH	13.2	14.3	15.4	17.2
WINDOW 1	13.2	14.7	14.7	17.7
WINDOW 2	13.4	13.7	14.1	16.3
AVERAGE	13.08	13.85	14.4	16.06

Table.A1 Results from Exmouth garage

The results are consistent with a well constructed structure and show no cause for concern. This building is unheated, and this can be seen in the slightly higher readings on the inside of the walls compared to other buildings. This gives a shallower moisture gradient through the wall.

3. Two buildings at Grange Farm in Somerset.

Description

Fig.A6 Grange Farm

This pair of similar buildings are part of a conversion of redundant farm buildings into offices. The walls are made from the larger ‘Heston’ bales, which give a wall depth of 1000 mm. The tops of the walls are finished with a potentially vulnerable parapet flat roof.

Fig.A7 Render on Grange Farm

It can be seen from the image above that there have been problems with the finish on the lime rendered walls. There were no large cracks, but the finish was falling off the walls in sections despite attempts to patch it.

Readings.

		DEPTH FROM OUTSIDE FACE OF WALL							
BUILDING	ELEVATION	100	150	200	250	300	350	400	450
1	WEATHER WALL	36.8	36.8	29.5	31.8	27.7	24.4	23.1	/
1	OPPOSITE WALL	20.9	18.5	17.7	17.8	16.9	17	16.4	15.4
1	SIDE WALL	13.4	23.8	25.1	23.9	18.5	18.5	17.8	16.3
2	WEATHER WALL	36.8	36.8	30.3	27	26.4	25	25.2	25.4
2	SIDE WALL	19	18.1	17.5	16.6	15.8	14.8	14.3	13.7

Table.A2 Readings from Grange Farm

The readings in the table above were taken by inserting the ‘Balemaster‘ from the outside of the building, and so should be read in the reverse order to the tables shown elsewhere in this thesis. The readings were all taken towards the bottom edge of the walls.

It appears that the problems with the render may have left the outside of the weather walls vulnerable to moisture ingress, as 36.8% is the maximum measurement possible with the ‘Balemaster’, and represents a potentially dangerous level of moisture.

The owner of the building reported problems with moisture ingress during the construction phase, but was reluctant to let us investigate by drilling more holes towards the top of the walls.

4. Straw bale panels at the University of the West of England (UWE)

Description

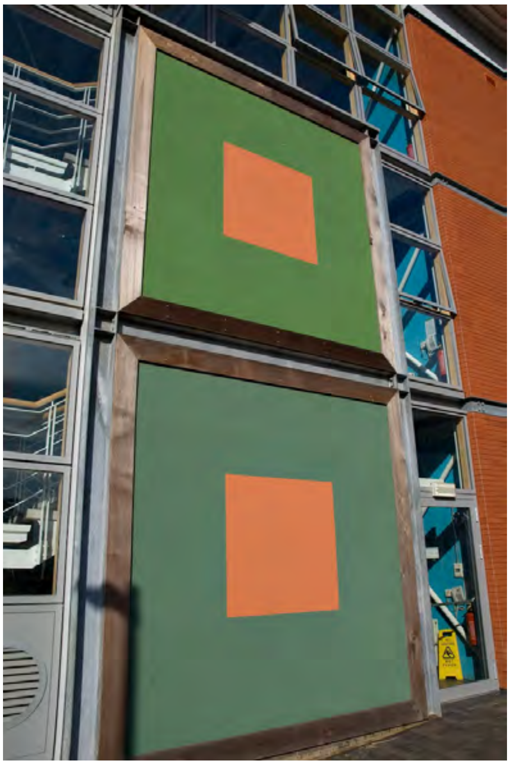


Fig.A8 Panels at UWE

One of the first uses of pre-fabricated straw bale panels in the UK was at UWE, in Bristol. Two large panels were used at each end of the external walls of a new building in the school of Architecture. The moisture content of the straw in these panels measured from 10.5% on the inside to 18% on the outside, apart from the bottom of the lower panel in the northwest elevation that showed a maximum of 22.3%. This may be due to the wooden architrave that surrounds the panel, and could form a water trap along the bottom edge.

Fig.A9 Single panel at UWE

At the same time, a single panel was erected in the grounds of the University for demonstration purposes. The panel has suffered some cracking and shows signs of water ingress.

A series of holes were drilled in the render to form a 4 x 4 grid of 16 holes, and moisture measurements were taken with the ‘Balemaster’. The average moisture content of the straw in the panel was 24%, and in many places was in excess of 36.8%. The full results can be found on the DATA CD ROM attached to this thesis.

Fig.A10 Base of panel at UWE

There was some heavy staining along the bottom edge of the panel, which indicated that water was being trapped between the bottom of the straw and the plastic membrane that it was sitting on.

Fig.A11 Section of render removed from panel

A triangular section of the render at the bottom of the panel was removed, and the straw behind it examined. Despite the high moisture readings taken from the straw its appearance was healthy (see chapter 7). There was a distinct separation between this straw and the lowest 25 mm of straw along the bottom edge, which was going black and rotten.

5. Straw bale panels at Liskeard.

Description

Fig.A12 Panels at Liskeard

An experimental array of eight panels were erected in a field near Liskeard in Cornwall, UK. They were built as part of a University of Bath research project to test the performance of a selection of different render mixes.

Fig.A13 RH and temperature sensors inserted into straw bale

Each panel contained an array of RH and temperature sensors that were connected to a data logger. The sensors where placed in the straw bales behind the render to asses how the moisture levels in the straw were affected by a variety of different lime and cement render mixtures.

Fig.A14 Timber cladding on panel

At each end of the array of eight panels there was a blank panel. It was decided to replace one of the end panels with a further straw bale panel, but this one would be protected by a ventilated timber rain screen.

The results from the rainscreen panel would be compared to those of the different rendered panels.

Readings

This research was carried out by the University of Bath, and the data from the RH and temperature probes is available on the DATA CD ROM

The results from the RH and temperature sensors in the rainscreen panel, compared the panel that used a standard lime render, are detailed in Chapter 7. When the new wood block probes had been calibrated and tested at the Totnes house, a pair were installed in the rainscreen panel. Unfortunately, after more than a year, all the panels had started to let in water from the top. This meant that there was no useful data to be taken from the by now saturated straw in the panel.

6. Hedgerow House, Eire.

Description

Fig.A15 Hedgerow House

This is a domestic dwelling in Leinster, Eire. The innovative design has the load bearing straw bale walls contained within a rectilinear timber framed structure.

Fig.A16 Straw bale wall of Hedgerow House

The author was asked to survey the property as part of a dispute between the clients and their architect. The survey results are contained in a report attached to this thesis, and the moisture data is on the CD ROM.

The following buildings had the new wood block probes installed in them as well as being surveyed with the ‘Balemaster.

7. Greyfield Timber. A sawmill at Huxhams Cross, Dartington, UK.

Description

Fig.A17 Interior of Greyfield Timber

This was a large two storey industrial building built using a timber frame that used glulam beams to span the width of the structure. Straw bales were primarily used to provide a degree of acoustic separation for the noisy milling machines used inside the building.

Fig.A18 Straw bales used in roof of sawmill

Apart from the size of the building, the other unusual feature of this building was the use of straw bales for insulation under the roof covering

Readings

At the request of the owner, the first visit to the sawmill was during the construction phase in order to measure the moisture content of the straw bales before they were built into walls. According to the owner the bales had been in storage for at least two years. Four bales were chosen from different parts of the stack. All the bales were found to have an even spread of moisture, with a minimum of 10.2% and a maximum of 12.4%. The moisture content was lower than might be expected and indicated that the bales had been stored in an environment with a low RH.

The second visit to the sawmill was two months later, and the straw bale walls had been completed. Readings were taken from four sites around the building. The readings at the four sites were:

29 Jan 2009	DEPTH THROUGH WALL							
POSITION	100	150	200	250	300	350	400	450
1, LOW	13.7	14.1	13.9	13.8	13.1	13	12.5	12.6
1, HIGH	13.4	14.1	13.7	14	14.2	14.2	14.3	14.2
2, WINDOW	15.1	18	19.3	19.1	16.8	16.8	16.6	16
3, LOW	20.6	25.2	18.5	21.5	18.3	17.8	17.2	17.1
4, HIGH	13.6	12.9	13.9	13.4	14.6	15.5	15.7	

Table.A3 Readings from Greyfield Timber

The table above shows that all of the bales have adsorbed some moisture during the build process.

The wall at position 1) shows an even spread of moisture through the wall, with no change from inside to outside. This is as might be expected in this unheated, well-aired building.

There is a higher level of moisture under the window sill with an increase towards the inside. This indicates a possible source of ingress from the window frame.

The bottom of the wall at position 3 is showing elevated moisture levels, again towards the inside of the wall. This might have been caused by the storage of wet wood against the wall.

During this visit, two pairs of the new wood block probes were installed. There were only two measurements taken before the business folded, and the sawmill building was dismantled.

The results of the two readings are shown here:

13/3/09	DEPTH THROUGH WALL	
	150	375
2) UNDER WINDOW SILL (BALEMASTER)	19.7	17.8
2) UNDER WINDOW SILL (PROBE)	21.8	20.8

23/3/09	DEPTH THROUGH WALL	
	150	375
2) UNDER WINDOW SILL (BALEMASTER)	17.4	11.7
2) UNDER WINDOW SILL (PROBE)	20.5	18.5

Table.A4 ‘Balemaster’ compared to probes at Greyfield Timber

In the case of the readings from the sawmill, the probes are showing higher levels of moisture than the Balemaster. There is no apparent explanation for this.

8. Ecology Building Society

Description

Fig.A19 Meeting house at Ecology Building Society

A circular load bearing straw bale building, constructed as an annex to the headquarters of the Ecology Building Society. Yorkshire, UK.

Fig.A20 Cracking in walls at Ecology Building Society

The straw bale walls were built on a random stone, dwarf wall. There were some significant cracks in the exterior render, but they don't seem to be having a marked effect on the moisture levels in the straw bale walls

Readings

A moisture survey taken with the 'Balemaster showed a steady moisture gradient through the walls.

	DEPTH THOUGH WALL								
	100	150	200	250	300	350	400	450	500
POSITION 1	9.8	10.8	11.2	12.5	14	14.4	15.5	17.4	19.3
POSITION 2	10.5	10.4	12.3	12.3	14.2	14.8	16.7	17.7	18.8

Table.A5 Readings from Ecology Building Society

Two pairs of the new wood block probes were installed in the walls, and instructions were left with the owner. Unfortunately, no results have been forthcoming.

9. Holiday Cottage in Yorkshire, UK

Description

Fig.A21 Atkinson Cottage

Mention was made in chapter 5 of a straw bale cabin built by Carol Atkinson on her farm in West Yorkshire. Following the success of this building Carol built a two-bedroom cottage nearby. The house was surveyed during a cold day in February 2009, and the nearly completed dwelling is shown protected from the elements by tarpaulins and large round bales from the farm.

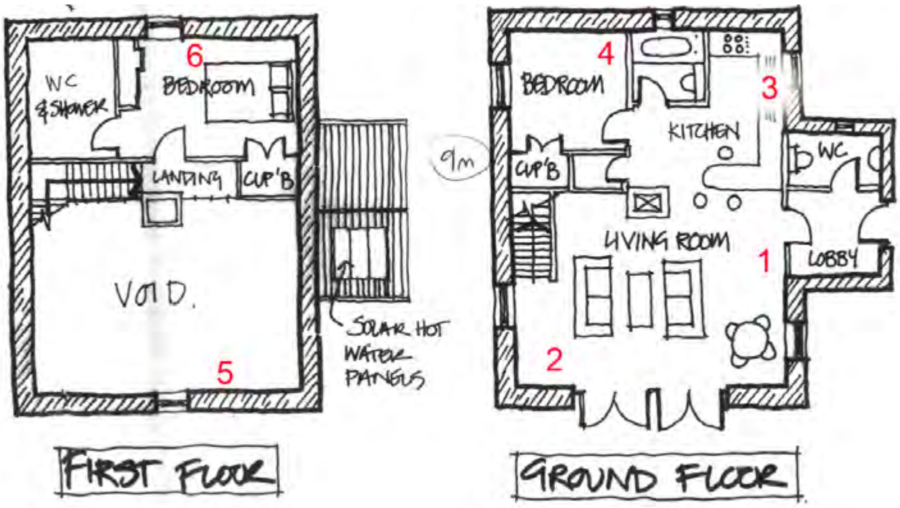


Fig.A22 Plans of the Atkinson cottage

The ‘Balemaster’ was used to survey the cottage at the locations marked in red on the plan. Most of the readings from the cottage showed levels of between 14% and 16%, except where there were observable problems.

Fig.A23 Water damage at Atkinson Cottage

Towards the top of the wall at position 1, the straw has become wet and visible signs of rot have started to appear. At this point the inside of the wall was measuring 36.8% to a depth of 250 mm. The moisture level in the rest of the wall is well below this level. All the data is on the CD ROM attached to the thesis.

Fig.A24 Probes installed in earthen render

Because the internal finishes hadn’t been applied to the walls, it was only possible to install one set of probes. Two pairs of one long and one short were installed at the top and bottom of the first floor wall next to position 5. The results are covered in Chapter 7.

10. Footprint Visitor Centre

Description

Fig.A25 Footprint Visitor Centre

The Footprint Centre was built for the National Trust on its site at Lake Windermere, UK.

The main structure of the building is a large section post and beam frame. The self supporting straw bale walls enclose the main living spaces inside the frame, as well as one wall which extends out to shelter the covered entrance area.

Readings

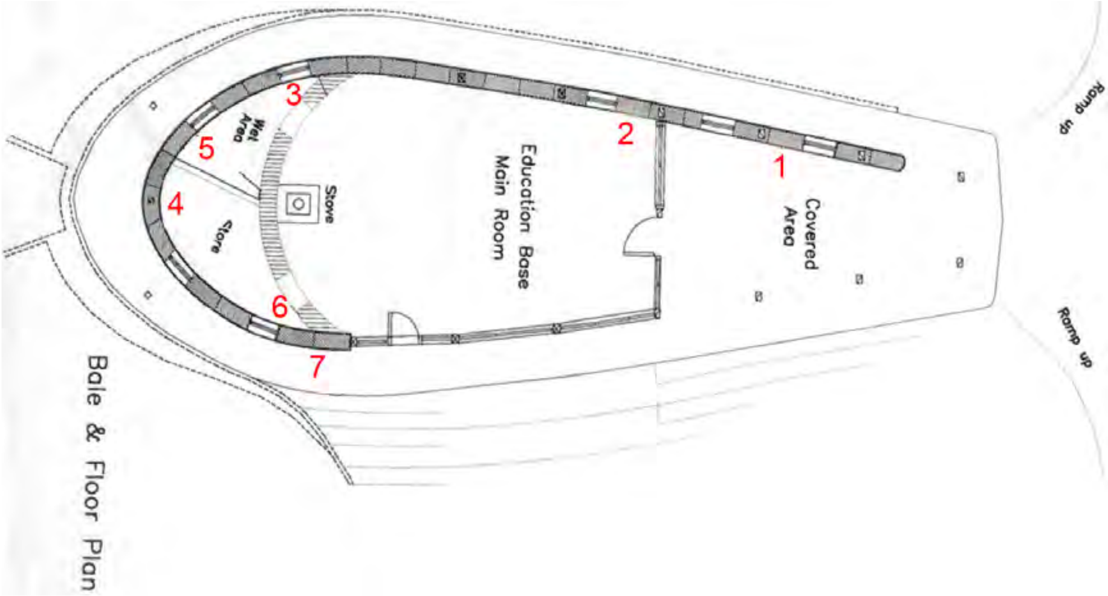


Fig.A26 Plan of Footprint Visitor Centre

The ‘Balemaster was used to measure the moisture content of the straw bale walls at the positions marked on the floor plan, above.

Most of the walls showed a normal moisture gradient, but there were two places where higher levels of moisture were recorded. Position 1, the exposed wall open to the elements on both sides, showed an unusual profile with higher levels of moisture towards the middle of the wall. This is the only time that this sort of profile has been recorded, and may be the remnants of a higher level of moisture through the whole wall that is drying out towards the sides (see below).

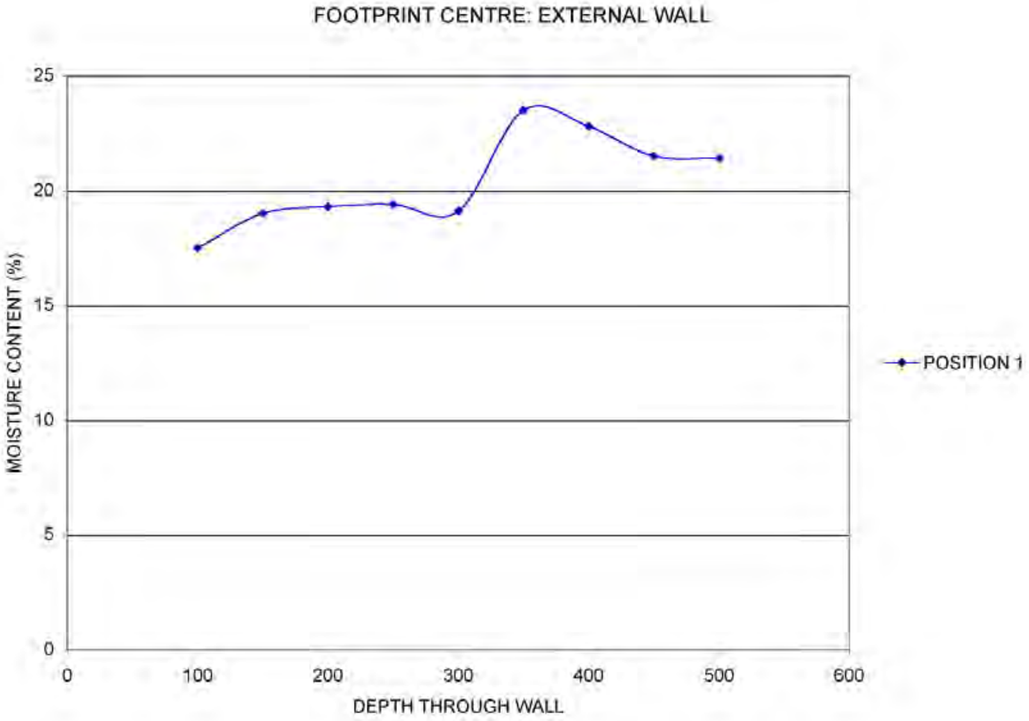


Fig.A27 Moisture profile of external wall at Footprint Visitor Centre

The other position where elevated moisture contents were recorded was at the intersection of the internal wall with the external wall at positions 6 and 7.

Fig.A28 Meeting of two walls at Footprint Visitor Centre

The acute internal angle, shown above, had been badly finished, and there were higher than normal moisture levels towards the outside edge of the wall.

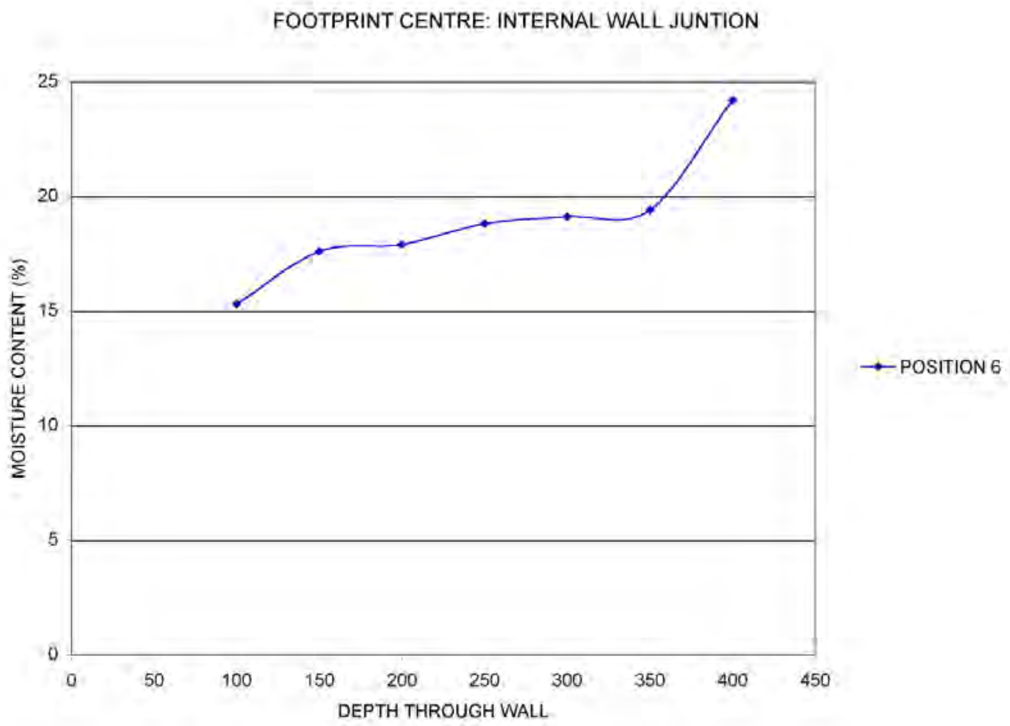


Fig.A29 Moisture profile at wall meeting

Two pairs of probes were installed in the walls of the Footprint Centre. The first pair at position 2 in the main room, and the second in the store room where higher moisture levels had been recorded at position 6.

The results have been discussed in Chapter 7, and are on the CD ROM.

11. Bristol Studio

Description

Fig.A30 Bristol Studio

This was a single large room built with straw bales used as infill in a simple hybrid timber frame structure. The bales were compressed as they were inserted, so the roof load is shared between timber posts and the bales. The southeast (front) elevation is completely glazed. The rear elevation is composed of three courses of bales on top of a rammed earth tyre wall about 1300 mm high that retains the ground behind it.

Fig.A31 Rammed earth tyres used as retaining wall

Readings

The building was surveyed on two occasions with the ‘Balemaster’. On the second occasion, five pairs of probes were installed at three sites around the building. Sites 1 and 2 saw two pairs installed at the top and bottom of the wall, and at the third site; a pair of probes were installed just above the rammed earth tyre retaining wall.

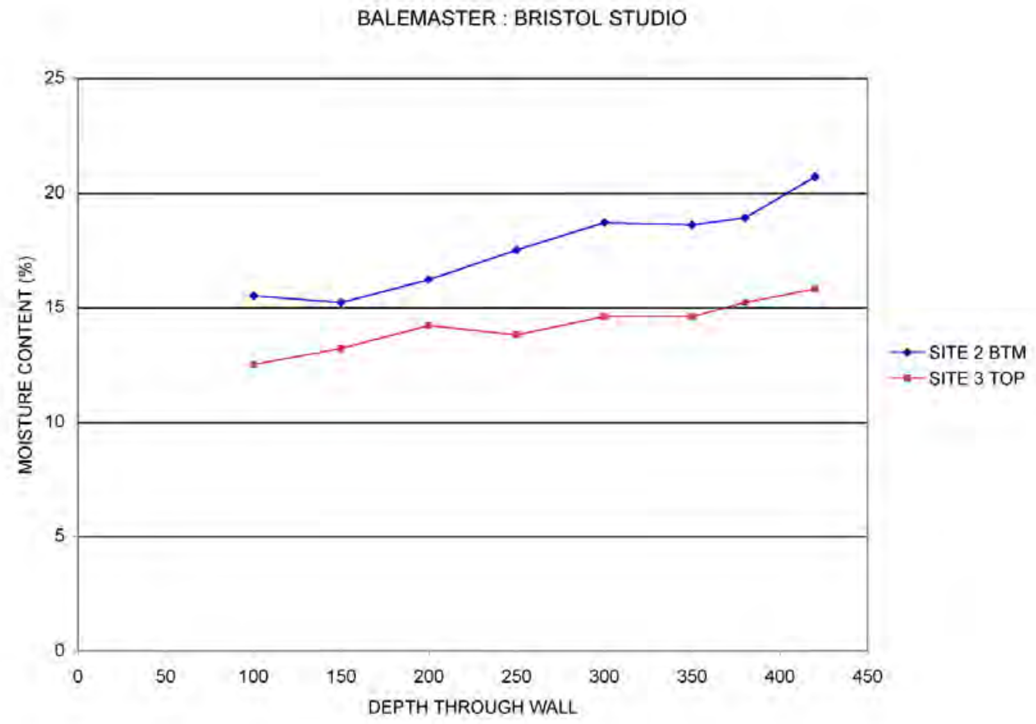


Fig.A32 Moisture profiles at Bristol studio

These two graphs compare the ‘snapshot’ moisture gradients produced by the ‘Balemaster’ on the day that the wood block probes were installed with the results from probes from June 2009 until November 2010

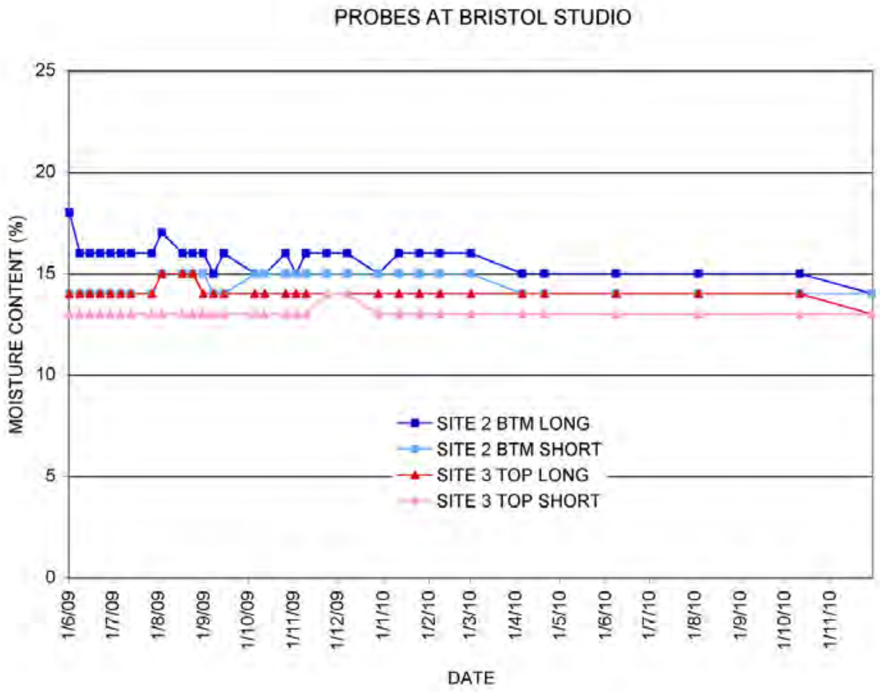


Fig.A33 Probe readings from Bristol studio

The trace from the probe described on the graph as ‘SITE 2 BTM LONG’ is reading the moisture at a depth of 350 mm into the wall and shows a value, at the start of the monitoring, of 18%. The ‘Balemaster’ reading at the same place (SITE 2 BTM), 350 mm into the wall also shows 18%. The same similarities can be read for the other probe positions, confirming a level of accuracy at this point.

As time passes it can be seen that the straw bale walls of the studio are gradually drying out. The long probes, that are measuring the moisture towards the outside of the wall are showing a reduction

Readings of 18%, 14%, 14% and 13% respectively, end up as 14%, 14%, 13% and 13%. It is not unexpected that while the probe at ‘SITE 2 BTM LONG’ that was reading 18% has fallen by 4% to 14%, the probe at “SITE 3 TOP SHORT’ has stayed at 13%. This is because this probe is on the inside of the wall and as the space is only occasionally heated, 13% is the expected moisture content that is unlikely to fall any further.

12. Cuckoo Farm

Description

Fig.A34 Cuckoo Farm

Cuckoo farm in south Devon, UK is a deliberate attempt to build a traditional vernacular farmhouse, but without using cob or stone for the walls. Instead, the structure uses an oak post and beam frame with straw bale walls wrapped around the outside.

Fig.A35 Render falling off wall at Cuckoo Farm

The straw bale walls have been finished in a home made lime render, which is failing. The owner-builders had mixed bagged hydrated lime from a builders merchant with fairly fine unwashed builders sand. This has lead to a soft crumbly render that will have to be replaced on most parts of the building.

Fig.A36 Moisture damage to bedroom wall at Cuckoo Farm

As well as problems with water ingress from the outside, due to the poor quality render, there are also places where water is entering the building directly. The image above shows where water is entering a bedroom through a faulty eaves detail.

Readings

Despite these observable problems, the straw in the walls is proving very resilient. As is detailed in Chapter 7, the walls of Cuckoo farm had higher levels of moisture than most of the other case studies, but in only one of the sites measured with the 'Balemaster' did the moisture in the straw measure as high as 36.8% (The maximum reading from the ‘Balemaster’, and the likely fibre saturation point of the straw).

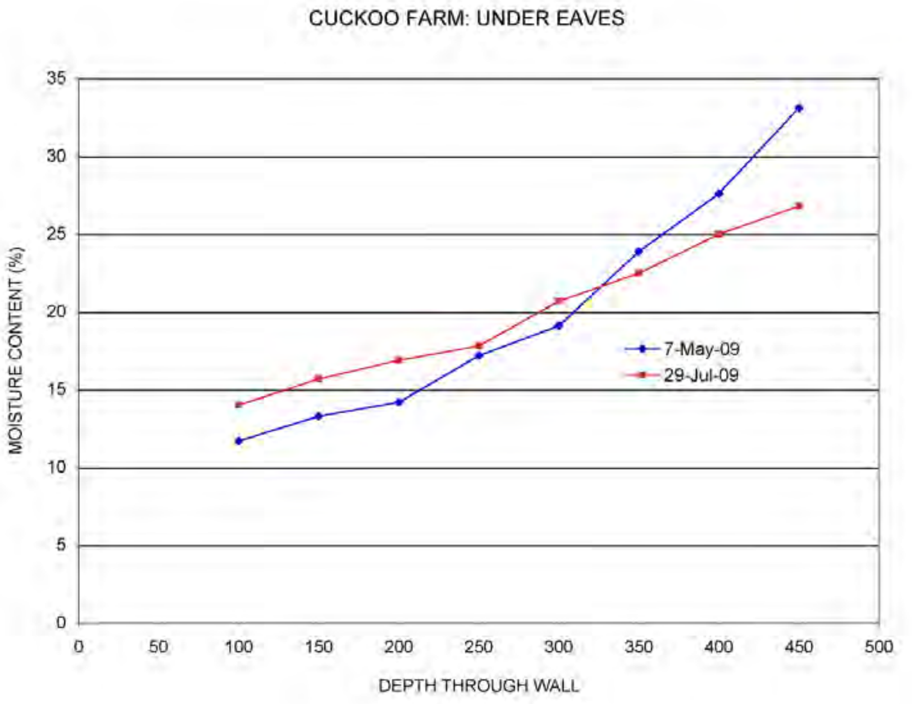


Fig.A37 Change in moisture gradients over time at Cuckoo Farm

The owners of Cuckoo farm are working to repair the problems with their house, including the soft and cracking render, and in all the places where the straw has been measured; it appears to be drying out.

The graph above compares the ‘Balemaster’ readings from the same site before and after a repair to the render was made. The interesting thing to note is that, like the drying of the wall in the Totnes House (section 7.4.6), the moisture appears to be redistributing itself through the wall. The moisture gradient on 7th May is steeper than on 29th July. The average moisture content has only reduced by 0.5% but where the moisture is higher on the outside of the wall in May, it has moved through to raise the moisture level on the inside of the wall by July.

Two pairs of the wood block probes were installed in the house in May 2009. Unfortunately the owners of the house lost the sheets that had been used to record the monitoring during the extensive repair work, so there are no continuous monitoring results to discuss. However, during two further visits to the farm, a comparative reading had been taken from one of the pairs of probes in a wall where a missing section of render had been replaced.

PROBES IN KITCHEN

	29-Jul-09	29-Nov-10
LONG	29.7	23.5
SHORT	17.8	13.3

The reduction in moisture level is consistent through the wall, and shows that the repair to the render is allowing the wall to dry out (the repair was only implemented two months before the second reading, so the rate of change isn’t necessarily as slow as it appears from the 15 month gap between readings).

13. Occombe Farm Education Centre

Description

Fig.A38 Occombe Farm Education Centre

This building was designed as a load bearing straw bale structure, with the rendered walls alone taking the loads of the roof

One of the drawbacks to this system is the potential for water to enter the straw during the construction phase, as the straw bale elements (the walls) have to be built before the roof can protect them.

Fig.A39 Water damage to walls at Occombe Farm

In this case, the roof was left half finished over the course of a weekend. During the 48 hours that the walls were left vulnerable, enough rain fell to saturate sections of the straw, which started to rot, as can be seen in the image above. The worst affected sections of straw were removed, and timber posts were added to strengthen the walls.

Readings

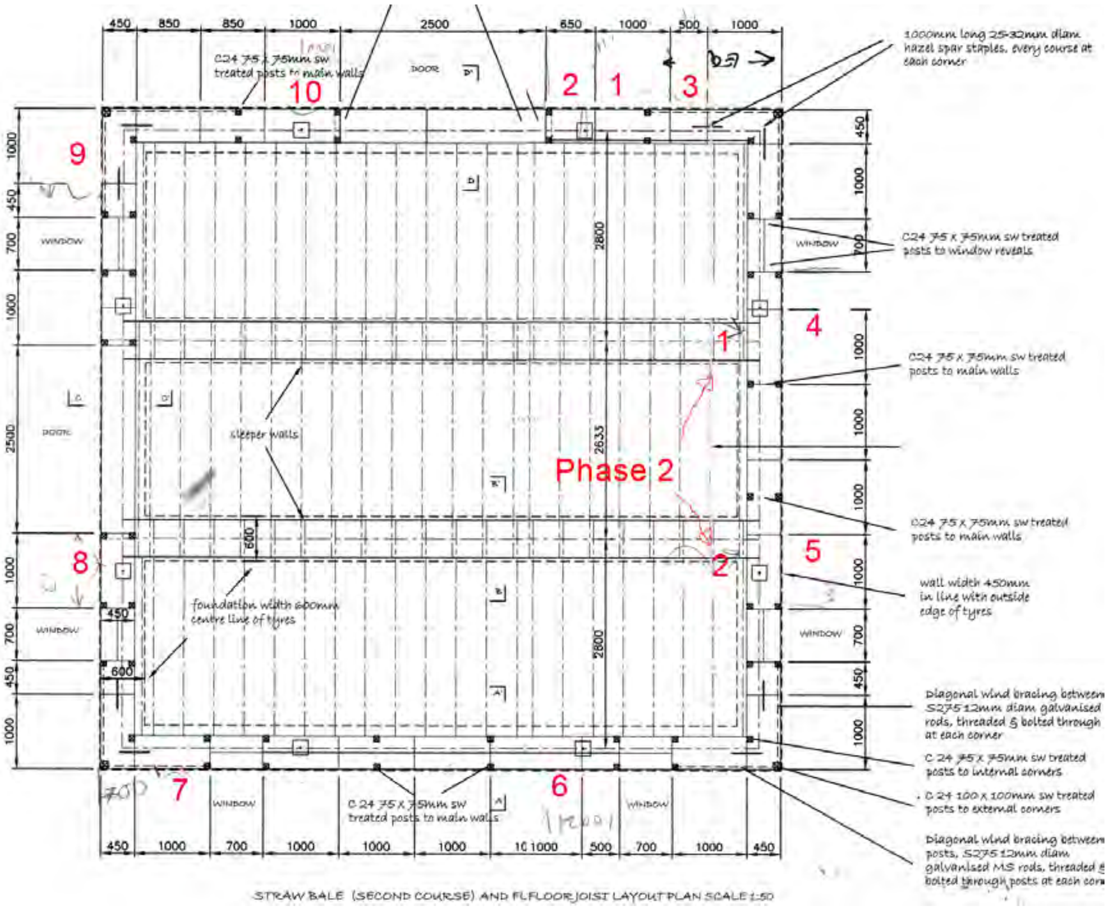


Fig.A40 Floor plan of Occombe Farm

In order to monitor the drying process of the remaining straw bale walls, ten sites were chosen at representative points around the building, shown on the plan above. The resulting data is discussed in chapter 7, and included on the DATA CD ROM.

After three months had passed, the interior walls of the building were rendered, and the monitoring was continued at two sites accessed from the inside. At this point two pairs of the wood block probes were installed

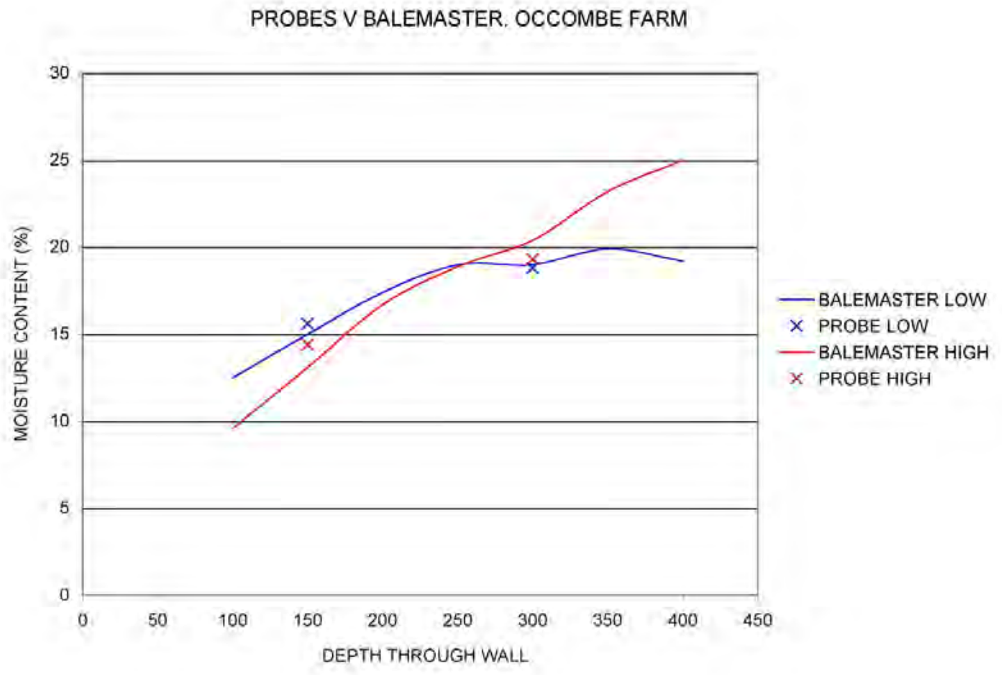


Fig.A41 'Balemaster' compared to probes at Occombe Farm

The graph shown above compares the readings from two pairs of wood block probes (one long, one short) with readings from the 'Balemaster' at the same two locations. This again demonstrates the relative accuracy of the wood block probes when compared to the 'Balemaster' in an example of a case study building, away from the controlled environment of the laboratory.

APPENDIX B. ENERGY USE IN A PASSIVE SOLAR STRAW BALE HOUSE

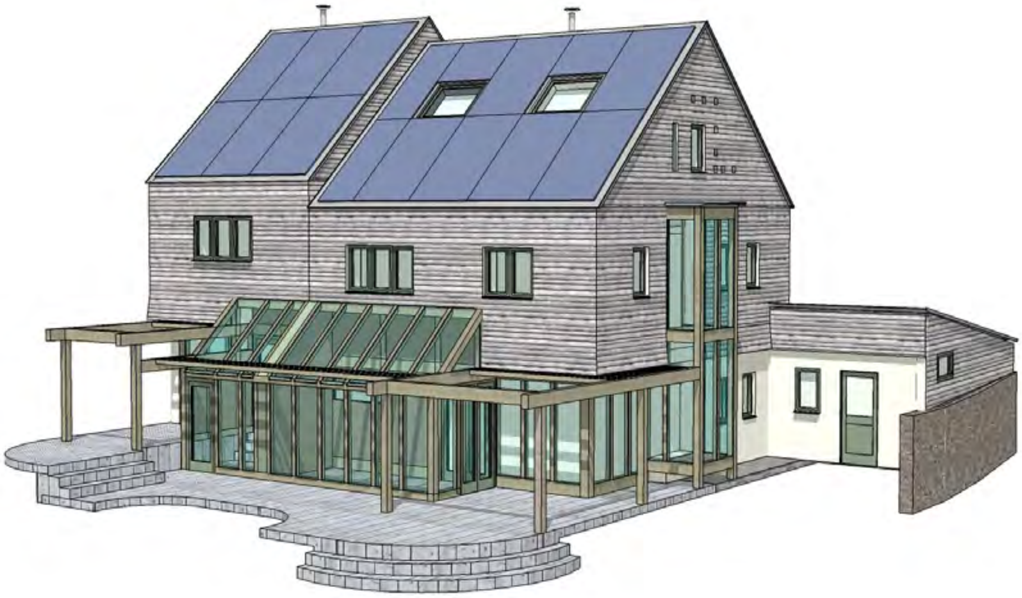


Fig.B1 3D model of Leechwell Garden House

The Author of this research is currently involved in the design and construction of a new straw bale house, currently at the planning stage.

The new house, called the Leechwell Garden House, has been designed to build on the experience of designing and living in the Totnes House.

Based on the monitored energy use of the Totnes House, it is hoped to be able to demonstrate that a dwelling constructed using natural materials coupled with a southerly aspect can have a primary energy need less than half that of the governments proposed ’zero carbon’ housing.

The single most important difference between the proposed Leechwell Garden House and the Totnes House is the orientation, as has already been discussed, the Totnes House is oriented to the north-east, whereas the Leechwell Garden House is south facing.

There are other differences; In the Totnes House the beams that support the first floor cantilever out of the frame to support the walls. This creates a thermal bridge through the insulation, the effects of which have been recorded using thermographic imaging. In the Leechwell Garden House the straw bale walls will run continuously from the ground to the roof.

The Leechwell Garden House is designed to be straightforward and affordable to build. The building has a gable ended, rectilinear form with a projecting sun space and timber gazebo on the south elevation. The ground floor of the south elevation consists of a direct glazed timber frame, with the gazebo carrying the summer shading elements for the glazing.

The south facing roof slope will be made up of building-integrated, combined photo-voltaic and solar thermal panels (BIPV-T) (2010). The area of this roof (70 m^2) is more than enough to accommodate sufficient BIPV-T panels to supply all the annual electricity and DHW needs of the house (Scheuren 2007). In addition to the sun space, the new house will have more direct glazing on the ground floor of the south elevation. This glazing is shaded from the high summer sun by an external matrix of parallel timbers, but the lower winter sun will be able to shine in and provide additional heat energy during the heating season.

Energy use in construction

The Leechwell garden House will also serve to illustrate the discussion on the embodied energy of materials and questioning the need for the increased embodied energy implicit in the additional technology needed to conform to the Code for Sustainable Homes and the Passivhaus standard. The design of proposed new straw bale house builds on the lessons learnt through the monitoring of the Totnes House.

Embodied energy

Embodied energy, recorded in MJ/kg, is the amount of energy used to take a material from raw state to the finished product and can be either measured to the point at which the material leaves the factory (cradle to gate), the point at which it arrives at the building site (cradle to site), or the point at which the building is demolished (cradle to grave). The embodied carbon (kgCO_2/kg) is the amount of carbon released into the atmosphere as a result of this process and is also known as the embodied CO_2 coefficient (Alcorn 2003).

The table below explains why the amount of embodied energy that goes into a domestic dwelling is of increasing importance if it is looked at as a percentage of the primary energy use of a building over a sixty-year lifespan.

There is an argument that an increase in embodied energy is justified if it results in an overall reduction in energy used, and the figures below bear that out. The extra embodied energy involved in building a Code for Sustainable Homes Level Six (CSH 6) house has resulted in a significantly lower total energy use. But looking at the embodied energy as a percentage of the total then forty percent of the carbon debt of that building over sixty years is tied up in the fabric. A dwelling built with timber and straw as the pricipal materials, and avoiding the use of other high energy materials where possible could perform to the same standards as the CSH 6 house (Carfrae *et al.* 2008) but with a further reduction in total energy use, and the percentage of the total taken up in the embodied energy of the fabric is reduced to 5%

Theoretical $120m^2$ House	**Embodied Energy (kWh)**	**Annual Heat Energy**	**Heat Energy used over 60 years**	**Total Energy Use (Embodied plus Heat)**	**Embodied Energy as percentage of total**
Housing stock	100,000	30,000	1,800,000	1,900,000	5%
Current new build	100,000	13,200	792,000	892,000	11%
PassivHaus/ Code level six	120,000	3,000	180,000	300,000	40%
Straw House	10,000	3,000	180,000	190,000	5%

Table.B1 Relationship between the embodied and heating energy in a selection of different dwellings of the same size
(The amount of embodied energy in any building will vary. *The figures are representative, and are used to argue the principle, not to demonstrate actual case studies)*

Energy use in Totnes House

The structure of the Totnes House was built around a traditional large section post and beam frame supported on minimal foundations, with an insulating wall of straw bales wrapped around the outside.

In terms of the primary energy use of the house, one of the main drawbacks was the orientation of the site. The house sits on the side of a hill and has a significant amount of glazing facing northeast to make best use of the outlook. The inevitable losses through this northeast glazing are counteracted by using clerestory lights between the roof pitches facing southeast, and a fully glazed south facing sun space.

Despite the less than optimal orientation the Totnes House performs very well in terms of its primary energy use.

In March 2006 a full Standard Assessment Procedure (SAP) was performed on the house using software called SuperHeat 5.1 (no longer available).

The calculations gave a SAP rating of 108 and a carbon index of 9.0 with a calculated space heating requirement of 6,758 kWh.

The energy use of the house has been monitored since completion, and in a typical year the actual space heating requirement is just 3,975 kWh (2008/2009), equivalent to 19.48 kWh/m^2. This is a significant reduction on the designed value despite maintaining average internal winter temperatures of 20.19ºC (day and night).

There are two possible reasons for this

- The SAP calculation software couldn't account for the gains through the sun space
- The combination of the high heat capacity of the render, with the low thermal transmittance of the straw in the walls, performs better than the U value alone would suggest.

The Primary energy use of the Totnes House can be compared to average figures from existing building stock and the energy use allowed under the two current standards mentioned, CSH 6 and Passivhaus (Fig.2).

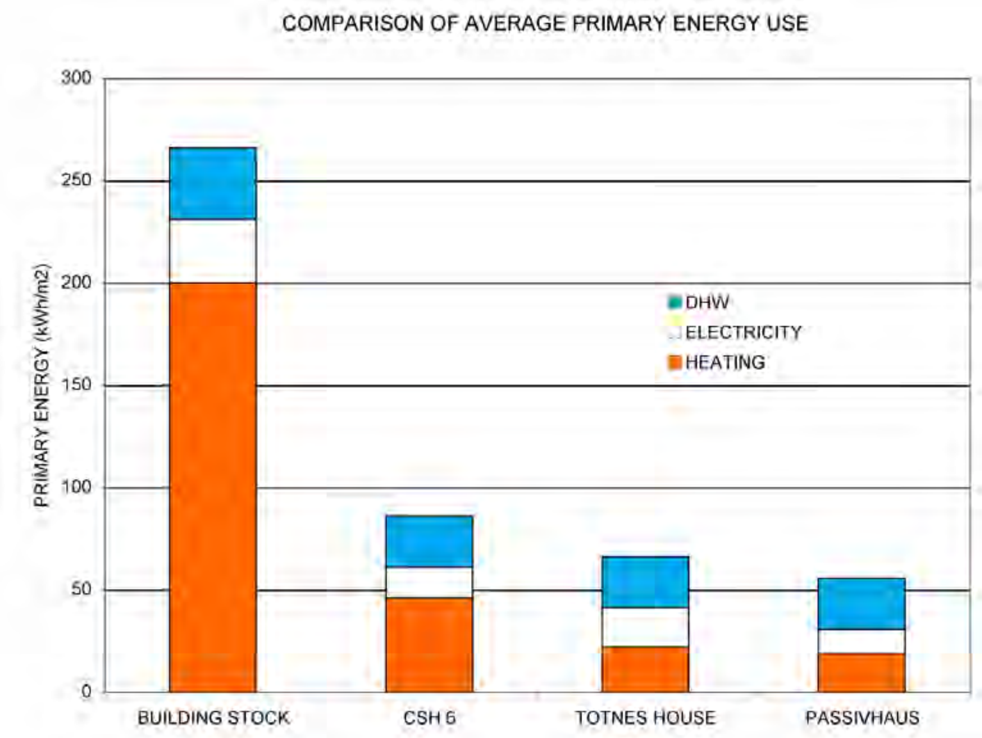


Fig.B2 Primary energy use of Totnes House compared to current standards.

As can be seen in the chart above, The Totnes House uses less energy than the CSH 6 house, and only slightly more than the Passivhaus.

In addition to the theoretical comparisons shown in Fig.139, the total primary energy use of the Totnes House for 2008/2009 can be compared to two existing high profile low energy developments: The BedZED housing project in Surrey, UK, and the Kingspan Lighthouse at the BRE innovations park, Watford UK (Goh and Sibley 2008):

Totnes House	83 kWh/m^2
BedZED*	82 kWh/m^2
Kingspan Lighthouse**	87 kWh/m^2

*The result from BedZED is an average of the actual use from 56 dwellings in the project

**The result from the Lighthouse is from the design data for energy consumption.

The conclusion that can be drawn from the results shown above is that despite facing northeast, the Totnes House compares favourably with current low energy designs, both in terms of design data and actual use.

The Leechwell Garden House, with the additional passive gains from its south facing orientation, should comfortably exceed all the current standards.

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