# Quantifying and Evaluating the Risk Posed to Straw Bale Constructions From Moisture

by

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# Copyright Statement

# ***Abstract***

The level of moisture a construction is exposed to may have an adverse effect on health and structure. Using straw, an organic material, as the construction medium, introduces concerns about biodegradability and spore germination, highlighting the uncertainties surround the level at which straw is susceptible to decay. A physical model is presented in this thesis offering a method by which to quantify and evaluate the risk posed to straw bale constructions from moisture. The model, utilising the development of an innovative Risk Assessment System based on fuzzy logic, is supported by empirical research conducted in static and dynamic environments.

The model relies upon the interpretation of data provided by monitoring devices, and an understanding as to the complexities of vapour transition through a straw bale and the interaction of moisture within. Using commonly descriptive terminology to describe the risk posed to the straw, the model, is capable of providing a greater understanding of straw bale construction and advising interested parties on potential weaknesses, taking into account: moisture, temperature, historic and predicted environmental conditions, limitations of analytical techniques, and the affect of direct sunlight. The concept of the model is to provide an early response mechanism to warn of the potential of adverse effects and thereby averting the need for destructive investigation and remedial action.

The interpretation of monitoring device data underpins the research conducted in this thesis, prior to which, there existed a gap in knowledge concerning the understanding of how moisture interacts with straw. The development of a novel compressed straw probe, as a monitoring device, offers the ability to establish an immediate moisture content measurement using a resistance meter, or of recent moisture levels using gravimetric analysis, supported by olfactory and visual verifications, enhancing the accuracy. Monitoring device results, compensated for temperature and density by equations developed from empirical data, are applied to a contour plot, via the Risk Assessment System, to provide an diagrammatic interpretation of the risk posed. Any potential problem is then flagged and a report generated providing advice.

Other contributions to knowledge made within the thesis consist of: monitoring device evaluations, determining the rate at which moisture is transferred through a bale, defining the interaction of moisture with straw, the capacity for moisture storage of renders and the subsequent implications, identification of transient moisture and the effect of solar gain, resistance meter calibration, and the hygroscopic, hydrophobic and hydrophilic tendencies of straw.

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# Chapter I-Introduction

## I.1-Aim and Objectives

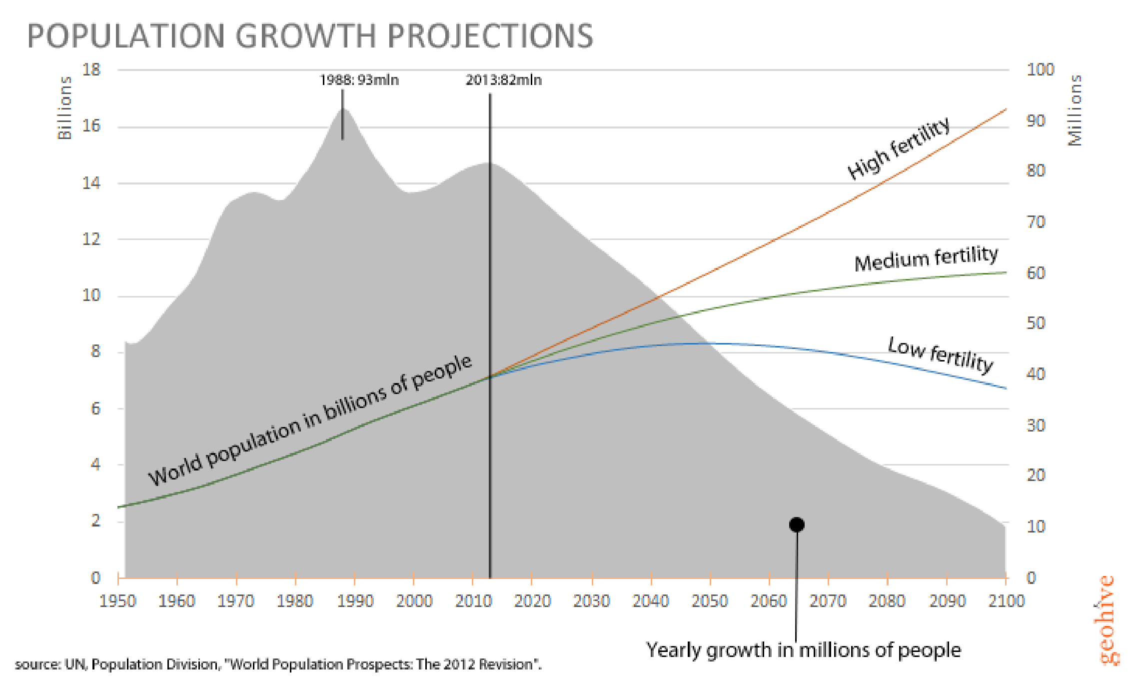
The aim of this thesis was to quantify and evaluate the risk posed to straw bale constructions from moisture. It brings into question the perceived confidence afforded to the construction method whilst investigating the following objectives:

1. To Confirm the point at which moisture becomes an issue to the straw.
2. To define the term 'risk'.
3. To assess different monitoring devices for strengths and weaknesses.
4. To describe the interaction between moisture in the atmosphere and the straw within a bale.
5. To assess how moisture occurs within a bale.
6. To determine the rate at of transfer of moisture and temperature through a bale.
7. To produce a basic visual identification system and model to promote confidence in different monitoring techniques.

The thesis begins by analysing the need for more sustainable construction methods within the built environment taking into consideration a growing global population and the impacts straw bale construction could potentially have on the economy, environment and society.

## I.1.1-Population Increase

The global human population reached 7.2 billion in 2012 (UN 2013) rising from 6.1 billion in 2000 with the potential to rise to 9.22 billion by 2075 (UN 2004a). The predicted figure was revised in the 2013 report which states a population rise of one billion in the next 12 years settling at 9.6 billion by 2050 (UN 2013) considering a medium fertility trend as illustrated by Figure I.1. This will place, amongst other strains, an additional demand on the construction industry. Engleman (2011) questions the further impact of this on the future of the planet; the unabated depletion of non-renewable resources together with questions over the availability of homes and the effect on the environment for food production.



source: UN, Population Division, "World Population Prospects: The 2012 Revision".

*Figure I.1: UN Prediction of Global Population (geohive 2013)*

The UK's projected population is estimated to be around 71.6 million by 2033 increasing by 10.2 million from 2008 figures (Directgov 2009). The National Housing and Planning Advice Unit (NHPAU) calculated that to keep up with the demand an average of between 223,000 and 255,000 new houses per year (dependant on migration) will be required by 2026 (NHPAU 2007), a figure revised by the Institute for Public Policy Research (IPPR) that suggests, based on 2011 trends, that in a high migration scenario 26.3 million households will be needed in the UK by 2025. The  Institute for Public Policy Research figure shows an increased requirement of 750,000 new homes, more than currently being constructed, alternatively the requirement may be as low as 440,000 scenario dependant (IPPR 2011).

The questioning stance of Engleman (2011) is supported by a variant of the Malthusian model which assumes that the worlds resources are finite and that population growth is a cause for concern indicating that there will come a point in time at which man's technological achievements cannot overcome the issues it has created and vital resources will run out (Furedi 1997); for example oil. Furedi also discusses the counter argument suggesting that people's standards of living are not necessarily dependent on the availability of land and resources. Despite this Ranganathan (2011) argues that resources underpin business and that this places a dependence on ecosystems, citing finding's made in the Millennium Ecosystem Assessment Report, written by the United Nations (2004b), the report suggests that global ecosystem services have been degraded by two-thirds due to human activity. Governments and agencies (GCC 2012) are seeking therefore to address the need to live more responsible lifestyles whilst balancing the need for social and economic growth by reversing the negative impact homo sapien has on the planet.

### I.1.2-Construction Resources

In evaluating the indicators for environmental pressure, amongst many other countries, the UK (HMSO 1994) and Estonia (Statistics Estonia 2008) were two countries that signed 'The Convention on Biological Diversity' at the 1992 Earth

Summit, United Nations Conference on Environment and Development. Statistics Estonia suggest that the rate that resources are consumed is placed secondary to the economy and that for minerals, energy and water, amongst other resources, consumers and manufacturers do not pay for resource depletion; including the greenhouse effect, landscape destruction, pollution or loss of biodiversity. The 2008 paper concludes  that a general view is taken is that “*wasting the treasures of nature is reasonable*” (Statistics Estonia 2008, pp.53).

The reduced dependence on non-renewable resources depends on society changing to embrace a sustainable future, the definition of sustainability was initially defined by the World Commission on Environment and Development in 1987 as “*Development that meets the needs of the present without compromising the ability of future generations to meet their own needs*” (Edwards 2010). This statement however identifies many conflicts and eludes to a highly complex subject.

The World Bank Group (DEPweb 2001) identifies the need to balance, with sustainability as the focus, the conflicts generated between (Figure I.2) the Economic sector (industrial growth, agricultural growth, household needs, services and efficient use of labour), the Social sector (equity, empowerment, participation, social mobility and cultural preservation) and the Environment sector (biodiversity, natural resources, carrying capacity, ecosystem integrity and clean air and water).

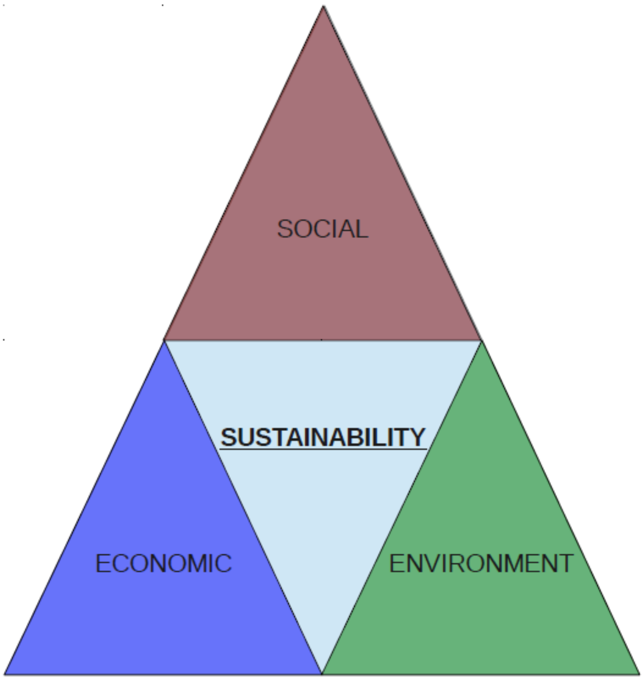


*Figure I.2: Sustainability concerns*

Destruction of the natural environment (air, earth and water) from man’s continuing quest to become more civilised and technologically advanced has in recent years provoked a worldwide debate culminating in amongst other agreements the Kyoto Protocol which set targets for 37 industrialised countries to reduce the amount of greenhouse gasses they produce (United Nations 2011). Wihan (2007) reports that 11% of all global carbon dioxide ($CO_2$) produced comes from the production of new materials for the construction industry. Analysing the UK's pollution statistics shows that the construction industry accounts for 47% of the nation's $CO_2$ emissions (BIS 2010) with housing contributing to 27%, of which 73% is used for heating space and water (Moore et al. 2007).

The UK government has in response set a target to reduce green house gas emissions by 80% by 2050, relative to 1990 levels, and aims to encourage new-build developments to be carbon zero from 2016 onward (DCLG 2007, Wienand et al. 2008) however, this will only address part of the problem.

The concerns over Man's impact on the planet signals a warning that new technologies must not only be able to provide a wider range of functionality, but must also be responsibly produced “*personally fulfilling, socially just and economically and ecologically viable*” (Dickson 1974, p.40). This in part extends responsibility to designers and manufacturers who need to understand not only the impact of a product, but should also assess the products life cycle (Wimmer et al. 2010). These needs can be extended for buildings which must be made more energy efficient in their use and construction and be capable of providing a continuing improvement in the standard of living without having a detrimental effect on the planet, or other societies (including the plant and animal kingdoms). Yet, buildings should be a place, as De Botton (2007, pp. 137) describes from the point of view of architecture, that “*will speak to us of a degree of serenity, strength, poise and grace*” a reminder of the buildings historic significance and what additional effects a construction had on the world; extensive mining, refining of hazardous chemicals, basic housing provision, social interaction, exploitation of the poor, provision of employment, political reform, breaking the boundaries?

### I.1.3-Embedding Sustainability

As noted in the general description of sustainability (Section I.1.2 p13), the question of what should constitute a sustainable development, or construction, is unresolved. It should seek to resolve conflicts between the social, economic and environmental sectors; BREEAM, LEED, NIBE and SBAT are examples of design and assessment tools that can be applied to address these issues whilst contributing to knowledge on the planning, construction and operation of buildings. However, each of the assessment tools approaches sustainability from different perspectives a point raised in Chen et al.'s (2008) evaluation which aimed to identify the different characteristics of some of the available assessment tools.

Another solution may be found in unison with the type of construction method applied; building with a renewable by-product that is locally sourced and has a natural life cycle. Using the stems of a harvested crop such as oats, wheat, rice, barley, or rye may provide a partial answer; in the UK wheat straw is the most widely available by-product of the agricultural industry. Straw as an organic material has a potentially low embodied energy, contains no toxic chemicals and, if baled and used as a construction material, provides exceptional energy efficiency ratings (King, B. et al. 2006). If the natural life cycle of straw between harvest and decay could be postponed through use as a building material, the construction of the building could be used to gain local interest in the immediate ecosystem. The interest could be used to draw attention to local biodiversity conservation issues bringing the community together to focus on sustainability and potentially highlighting conflicts between aspects of the economy, society and the environment.

## I.1.4-Wheat Straw as a Resource

Resources are assets that, at a given moment, have a use or potential use. Society will dictate what a resource is according to their need for it; until recently coal was a highly prized resource yet recent changes in mindset have reduced this value (Furedi 2010). Wheat throughout human civilisation has been a valuable resource and regarding human nutrition wheat forms one of the most important of all cultivated plants (Evans et al. 1981). It is intrinsically linked to nutrition (grain), agriculture (grain and plant) and the built environment (stem of the plant).

*Figure I.3: Wheat Field*

Cultivated wheat species include common wheat (bread wheat), spelt, durum, emmer and einkorn and each one has different characteristics to the other. Evans et al. (1981) describes wheat's value throughout human history, from the first evidence of cultivation near Aswan, banks of the Nile, around 16000-15000 BC, to more substantiated evidence in Greece towards 6000 BC; the ancient Egyptians having different symbols for barley and emmer demonstrating that they had different values for each. Germanic tribes preferred Spelt for disease resistance, the ability to be sown in autumn at higher altitudes and farther north than other wheat species, and for the quality of its flour. The Romans experienced civil disorder over grain prices as their empire expanded and farming methods changed to accommodate more bread wheat; it was Augustus who was heralded for quelling the disorder and his name has therefore always been associated with his relationship to wheat harvesting; hence August. The Gauls were more accepting of the Romans for their wine and bread, the Germanic tribes preferred their own beer, porridge and dark breads.

The spread of wheat, and it's different varieties, continued and is considered an important method of "*determining the nutritional status of millions of human beings*" (Evans et al. 1981, pp.149). This close relationship with cereal crops extended to construction, the stems of the plants are used as a binder to provide strength to reinforce the structural capabilities of bricks and renders (Lacinski 2000) and for use as thatching material. This abundant resource is intrinsically linked with human history, primarily due to the grain production, but also as a construction material.

In present day farming the by-products of harvesting, the stem and roots of the plant, remain on the field and whilst the root may be turned with the soil during ploughing it is not recommended, unless finely chopped, that the stem be disposed of in the same way; "*large quantities of straw, partially buried in soil, provide an ideal breeding habitat for specific pests and many diseases of cereals survive on undecomposed straw*." (Grossbard 1979). To dispose of the straw, as Atkinson (2010) notes, it can be used for dietary fibre for livestock, to grow mushrooms, mulch for vegetables and fruit, energy production in power stations, for biobutanol production, and for bedding with the added advantage of being able to be used as a fertiliser at a later date saving energy on the manufacture of fertilisers. Sodagar et al. (2011), using data from the Biomass

Energy Centre, indicates that 40% of all straw is shredded behind the harvester to provide the soil with added nutrients, modifying the structure, and improving water and nitrogen retention yet there remains a significant amount of unused straw.

## ***I.2-Straw and Construction***

Straw has been used in construction for thousands of years, in adobe blocks, plasters, thatch and Lehmwickelstaken (straw and clay infill) however, in 1857 John F. Appleby from Wisconsin (USA) invented the twine binder (Cornways [no date]). It was the advent of the first baling machines in the mid 1800's that would provide a quick and effective solution for resource deprived settlers of Nebraska to achieve sufficient shelter from the elements. With few other available building resources it was quickly discovered that walls could be constructed by stacking straw and hay bales on-top of one another; straw bale building was born. The authors King, B et al. (2006) and Jones, B (2002) give the history, challenges and art of building with straw, the UK television station Channel 4's Grand Designs programme (2011) has also featured an oak frame straw bale house constructed by Kelly and Masoko Neville in the Cambridgeshire fens and Ben Law's self-sufficient woodland cottage made famous for it's planning setbacks.

### I.2.1-Straw Bale Construction

Baling has allowed a loose and somewhat awkward by-product of the agricultural industry to be secured in tight uniform blocks with the ability to stack and store the material neatly and simply. 'Uniform' is used here in general terms as bales may vary as Carfrae (2011) reports from Ashour's findings by up to ±7.2% in size, ±25.1% in weight and ±21% in density.

During photosynthesis a plant will absorb $CO_2$ and release oxygen effectively locking-in the carbon molecule that governments are looking to reduce. Therefore, a renewable organic material that is readily available such as timber would provide a large carbon store (Fix et al. 2011) however, the timber must be grown in synchronisation with demand, noting the ecosystem that develops as a part of it, trees taken from an an ecosystem that has taken hundreds of years to develop may consist of complex intertwined relationships and therefore may not be viewed as renewable. The argument concerning timber's use in construction is therefore dependant on the species and practices implemented in the harvesting. Sodagar et al. (2011) discuss the concerns surrounding the potential for carbon reduction of straw bale housing, the use of straw as the major contributing material over timber.

It can be argued that because the straw has to be collected from the field to make way for the next crop, the $CO_2$ emissions produced during harvesting can be attributed to an offset for grain production (Atkinson 2010) however, at present the grain is the resource not the straw and this view could only be changed if straw became a more valuable resource. The transportation of bales to site if kept to a short distance provides another potential emissions saving in comparison to many other building materials transported from potentially thousands of miles away; if not necessarily the actual product directly, the raw materials used in the manufacturing process.

Straw can be used as a main construction material, in bale form, and with the provision of adequate protection in the form of a 25mm thick application of a lime render or stucco, this renewable resource can be preserved from the natural life cycle, post harvest, prior to decomposition. Watson (2010) suggests that in the UK alone it is estimated that with the surplus four million tonnes of straw produced every year 450,000 houses, of 150$m^2$, could be built using around 400 bales over a 100 $m^2$ footing (Bigland-Pritchard and Pitts 2006). The National Housing and Planning Advice Unit requirements of 255,000 new houses per year could easily be fulfilled and progress towards reducing the total carbon emissions of the construction industry. In 2011 out of 12.2 million tonnes of straw produced in the UK 5.6 million tonnes remained unused (AHDB, 2013). This figure is variable however, one year may produce a bountiful crop compared to another year, as in 2009 in the UK which saw a decrease of 17% in wheat grain production due to poor planting conditions and low cereal prices in 2008 combined with wet harvesting conditions in 2009 (NFU, 2010). Potential disruptions to a construction project include unfavourable growing conditions for a particular season and the ability to source the straw locally.

### I.2.2-Construction with Straw Bales

One benefit of a straw bale construction is the thermal efficiency generated by the walls with reported values for thermal conductivity between 0,038 and 0,1 $Wm^{-1}K^{-1}$ (Grmela et al. 2010). The underlying principle of construction with straw bales is simple, consisting of two basic methods of construction: Nebraskan style (load-bearing) and framed structured (infill) (Jones 2002). Goodhew et al. (2010) discuss the use of structurally insulated panels, framed structures and hybrid designs including Strammit boarding, evaluating the Carfrae House in Totnes (awarded Federation of Master Builders: Eco-house of the year 2007) which has a primary energy use conforming to German PassivHaus standard.

The range of different types of construction and how and why they are constructed are numerous, from individual self builds including extensions, to the hybrid designs of MODcell, or the community based settlement of Sieben Linden.

### I.2.3-Effect on Society

Due to the ease of construction many straw bale buildings around the world have been raised by unskilled volunteers, representing communities and individuals, happy to help with a build in exchange for the sense of personal achievement, promise of a hot meal and social union that comes with the experience, or as Bigland-Pritchard and Pitts (2006. pp. 374) state from Edminster observations a “*sense of belonging and a connection to place*”. This is normally done under the instruction of at least one skilled site manager (Wihan 2007) and Goodhew et al. (2010) also raise the subject of skilled on-site personnel.

As described by the World Bank Group (DEPweb 2001): the economy and environment must be balanced with society (equity, empowerment, participation, social mobility and cultural preservation). The ability for inclusion that straw bale construction offers can engage people on a social and personally intimate scale corresponding to the Marxist view regarding the aspects of alienation, now adopted by sociologists and psychologists as being a feeling of powerlessness (individuals feel controlled or manipulated by other people or systems), meaninglessness (normally work related, a division or fragmentation from the production task), self-enstangement (the experience of depersonalised detachment from their work) and normlesness and isolation (social alienation and the breakup of integrated communities) (Dickson, 1974). By involving local communities and regarding the individual's need for personal fulfilment a number of complex issues could be addressed.

In 1994 the Ecovillages and Sustainable Communities Conference suggested that the development of Eco-villages would require highly developed social skills together with carefully designed communities. The vision stated that it must encompass consideration of the ecosystem, built environment, economics and government, and group visions supporting the health of residents “*on a physical, emotional, and spiritual level*”(Kennedy et al. 2002. pp.88). Possibly a more controversial approach would involve a total change to the economy and society; “*environmental governance and sustainable consumption is proposed by a broad body of thought known collectively as the* '*New Economics*'” promoting well-being above economic growth seeking to reunite economics with the foundations of the environment and society, curbing the negative impact of globalisation (Seyfang 2010, pp.7627). The paper proposes five topics to influence sustainable consumption under New Economics: “*localisation, reducing ecological footprints, community-building, collective action and building new infrastructures of provision.*”

There are a growing number of communities world wide that are attempting to readdress complex social issues in a number of different ways, from Sieben Linden's model of how a variety of different human communities can live more responsibly amongst Nature, to the Findhorn Foundation who's vision is to help “*unfold a new human consciousness and create a positive and sustainable future*” (Findhorn Foundation, [no date]), or the Canelo Project (2011) which seeks to connect people, culture and Nature. All of these communities have employed straw bale construction to some degree however, a more detailed review falls outside the scope of this thesis.

## I.2.4-Effect on the Environment

'The environment' within the context of this section relates to the natural world. The built environment is: “*the physical world that has been intentionally created through science and technology for the benefit of mankind*” (NARSA 2008, pp.2). Intensive non-sensitive agricultural practices is a human engineered environment that subjects land to unsustainable resource production to keep up with a global demand, but as Rands et al. (2010) explains leads to elevated prices and encourages expansion.

Research conducted by the European Commission into biodiversity highlighted: “*the well-being of every human population in the world is fundamentally and directly dependent on ecosystem services*” (UK-GBC 2009, pp.2), yet there is a dramatic decline in habitats and species the world over. The report highlights the potential of the built environment to impact negatively on biodiversity, suggesting, that with careful development and refurbishment the ecology of a site could be increased; it provides details of the Westfield Living Wall at Shepherds Bush, West London as a case study.

Straw bale building offers a way to reconnect with nature; if examined from a holistic approach it could become a mechanism to promote biodiversity conservation through use as an educational tool to allow people to re-engage with nature and themselves, a strategy also proposed by Atkinson (2010). As a crop wheat can support a significantly diverse range of life, if grown organically (Siddiqui et al. 2005), and, as with any construction, a straw bale building can provide shelter for birds and bats which will come to an area that can support populations of insects and other wildlife present through effective land management. At the end of a building's life the straw could be used as compost extending the usefulness of the material to provide an ecosystem for bacteria and fungus to decompose the material to basic nutrients (fertilisers) in order that the process could be restarted (Robinson et al. 2011).

### I.2.5-The Problem with Straw

Lawrence et al. (2009a) provides a comprehensive list of literature detailing research conducted into fire resistance, vermin resistance and structural performance, while Walker (2004) concluded that the numerous different building styles and methods of construction associated with straw bales complicate the study of structural analysis. Both studies identified one overriding concern linked with straw bale construction; moisture. With sufficient moisture the straw will decompose reducing the longevity of the construction (Leary et al. 1998), without moisture however, micro-organisms cannot survive and the material will be preserved.

Straw bales must be kept dry during storage, construction, and as part of the building fabric. The lack of moisture will prevent the colonisation of bacteria, moulds and fungi, inhibiting the potential risk to the health of the occupants and of the structure of the build (Clynes 2009). Jollie (2000) sums up the effect of sustained high levels of moisture as causing structural damage, serious health problems due to mould growth, and a reduction in the thermal insulating property of the plant material. Moulds will attack the constituent parts of straw differently, at different rates depending on environmental conditions and the plant characteristics.

# I.3-Plant Physiology

Evans, et al. (1981) give an account of wheat’s DNA and gene profiling, explaining how different strains have been bred to become more disease and pest resistant, standing up to harsher climates and producing greater yields; although technology has advanced since the book was written the principles remain the same.

## I.3.1-Physical Structure

In analysing straw's susceptibility or resistance to moisture it is important to understand the structure of the plant. Describing the general physiology of plants Forbes and Watson (1992) explains that cell walls are constructed of cellulose, a carbohydrate consisting of long sugar chains, that are bound together with pectin another carbohydrate, while lignin provides the main reinforcement material within the plant also providing protection from microbial attack. Beginning in the root, dead tubular cells joined end to end known as xylem transport pure water around the plant by osmosis due to the high ion concentration within the cells. Xylem provide some structural rigidity while the phloem transport the nutrients as highly concentrated sap containing sugars and other products (Salisbury 1992). Wheat is a Monocotyledon having only one embryonic leaf, the atactostele vascal tissue (xylem and phloem) is scattered around the tube of the stem in an disorganised arrangement (Figure I.4).

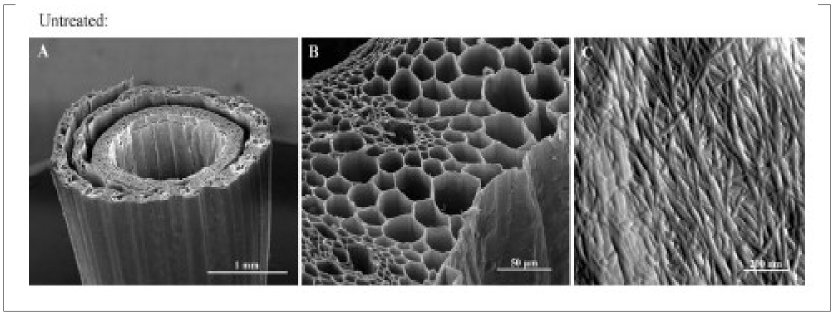


*Figure I.4: Image of untreated wheat straw (Kristensen et al. 2008)*

There are three elements to describe the way in which sap ascends a plant. In a living plant water is drawn into the xylem by osmosis, passes through to the leaves and is transpired back to the atmosphere through the stomates; a process known as 'the driving force'. 'Adhesion' is the hydration force between cell walls and water molecules, while 'cohesion' is the attraction between water molecules themselves both caused by hydrogen bonding. Cohesion is a very powerful force that allows water to be drawn up through the plant (osmosis), evaporation occurring at the top of the plant. (Boundless [no date])

The structure of a plant is maintained by the pressure and incompressibility of the water within the protoplasts (Grossbard 1979) and the cohesive properties of water create a high tensile strength within the xylem of a plant thus, water can be pulled up the stem. Diffusion although a slow process within the plant causes pressure differences allowing 'bulk flow'. A felled tree starts to loose sap-water due in part to the hygroscopic nature of the cell walls equilibrating with the relative humidity of the surrounding atmosphere; a process referred to as 'seasoning'. The moisture loss will cause shrinkage of cell walls and a change in dimensions.

## I.3.2-Degradation of Plants

Only when a cell wall contains enough water can it be attacked. Micro-organisms must therefore have access to moisture before acquiring the ability to produce enzymes that can break the cell walls down allowing access to the moisture and sugars used for growth and development. Oxygen and the sugars are converted into water, carbon dioxide and energy (Coggins 1980).

Prior to the attack, on the more easily digestible cellulose and hemi-cellulose, primary colonising micro-organisms must remove the silica and lignin that form part of the plants natural defences. Silica forms the waxy external surface properties of straw, the content of which is dependant on growing conditions (Wihan 2007). Crestini and Argyropoulos (1997) discuss the mechanical properties and biodegradability of the alkali soluble lignin in straw: “*the nature of lignin-hydroxycinnamic acid-polysaccharide interactions in plant cell walls is fundamental to our understanding of cell wall biosynthesis and biodegradation*”. (Crestini and Argyropoulos 1997, pp.1212)

The decomposition of straw is a complex process, the process will lower the pH of adjacent liquids causing manganese and iron to become soluble. The soluble minerals provide further development hastened further in the presence of cobalt, yet decay is limited without an interacting mixed population of micro-organisms; some micro-organisms cannot exist without others first establishing a foot hold. In this case there are various stages at which decay will happen, without the primary micro-organisms, the secondary and tertiary cannot be established (Evans et al. 1981). Bowen and Harper (1990) discuss the natural resistance of straw, along with lignin and silica, and identified phenolic acid levels of 1-3% that inhibit decay; the paper continues by discussing the enzymes produced by the micro-organisms to overcome resistances. “*Actual growth of mould on a special material not only depends on suitable environmental conditions but also on its chemical and physical characteristics*” (Sedlbauer 2011, pp.2)

The presence of moisture will affect rates of decay, yet temperature must also be considered; some moulds are capable of growth at -5°C and 62% relative humidity, yet the optimum temperature for most is above 20°C and 95%RH (Jolly, 2000). The rate at which straw will decompose is listed by Summers (2003) as being dependant on nutrient and oxygen availability, temperature, and free moisture. For those problems to occur in a construction the following conditions must be satisfied (Straube 2009):

- an available moisture source,
- a route for moisture to travel,
- a driving force to encourage movement of the moisture, and
- the susceptibility of the material to damage.

Straube also highlights the main sources of moisture in building fabrics: driving rain causing moisture penetration through the protective measures, condensation from air cooling within the fabric, built-in moisture present from initial construction, and wicking and splash-back from insufficient clearance above foundation level ('good boots'). However, the paper also identifies the drying potential of a fabric as being as important, highlighting the need for a construction to have effective evaporation from internal and external surfaces together with good drainage, and vapour transportation by diffusion and air flow.

### I.3.3-The Wheat Plant

Wheat accounts for the majority of cereal crop production in the UK (Figure I.5), in 2007 6,323,000 tonnes of straw was produced (Copeland and Turley 2008) and is therefore the crop of choice in UK straw-bale construction.

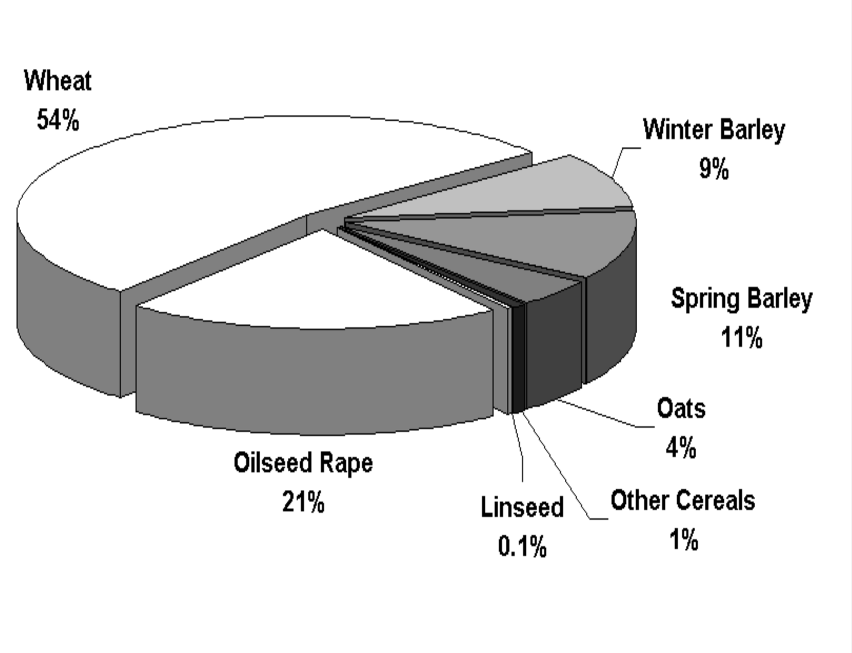


*Figure I.5: Proportion of British straw production (2007) (Copeland and Tirley 2008)*

Wheat straw consists of around 41% cellulose, 29% hemicellulose and 11% lignin (Butterworth 1985), the remainder includes silica of which rice has a higher content than other crops and hence is slightly more resistant to microbial attack. The wheat plant is for the most part self-pollinating, yet cross-pollination can occur depending on the climate, genome and the pollen distribution (GMO Compass, 2006). Harvest occurs during the 'Dry Down' stage, beginning around 30 days after fertilisation, the grain moisture content is closely monitored and is harvested around 20%MC, then mechanically dried to under 14.5% to prevent decay or germination (Wheat Genomics [no date]). The stem remains on the field to air dry prior to baling.

Wihan's thesis (2007) reports on studies into the tissue development of straw: nodes, which are the sections of the plant used for development during growth, are more susceptible than the remainder of the stem to decomposition due to the nutritional value of the tissue. The leaves of cereal crops (in all except rice) have twice the amount of nutrients as the internodes; it may therefore be expected that micro-organisms attack leaves and nodes prior to the stem tissue.

## *I.4-Straw's 'Nemesis'*

The resulting presence of moisture in the UK's temperate maritime climate enhances the need for protection and good design compared to other drier climates potentially more suited to straw bale construction.

### I.4.1-'Know your Enemy'

Moisture is the 'enemy', the main fuel for degradation without which micro-organisms will not develop; the main question should therefore be: 'at what level will degradation occur'? In discussing this subject, in general terms, Oliver and Stirling (1996) provides the basis for Figure I.6 stating that: “*most buildings are not made under factory conditions, and therefore contain a variety of inherent weaknesses*”. If the materials used are organic then they will be susceptible to decay at certain moisture contents or relative humidities.

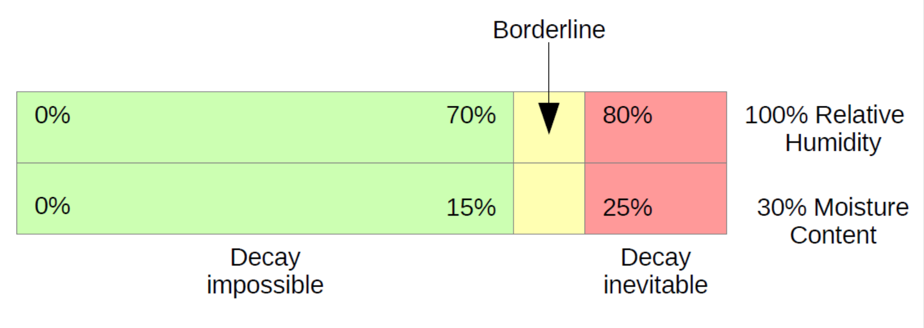


*Figure I.6: Diagram based on idea from Oliver et al.,1996 p24*

The Collins Dictionary defines moisture as ”*water or other liquid diffused as vapour or condensed on or in objects*” (Collins 2014). Concerning water, it's state or presence, is as either an incompressible solid (ice) of a definable shape and volume in which molecules are packed into a rigid array, a slightly compressible liquid (water) of a definite volume but indefinite shape due to the mobility of molecules, and as a gas (vapour) of uncertain shape or volume and with a high compressibility as a result of the independence of molecules.

## I.4.2-The Chemistry of Moisture

The strong bond between water molecules is known as the Van de Waals force, hydrogen's covalent bond together with the highly electronegative atom of oxygen, these dipoles of positive and negatively charged forces attract the atoms in the same way as a magnet. The orientation of the atoms is due to the electron arrangement and the forces produced by hydrogen bonding, it is the strong negative force that arranges the molecules in one direction (Burns 1995 pp.383). The hydrogen atom gives up it's electron to the oxygen atom, allowing it to become similar to a positively charged bare proton acting to attract negative charges and giving water its high boiling point (Callister 1994).

The greatest molecular attraction appears at the centre of a liquid and is the reason water forms droplets drawing the molecules away from the external and less attractive atmosphere. The exceptions to this effect are in the presence of surfactants and other pollutants that cause a hygroscopic effect. Hydrophilic and hydrophobic effects are generated by a materials electromagnetic forces.

Water has a specific heat value of 1.0 cal/gK (4.184 J/gK) requiring one calorie of energy to raise one gram of water by 1.0°C. A large amount of thermal energy is therefore required to heat water is due to it's strong hydrogen bond conversely, a large amount of energy is released with just a small drop in temperature. This high thermal capacity can therefore create temperature depressions within a material as heat is drawn from the material to evaporate the moisture (Saïd 2007). As a highly polar substance water (Figure I.7) is a good solvent for many ionic substances, it's chemical formula $H_2O$ has $1.0x10^{-7}$ M $H_3O+$ (Hydronium) and OH- (Hydroxide) at 25°C.

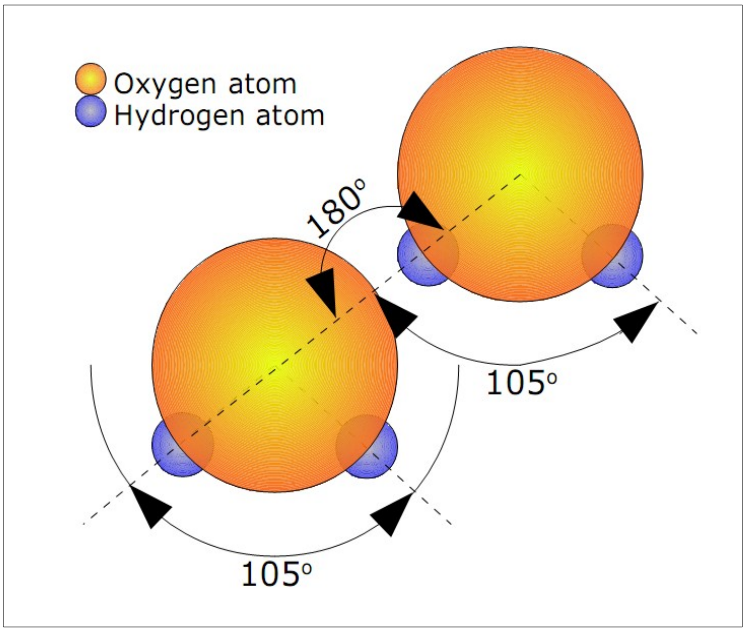


*Figure I.7: Arrangement of water molecules*

A molecule escaping the liquid phase must have enough kinetic energy to break free of the bonds and become vapour (vaporisation). The energy comes from chance collisions with other molecules which raises the molecules latent heat and cools the remaining liquid (McMullan 2002). As a note evaporation will only occur when the liquid is in a volatile state and vapour is released into the surrounding atmosphere.

Burns (1995) states, when describing John Dalton's discovery, that if water vapour was added to dry air the pressure would increase, surmising that: vapour pressure is the total of the combined partial pressures of each separate gas. Water vapour will: "*rapidly occupy any given space and exert a vapour pressure on the sides of any surface they are in contact with*" (McMullan 2002, pp99). The maximum amount of vapour that can be held by air at a given temperature is termed the Saturated Vapour Pressure (SVP). The pressure caused by vapour in a warm area will encourage moisture transfer to a colder area of lower pressure where the moisture vapour will condense.

A system in equilibrium is obtained when the rates of condensation equal that of vaporisation, therefore, in a closed environment heating a liquid will increase the rate of vaporisation and reduce condensation giving a higher equilibrium vapour pressure yet eventually dynamic equilibrium would balance it out once more. When air is cooled to saturation then any surface in contact with this air, that is at the same temperature or cooler, will be subject to condensation and is referred to as being at: dew point temperature. The point at which this occurs within a building fabric will cause interstitial condensation to occur (Figure I.8).

For the purposes of experimentation it is possible to generate an atmosphere using moisture, a sealed container and salt solutions (Duggal 1981), using a selection of salts as documented by BS EN ISO 12571:2000 the salt will exact an equilibrium with the immediate environment modifying the relative humidity irrespective, to the most part, of temperature.

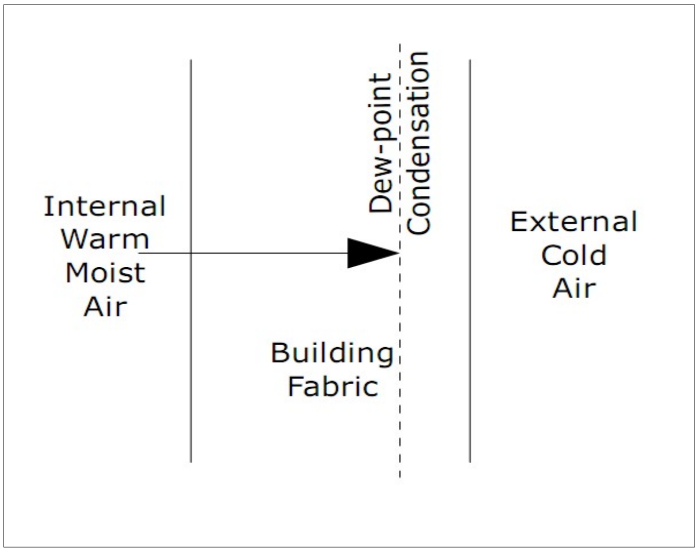


*Figure I.8: Basic diagram of Interstitial Condensation within a building fabric*

## I.4.3-Scales and Measurement

Moisture can be measured in various different ways; relative humidity is the measure of the amount of moisture in the air at any given temperature (Equation I.1).

$$\varrho = \frac{P}{P_s} \times 100$$

$$\begin{aligned} \varrho &= \text{ Relative Humidity} \\ P &= \text{ Vapour Pressure of sample} \\ P_s &= \text{ Saturated Vapour Pressure of sample} \end{aligned}$$

*Equation I.1: Relative Humidity.*

From the knowledge of relative humidity and temperature several aspects of the environment may be calculated using either a Psychrometric chart or by individual calculations including dew-point, enthalpy, humidity ratio, absolute humidity and densities.

For example: If air in a bathroom, at 15°C and 60%RH, is raised to 20°C and 95%RH by someone taking a shower, then the dew point will be increased from 7.3°C to 19.2°C thereby increasing the risk of condensation forming on any surface offering a lower temperature. Therefore, there is a requirement for ventilation; indeed this is a mandatory requirement in the UK in both kitchens and bathrooms.

Obtaining a gravimetric analysis of a sample presents the results for the measurement of the moisture content of a material as a percentage of mass. Two methods can be employed, using either wet basis or dry basis, these offer a percentage in the difference in mass of dry material weight against wet (Equations I.2 to I.5).

$$C_{wet} = \frac{100}{1} * \frac{m_{wet} - m_{dry}}{m_{wet}}$$

*Equation I.2: Moisture content wet basis*

$$C_{dry} = \frac{100}{1} * \frac{m_{wet} - m_{dry}}{m_{dry}}$$

*Equation I.3: Moisture content dry basis*

$$C_{wet} = \frac{100 * C_{dry}}{100 + C_{dry}}$$

*Equation I.4: Wet from Dry Basis*

$$C_{dry} = \frac{100 * C_{wet}}{100 - C_{wet}}$$

*Equation I.5: Dry from Wet Basis*

$C_{wet}$ = Moisture Content wet basis
$C_{dry}$ = Moisture Content dry basis
$m_{wet}$ = wet weight
$m_{dry}$ = dry weight

Both the wet and dry basis methods appear in literature concerning straw bale construction however, there is often a lack of clarity between which result the data is presented in leading to confusion over the limitations of straw as a building material. The importance therefore of stating whether results are presented in wet or dry basis is critical to the advanced understanding of the subject.

This thesis will present all data in dry basis (%$MC_{dry}$) unless otherwise stated for comparative review or citation. Using dry moisture content provides a higher degree of division for data analysis and thus a larger range to enable the results to be viewed in greater detail (Figure I.9).

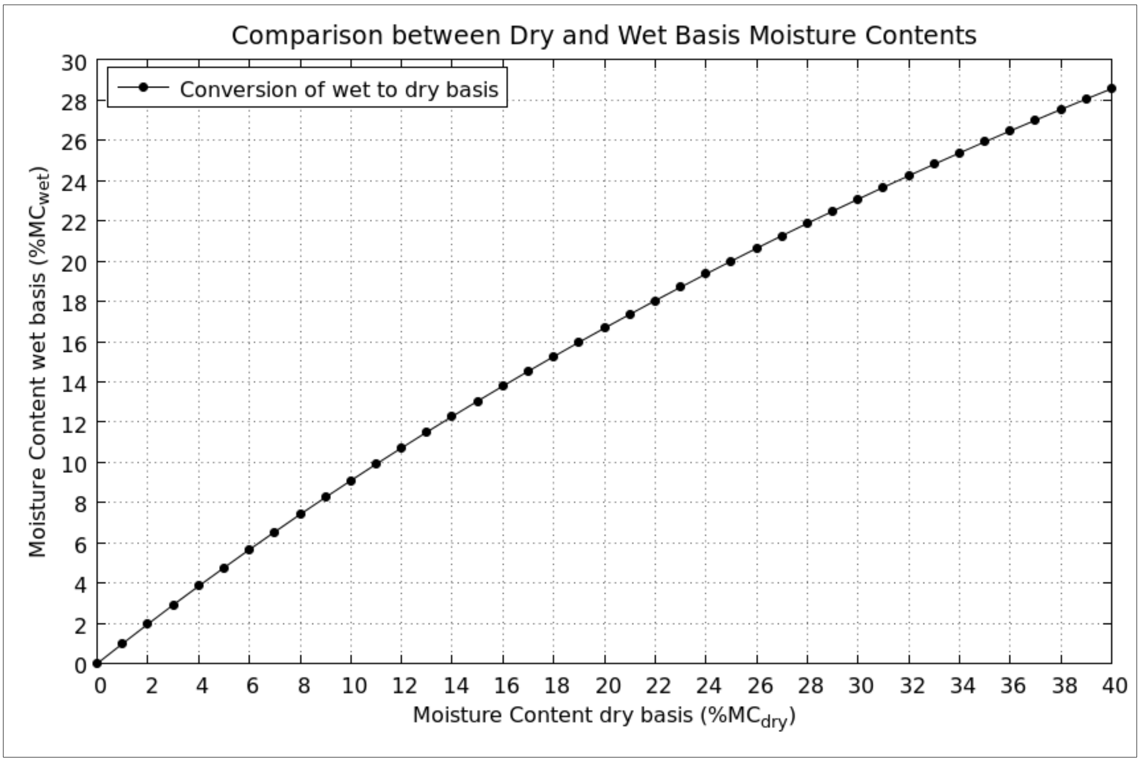


*Figure I.9: Comparison of wet and dry basis moisture content*

Figure I.9 illustrates the difference between measurements taken in dry basis (x-axis) and wet basis (y-axis) highlighting the range difference; for example an $MC_{wet}$ of 20% corresponds to a reading of $25\%MC_{dry}$ . If readings are confused then a misinterpretation of results could lead to a misdiagnosis of the level of moisture resulting in a potentially dangerous situation developing, or remedial work being carried out for no reason.

The implications of this and the boundaries of moisture content for straw are discussed in Section II.1 (p46). Wihan (2007) presents results in wet basis following Summers et al.'s (2003) advice that the majority of agricultural, food and straw bale building industries use this measurement over the dry based. King et al. (2006) draws attention to the need to describe bale density in terms of dry density.

## *I.5-Justification of Research*

Straw bale construction may offer not only a way to reduce the impact of current construction techniques on the environment, but also to re-engage people with Nature allowing them to envisage what is involved in the life cycle of a construction. However, straw bale construction is not an established method and although there are a number of buildings in the UK a mainstream acceptance remains in the future.

### I.5.1-Public opinion

Hamilton-Maclaren et al's. (2013) investigation analysed the potential for the reluctance of a customer to purchase a property constructed using a particular method and the effect that has on the construction industry. There were 572 responses to the survey rating answers on a scale of one to five with the provision of an additional comments box concerning factors important to purchasers of houses and in particular of alternative constructions. The authors constructed a questionnaire identifying cost, energy efficiency, maintenance and mortgage availability as factors likely to affect a purchaser's choice. The questionnaire found that around 81% of people had heard of straw bale construction, 29% would consider buying and 32% returned a maybe. Amongst the greatest concerns offered as suggestions, that reduced the appeal of this method of construction, were: that of fire, followed by a concerns over potential for rot, the appearance of the construction, maintenance, and the strength of the building. Conversely the appeal of low environmental impact and good insulation values were given as positive aspects. The paper suggests that respondents are interested in minimising their environmental impact, but would require more guarantees attached to the building, the presence of which could influence mortgage and insurance companies also. In conclusion it states that greater awareness and education is needed to encourage potential buyers to choose something other than what they find familiar.

Hamilton-Maclaren et al.'s (2013) work is encouraging for the straw bale construction industry; general awareness raised due to the promotion of the method on Grand Designs (2014) and in community based projects such as Sieben Linden (no date). If however, the questionnaire had been aimed at a better informed group or potential straw bale home owners, respondents may have cited concerns differently. The main concern of moisture and guarantees against rot may have scored significantly higher in this case, indicating that a greater knowledge of moisture, moisture monitoring and modelling would be needed to convince potential buyers to accept the method. Greater acceptance would in turn convince the construction industry to rise to the demand, and for insurers and mortgage companies to do likewise.

### I.5.2-Thesis structure

Chapter 2 (p45) gathers together the existing literature in order to determine the extent of knowledge in the relation to moisture, perceived risk and of straw assessing techniques used to obtain a reliable indication as to the straw's moisture content together with the interpretation of the results. The chapter concludes by discussing the identified gaps in knowledge formulating the research problem and refining the objectives as laid out on page 11.

Chapter 3 (p88) describes the methodological approach adopted by the thesis investigation defining different subject areas and variables associated with the method of study. The chapter continues to define the research problem identifying areas of research to be discounted, defining the term 'risk', and evaluating the potential benefits of the overall research aim.

Chapter 4 (p104) presents the method and results for Part 1 of the Preliminary Investigation. Part 1 encompasses a preliminary case study investigation and laboratory experimentation conducted using wood-block probes.

Chapter 5 (p127) presents Part 2 of the Preliminary Investigation representing a change in research procedure based on weaknesses observed with the wood-block probe. Part 2 introduces two new monitoring devices and initial results of a Test Rig investigation, detailing the construction and application of a model to interpret the risk posed from moisture. The chapter culminates in an experiment to investigate the effect of bale density on resistance meter measurements.

Chapter 6 (p179), the Focussed Investigation, details the experiments conducted in light of the literature review, and both parts 1 and 2 of the Preliminary Investigation. The effect of density on resistance meter readings is assessed first, followed by detailed temperature experiments conducted in both the laboratory and the Test Rig. The chapter concludes with an investigation into moisture transfer.

Chapter 7 (p234), the Model chapter, represents a culmination of the data and arguments used to critically analyse each monitoring method with relation to defining an evaluative technique to utilise in the monitoring of a straw bale construction. This discussion feeds a model which is presented, evaluated, then applied to straw moisture data obtained during the Test Rig and Monitoring Site investigation. It includes also the development of equations to compensate for both temperature and density of straw, and presents a novel method of evaluating risk.

Chapter 8 (p282)concludes the thesis with a review of progression to date, listing the contributions to knowledge and further work that is required.

## I.5.3-Summary

Straw bale construction offers a method by which to replace non-renewable resources with a by-product that is intrinsically linked with human nutrition and grown annually in many parts of the world. A material locally sourced, with the potential to improve biodiversity conservation, and by including local communities in the construction project, promote well-being and education with the potential benefit of reducing the impact of alienation.

One identified weakness inherent in straw bale construction can be found due to straw's organic origins. Without the correct protection the natural cycle of the planet will cause the breakdown of the cellular structure into base components; a return to state. In order to promote the benefits of straw bale construction the interaction of moisture and the level at which straw will decay needs to be known.

# *Chapter II-Literature*

## ***II.1-Introduction***

Straw is an organic material that is subject to the natural life-cycle of the planet and will be broken down by micro-organisms if adequate protection is not afforded. In using this material in construction the inevitable return to state must be delayed whilst utilising the benefits of high insulation values, local availability and non-toxic elements (Bigland-Pritchard and Pitts 2006). It could also provide potential for social inclusion and greater biodiversity conservation awareness amongst the general public. The key to preventing the onset of decay is to minimise the amount of moisture available to the micro-organisms associated with the degradation of straw.

## II.1-Straw and Moisture

To date there has been little agreement or definitive evidence to suggest the level at which moisture starts to cause decay in straw bales used for construction. Much of the literature implies 20%MC as being the limit at which decay will begin, although it also suggested that decay is not significant until 25%MC is reached; the majority of literature is in agreement however, that moisture content's of below 15% provide adequate protection.

### II.1.1-Moisture Regimes

In explaining the relationship of moisture's interaction with straw, Straube (King et al. 2006) describes the significance of pores in a structure and the resultant increase in surface area of the material. The paper continues to account for how capillary suction occurs as a result of water's polar nature, and how this polarization aids adsorption. Adsorption is the tendency of vapour molecules to be captured by the surface of hydrophilic materials; the force of this attraction is reduced as energy is added into the system.

Straube (King, 2006) provides insights into interactions of water vapour with porous materials, Figure II.1 shows the moisture content (y-axis) of a porous hygroscopic material related to relative humidity (x-axis) identifying five distinct regimes that occur at varying relative humidity's. Regimes A-C occur within the hygroscopic regime, the build up of moisture's surface tension generates the ability to form a meniscus in the smallest pores leading to the second regime, D, in which the larger pores contain free water and the medium is assumed to be under a continuous liquid phase. Finally a supersaturated state is reached at 100%RH (E) representing the maximum amount of water that will wick into the material beyond which an external force must be provided. In order that a wetted material dries completely the surrounding relative humidity must be reduced because the: "*Capillary and adsorbed moisture can only be dried by evaporation followed by diffusion*" (King et al. 2006, pp.6).

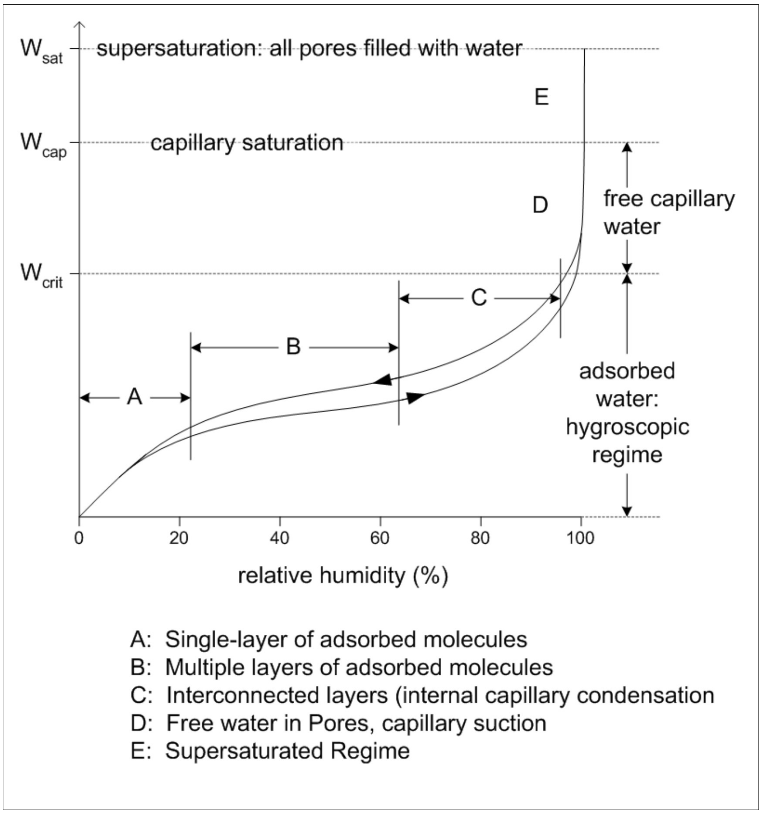


*Figure II.1: Moisture storage regimes within a porous hygroscopic material (King et al. 2006, pp.4)*

## II.1.2-Chronology of Uncertainty

In recent years several attempts have been made to suggest the limits at which straw is susceptible to decay; Table II.1 is a list of sources that have suggested likely values based on laboratory experiments, field trials or on construction knowledge gained from the field. A column has been added to clarify whether the results are presented in dry or wet basis (Section I.4.3).

The relationship between suggested advice is brought into question however; the uncertainty of defined limitations promoting a lack of confidence in the construction method. Figure II.2 tracks the history of the data highlighting the grounds for the advice, whether or not stated values are based on previous research, experimentation conducted by the author, or an unknown source. The figure translates the authors original words into, 'safe' meaning there will be no damage from decay, 'of concern' suggesting that evidence is unclear, and 'decay' meaning that decay is inevitable. Some of the suggestions are time dependant, shown on the diagram as 'td'; boxes highlighted yellow were not checked.

Lawrence et al. (2009a), Figure II.2, collated much of the advice and used this, together with the empirical research done by the authors, to draw on the conclusions presented. The figure also draws attention to the debate, or lack of debate, surrounding moisture content's between 20-25%, the majority of research avoiding this range as an unknown or inexplicable region to advise upon.

*Table II.1: Suggestion for moisture limits in straw bale walls*

| **Reference** | **Advice provided as to moisture content limits** | **Basis** |
|---|---|---|
| CMHC 2000 | Recommend keeping straw under 20%, decay beginning typically at between 25 to 30%. | Not stated |
| Jolly 2000 | Extreme diurnal variances in relative humidity with peaks of 98% did not indicate damage to the straw however, over 85% for prolonged periods does pose a problem. | N/A |
| Summers et al. 2003 | Rice straw was shown to withstand 27% before any development of micro-organisms or decomposition however, moisture contents of over 25% should be avoided. Moulds could initiate at between 15-18%MC when compared with a water activity of 0.7. | Dry |
| Straube and Schumacher 2003 | Recommend that the relative humidity be kept below 80%. | N/A |
| USDoE 2003 | When purchasing a bale ensure that bales are below 14%MC and have always been dry. | Not stated |
| Goodhew et al. 2004 | Below 14%MC is believed to be insufficient for biological activity | Dry |
| Summers et al. 2006 | Micro-organisms are not very active at low temperatures. At certain temperatures between 20ºC and 65ºC most will thrive. At 15-18% moulds could develop but bulk moisture content over 25% should be avoided. | Dry |
| Bruce King et al. 2006 | Recommends that only bales under 25% be used in building structures; (referring to rice straw) | Dry |
| Lawrence et al. 2009a | Below 15% generally accepted as safe. Decay is limited below 25% and is time dependant. Above 85%RH (25%MC) degradation will occur. | Dry |
| Carfrae et al. 2009b | A received wisdom sets the safe maximum at 25%, but Carfrae suggest that there be two caveats added to do with short and long-term exposure to higher levels of moisture. | Not Stated |
| Dick and Krahn 2009 | Microbial activity declines greatly at moisture content's under 20% (70%RH)<br>*"All samples taken...remained under the ideal moisture content of 20%, indicating that the likelihood of bacterial growth, or rot, within the bales was low."* (pp.3) | Dry |
| Straube 2009 | At over 80% RH (equating to 20%MC) mould growth will occur over a sustained period, this is lower than wood due to straw's significantly higher surface area. | Dry |
| Goodhew et al. 2010 | Evidence suggests that straw not exceeding the capillary saturation value around 37%MC for long time periods appear undamaged. | Dry |

Concerning the history of research in this area the report conducted by Jolly (2000) provided the research data and analysis for another report by the Canadian Mortgage Housing Corporation  (CMHC 2000); although the two reports are intrinsically linked they present different information in the writing up. The report by the Canadian Mortgage Housing Corporation (CMHC 2000) presents advice (Figure II.2) based on unreferenced knowledge possibly from advice given by owners, builders and the agricultural industry.

Jolly (2000) reasons that straw bale walls are highly dynamic due to the straw's hygroscopic nature together with the application of highly vapour permeable renders. Jolly's advice is based on empirical work and the initial development and use of hygrometers, wood-block probes and resistivity meters. The report suggests that although humidities of up to 98% can be tolerated for short periods, the straw, depending on the time period involved, will deteriorate at above 85%RH. Wihan (2007) commenting on relative humidity summarises Summers et al.'s (2003) advice that extensive decomposition of straw occurs only when the air in a wall remains above 98%.

Summers remarks on the apparent ability of straw to tolerate moisture content's in excess of 15%. The tolerance is due to uneven moisture distribution throughout the bale, as moisture tends to migrate and condense randomly (Summers 2003). The paper surmises that a margin of safety should be established at 25%MC. This supports reasons for using relative humidity as a guide to assessing the risk posed rather than the direct moisture content of the straw as Straube (2009) rationalises; straw will not very effectively 'wick' water due to limited capillary suction. It would also indicate that the whole bale should be filled with relative humidity sensors in order to establish the risk posed to the straw.

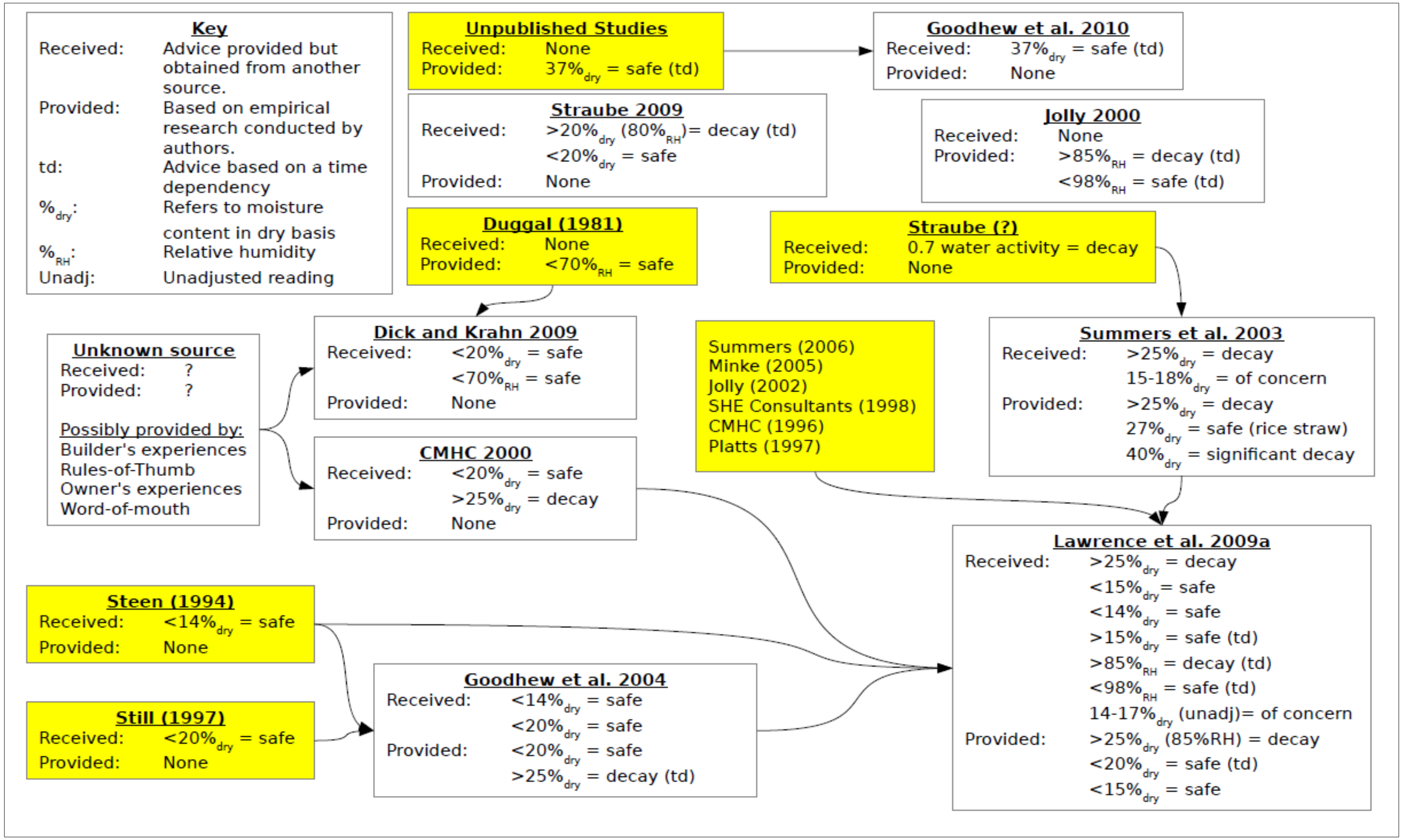


*Figure II.2: Translating the advice*

Goodhew et al. (2004), using wood-block probes developed from Fuller's original study, accept that moisture contents and temperatures are only part of the reason for straw degradation, adding: regional climate, building design, detailing, and building situation. Carfrae et al. (2009b) concluded from observations in a case study using a new design of wood-block probe and a Balemaster that a wall subjected to 37%MC exhibited “*no apparent damage*” (Carfrae et al. 2009b, pp.8). This level was recorded towards the external surface of a wall rendered in 25mm lime and took five weeks to return to below 25%MC. This would conform to Jolly's (2000) advice ($98\%_{RH}$ = safe (time dependant)) however the effective temperature was not apparent within the report, if the temperature below the external render rarely rose above 10°C the risk from microbial activity would be minimal.

Questions of pH have also been raised as to the effect of the render on the straw in the immediate vicinity, a more alkaline environment decreasing straw's susceptibility to decay. King writing for the Building Safety Journal (2004, p.41) discusses the stucco/straw interface concluding that straw may eventually degrade where water is 'held' against it.

Carfrae's thesis (2011) identified two key areas of research to address, the effect of high moisture content on straw and the most effective method of in-situ monitoring of a straw bale wall; in addition, the most appropriate method of construction to use in a temperate maritime climate was investigated. The thesis explains that straw will tend to equilibrate with the air surrounding it due to the hygroscopic nature and based on research by Summers states that at moisture content's below $25\%_{dry}$ there is: “*virtually no risk to the integrity of the straw, and the health of any human inhabitants*” (King et al. 2006, pp.64). However, it is unclear whether Summers applies this to rice straw, or all types of straw.

The term risk is used in multiple sources of literature, Bigland-Pritchard and Pitts (2006) use risk with fire safety, negative aspects on human health from pesticides and fungicides, pests, mould growth and moisture, Hamilton-Maclaren et al. (2013) from a financial and decomposition aspect, and Lawrence et al. (2009b) for durability. Bronsema (2010) comments on risk categories when commenting on isopleth studies utilising colours to identify high, medium and low risk environments with the potential for decay; see Figure II.9 page 71. Risk therefore is utilised in literature, but is generally not discussed or contextualised.

Carfrae questions, in summing up the literature, what constitutes a 'safe' level, identifying the levels between 20-25%MC as unknown in terms of long term exposure and risk of damage. Straube (2009, pp.9) poses the question: “*how much moisture can be stored and for what duration without crossing a performance threshold?*”. Summers et al. (2003), referring to water activity, reports that yeasts require a water activity of 0.8 and bacteria generally over 0.9 to survive, calculating that a water activity of 0.7 would correspond to an moisture content of between 15-18% (13-15% wet basis) and little micro-organism growth. Water activity is the equivalent moisture availability in a given substrate for microbial activity at which the sample is in equilibrium with the relative humidity (Wihan 2007, Ashour 2003, Summers et al. 2003). Water activity is one hundredths of the relative humidity.

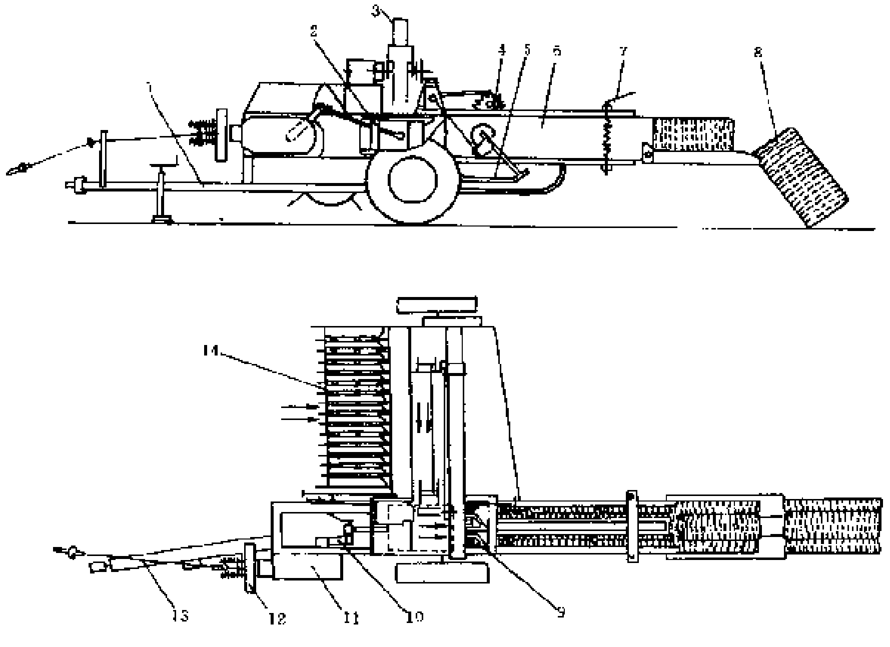
Moisture interaction within a straw bale is a complex issue, in both the measurement and analysis of results in relation to decay. Relative humidity essentially only confirms the measure of moisture within the atmosphere for that particular temperature and at that particular point in time. A more direct measure of moisture content would therefore reveal the true moisture level dictated to by the rate at which moisture will condense and the rate of change of the straw's temperature opposed to the air temperature. However, this is a multi-valence problem, that is not clear cut, therefore to further understand the complexities of straw and moisture's interaction Sorption Isotherms have been studied (Section II.2 p58). Sorption Isotherms attempt to relate relative humidity of the air to moisture content of the straw offering a simple conversion scale that can be used to further describe the interaction of moisture with straw by identifying desorption and adsorption trends.

### II.1.3-A fuzzy construction material

A straw bale is an amalgamation of randomly bound biodegradable organic matter consisting of either wheat, rice, barley, rye, or oat stems and occasionally unharvested seed-heads omitted by the combine-harvester, other plants from the previous years crop, and potentially some weeds. The straw is gathered, post harvest, by a baling machine (Figure II.3) which rakes the straw from the field into the screw or raking mechanism where it is passed into the compression chamber, rammed into a cuboid shape, tied and dropped back onto the field in the form of a bale. The bale therefore becomes a chaotic union of different lengths of stems; chopped, folded, broken, and bent, and laid in roughly the same direction.

The bale, in comparison to mass produced clay bricks, chiselled blocks of stone, or sections of timber, are not 'standardised'. Bales can vary randomly in density (Carfrae, 2009a. blog), moisture content (Grmela, 2010. p.2), size and contaminants (dust, alien plants, fungi spores, etc.) combined with a difference in the length of stems and quality of the crop. The potential for variability is therefore greater than most common building materials.

A question may therefore be proposed: are conventional measurement techniques able to evaluate a straw bale wall, or is a new approach required? Straw bales are sometimes referred to, in the industry, as '*fuzzy building blocks*' because of their appearance however, this observation could be expanded to describe the physical properties and further interactions within the bale. The straw, once a living entity and now preserved (or mummified), is now a collaborative partner in a second life providing a structure, it is a series of tubular lengths collected together with internal and external surfaces, with pores and textures. The bale contains an internal atmosphere separated from the external atmosphere by some form of protection (lime render, stucco, clay), and is subject, for the most part, to it's own environment; a place where objects and space collide, and exchanges and interactions take place unseen to the naked eye, yet are potentially observable with the correct monitoring devices and techniques.



KEY:
1. Tow beam; 2. Piston; 3. Conveying and feeding equipment; 4. Bale length controller; 5. Needles; 6. Compression chamber (bale chamber); 7. Bale density adjuster; 8. Bale; 9. Needle-and-tying mechanism; 10. Crank; 11. Main gear box; 12. Flywheel; 13. Universal joint gearing axis; 14. Pick-up reel.

*Figure II.3: Baling machine (FAO, 2002)*

The monitoring of a straw bale construction is advisable due to straw's propensity to decay if conditions are met (Lawrence et al. 2009a; Clynes 2009; Carfrae 2008); decay is a natural part of the life cycle of the planet, a return to state, the changing of one resource to another. Straw represents a potential breeding ground and home to micro-organisms and other infestations: a dining hall, an ecosystem, a universe of food and moisture. The  risk posed to the straw is paramount when being used as a construction material, keeping it protected from moisture is the first step to preserving the resource's abilities from the ravages of decay.

## II.1.4-Moisture

Within a bale there are collisions of objects in space, space being in this case everything within the dimension of the extremities of the bale. The comparative size of a water vapour molecule, 2.75Å (Chaplin, 2012) or $2.75\text{x}10^{-07}$mm, to a 1mm wide air gap in a bale may be considered as a grain of sand in a corridor 1000 km's wide. Therefore, if Summers' (2003) unconfirmed assessment that 90% of a bale is air, there is a comparatively large amount of free space for a water vapour molecule to travel, yet it is the ability of a straw bale walling system to slow air moment that provides straw with it's thermal capacity, using air's natural insulation value trapping and restricting thermal flow.

The progression of moisture through a bale may therefore be impeded by the straw itself, air gaps in a bale occurring randomly will exhibit differences in dimensions, distribution and occurrence, varying also with bale density.

## II.2-Sorption Isotherms

Sorption Isotherms are conducted to gain insight into the effect of relative humidity and temperature on the moisture content of a sample. There are two documented methods, both subject the sample to a specific relative humidity and temperature condition measuring the mass of a sample until stabilisation is achieved. In the first method multiple samples are subjected to individual relative humidity, under the second method one sample is subjected to a cyclic regime of relative humidity. The dry mass of the straw may be obtained prior to, or after the experiment. Therefore, a sorption isothermal study represents the absolute mass obtainable by the sample at the particular condition, given the method applied.

Figure II.4 illustrates an isothermal study conducted on timber together with different phases involved: desorption the removal of moisture from the surface of a material and adsorption the deposition of moisture onto the surface; differing from absorption which describes the passage of moisture into the structure of the material. As the relative humidity surrounding a sample is dropped (Figure II.4) the surface moisture content of the sample is reduced, highlighted by the 'initial desorption' and 'desorption' curves. Upon an increase in relative humidity the adsorption curve is produced as moisture collects on the surface of the sample. The two phases (or curves) will produce a hysteresis, the oscillating desorption phase offers a midpoint and a compromise of data when the true phase is unknown; Carfrae et al. (2009b) suggests that the oscillating desorption is a constant ratio of around 0.85%.

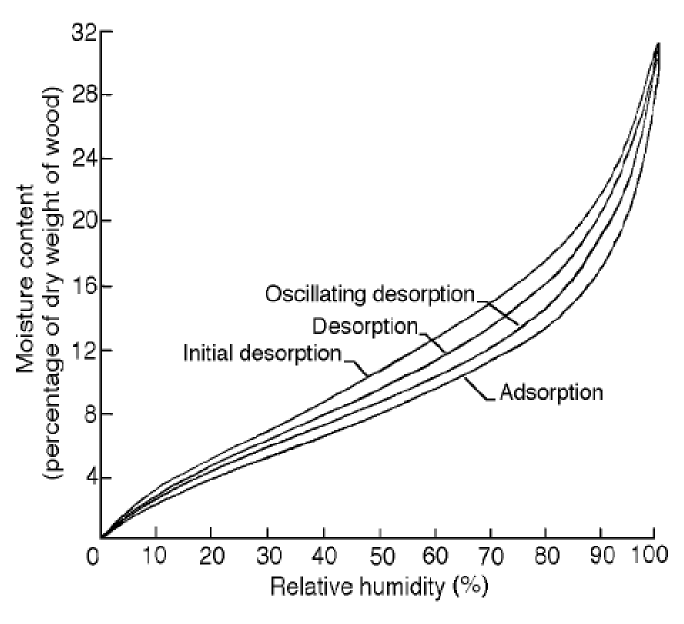


*Figure II.4: Isothermal study of wood (Forest Products Laboratory 1999)*

Concerning individual studies, Lawrence et al. (2009a) undertook to describe the moisture content of straw from the surrounding relative humidity by way of an empirical mathematical equation, building on Hedlin's sorption work for five different types of straw at 21.1°C (70°F). Hedlin's results were also compared to oats, barley, flax and another two wheat’s at 14 different relative humidity's giving similar results. Lawrence et al. (2009a) citing Perry and Green's argument states that temperatures between 15-50°C should not affect the straw's sorption isotherm results due to straw's porous structure and vapour's ability to condense into wider diameter pores at lower temperatures. It is also argued that there is less requirement for temperate studies below 10°C because fungus generally can not develop at these temperatures; 20-65°c being optimum temperatures for growth (Summers et al. 2003).

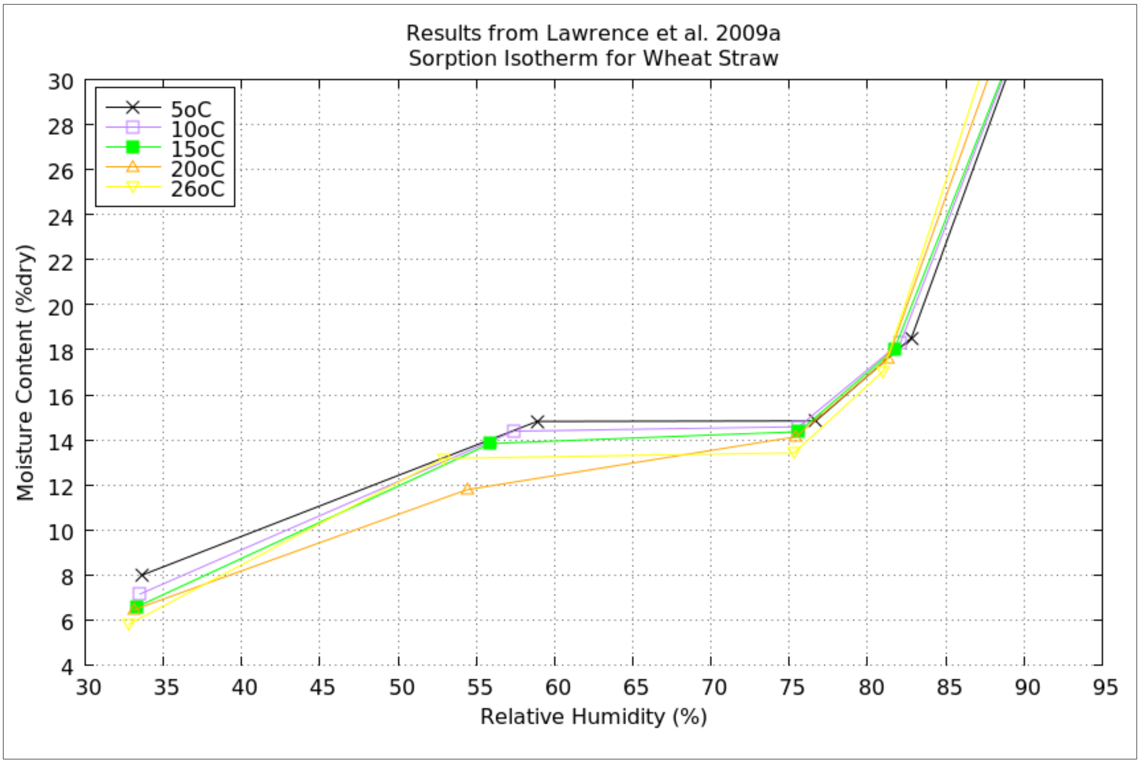


*Figure II.5: Results of Lawrence et al. 2009a*

A series of isotherm tests were undertaken (Figure II.5 reproduced from data given in Lawrence's 2009a paper) using salt solutions to generate atmospheric humidities at temperatures between 5-30°C (5° increments) on inorganically grown wheat straw samples, each sample measuring 20g (35mm diameter *185mm length) tied to a density of 125kg/m$^3$. The samples were oven dried prior to the experiment, which subjected the samples to seven days at the required relative humidity and temperature, followed by further 24 hour intervals until the masses remained within 0.1%, a method contested by Phanopoulos et al. (2000). The results show that the moisture content is reduced by 1-2% at each relative humidity for temperatures between 5-26°C, except at 98%RH (not shown).

Equation II.1 (Equ$_{Law}$) was developed by Lawrence et al. (2009a) and shows a close approximation to the results at 20°C; this shows that an atmospheric relative humidity reading of 90% equates to a moisture content of 33% for straw (when i=1.6). The equation appears in another form (Lawrence 2009b) with 'i' represented as '1' altering the results (this is discussed in Section VII.3.6 p247). In conclusion these investigations were conducted to raise confidence levels concerning the risk posed to straw bale constructions from moisture, but the paper explains that this was an initial assessment for the approximation of a method to convert relative humidity to moisture content, therefore suggesting that further work was required. For the purposes of this thesis 'i' will be read as '1.6'.

$$C = \frac{C_s}{1 + n\left(\frac{K_m}{\phi} - 1\right)^{\frac{i}{3}}}$$

$C = Moisture\,Content\,(\%)$
$\phi = Relative\,Humidity\,(\%)$
$K_m = 0.9773 \qquad i = 1.6 \text{ or } 1$
$C_s = 400 \qquad n = 44$

*Equation II.1: $Equ_{Law}$: Convert Relative Humidity to Moisture Content (Lawrence et al. 2009a and b)*

Carfrae et al's. (2009b) method differs to Lawrence's as Lawrence uses multiple samples subjecting each to an independent atmosphere over time. Carfrae uses an environmental chamber to subject a number of samples to an increasing then decreasing relative humidity, effectively 'cycling' the samples. Carfrae used this technique to calibrate the Balemaster and four species of timber, identifying Ramin as the best timber for a new design of wood-block probe; the use of Ramin over Oak was published after several wood-block probes had been constructed for use in this thesis, as is discussed within the Preliminary Investigation Chapter – Part I (Section Chapter IV- p104).

Both Carfrae and Lawrence's approaches are different and provide subtly different results. Carfrae's method is able to show straw's adsorption and desorption isotherms which may provide clearer evidence as to what is happening to the straw within a bale in a dynamic situation. Carfrae's method however, has potential inherent inaccuracies due to the potential for mould development when subjecting straw to high relative humidity's for sustained periods of time, or at least until the mass of the sample stabilises. The development of moulds whilst subjected to raised relative humidity's could change the mass readings affecting the gravimetric analysis (section II.4.1 p72).

Lawrence's approach starts with dry straw and subjects it to an adsorption phase, therefore these results may read slightly low if compared to the desorption data. There is also a question over the physical changes brought about by drying the straw prior to the experiments and whether this may influence the results (Phanopoulos et al. 2000).

Forest Products Laboratory (1999) produced an isothermal study and equation for analysing timber. Equation II.2 ($\mathrm{Equ}_{\mathrm{FPL}}$) was developed to derive the equilibrium moisture content from relative humidity and temperature for timber representing the oscillating desorption phase value.

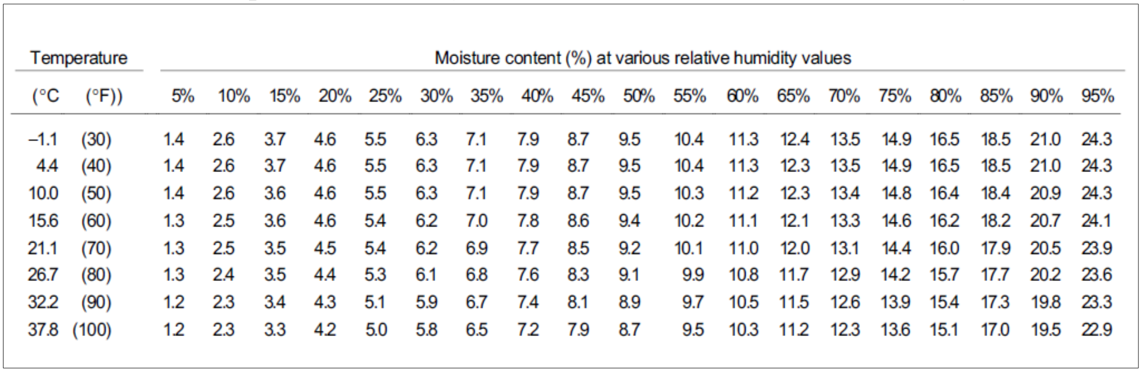
$$C=\frac{1{,}800}{W}\left[\frac{Kh}{1-Kh}+\frac{K_1Kh+2\mathrm{K}_1K_2K^2h^2}{1+K_1h+K_1K_2K^2h^2}\right]$$

$$\begin{aligned}
&C= \ \mathit{Moisture\,Content}\ \ (\%)\\
&W= \ 349+1.29\mathrm{T}+0.0135\mathrm{T}^2\\
&K= \ 0.805+0.000736\mathrm{T}-0.00000273\mathrm{T}^2\\
&K_1= \ 6.27-0.00938\mathrm{T}-0.000303\mathrm{T}^2\\
&K_2= \ 1.91+0.0407\mathrm{T}-0.000293\mathrm{T}^2\\
&T= \ \mathit{Temperature}\ \ ({}^{o}C)\\
&h= \ \mathit{Relative\,Humidity}\ \ (\%)
\end{aligned}$$

*Equation II.2: ($Equ_{FPL}$): Calculation of moisture content for timber (Forest Products Laboratory 1999)*

Table II.3 provides an overview of results obtained from the $\mathrm{Equ}_{\mathrm{FLP}}$, from the results it can be seen that at temperatures lower than 15°C moisture content the timber remains constant irrespective of relative humidity, corresponding to Lawrence's advice.

*Table II.2: Equation results for timber (Forest Products Laboratory 1999)*



| Temperature | | Moisture content (%) at various relative humidity values | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (°C | (°F)) | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% |
| –1.1 | (30) | 1.4 | 2.6 | 3.7 | 4.6 | 5.5 | 6.3 | 7.1 | 7.9 | 8.7 | 9.5 | 10.4 | 11.3 | 12.4 | 13.5 | 14.9 | 16.5 | 18.5 | 21.0 | 24.3 |
| 4.4 | (40) | 1.4 | 2.6 | 3.7 | 4.6 | 5.5 | 6.3 | 7.1 | 7.9 | 8.7 | 9.5 | 10.4 | 11.3 | 12.3 | 13.5 | 14.9 | 16.5 | 18.5 | 21.0 | 24.3 |
| 10.0 | (50) | 1.4 | 2.6 | 3.6 | 4.6 | 5.5 | 6.3 | 7.1 | 7.9 | 8.7 | 9.5 | 10.3 | 11.2 | 12.3 | 13.4 | 14.8 | 16.4 | 18.4 | 20.9 | 24.3 |
| 15.6 | (60) | 1.3 | 2.5 | 3.6 | 4.6 | 5.4 | 6.2 | 7.0 | 7.8 | 8.6 | 9.4 | 10.2 | 11.1 | 12.1 | 13.3 | 14.6 | 16.2 | 18.2 | 20.7 | 24.1 |
| 21.1 | (70) | 1.3 | 2.5 | 3.5 | 4.5 | 5.4 | 6.2 | 6.9 | 7.7 | 8.5 | 9.2 | 10.1 | 11.0 | 12.0 | 13.1 | 14.4 | 16.0 | 17.9 | 20.5 | 23.9 |
| 26.7 | (80) | 1.3 | 2.4 | 3.5 | 4.4 | 5.3 | 6.1 | 6.8 | 7.6 | 8.3 | 9.1 | 9.9 | 10.8 | 11.7 | 12.9 | 14.2 | 15.7 | 17.7 | 20.2 | 23.6 |
| 32.2 | (90) | 1.2 | 2.3 | 3.4 | 4.3 | 5.1 | 5.9 | 6.7 | 7.4 | 8.1 | 8.9 | 9.7 | 10.5 | 11.5 | 12.6 | 13.9 | 15.4 | 17.3 | 19.8 | 23.3 |
| 37.8 | (100) | 1.2 | 2.3 | 3.3 | 4.2 | 5.0 | 5.8 | 6.5 | 7.2 | 7.9 | 8.7 | 9.5 | 10.3 | 11.2 | 12.3 | 13.6 | 15.1 | 17.0 | 19.5 | 22.9 |

It could therefore be assumed, as an argument has been made on the grounds that timber can reflect the moisture content of straw due to the similarity in material structure, that this equation could be used to compliment $Equ_{Law}$. Figure II.6 demonstrates the comparison of the equations, $Equ_{Law}$ (i=1) and $Equ_{FLP}$ showing similar results.

Wihan (2007) in analysing Jolly's (2000) results from field trials identifies that the relative humidity, adjusted using isothermal conversion to moisture content, plotted against the measured moisture content, gave a 1-2% negative disparity in readings. Wihan concludes that the effect is a product of the diurnal variations and represents an area for further investigation.

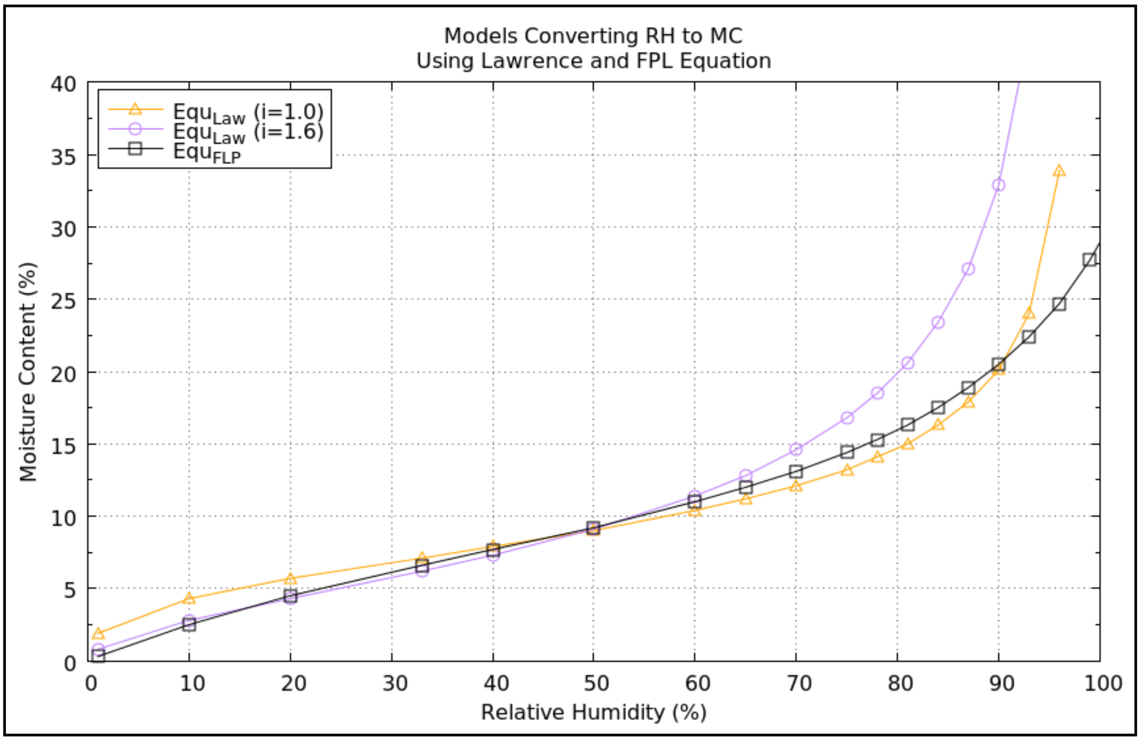


*Figure II.6: Comparison of Lawrence (Equation II.1)and Forest Products Laboratory equations (Equation II.2)*

Through the combination of these techniques and equations a more robust and accurate model could be suggested for straw. Isothermal studies present a method of calculating the theoretical moisture content of the straw from the surrounding atmosphere, and rely therefore on acquisition of data from a relative humidity sensor, yet this can be expanded to describe the onset of decay. Decay is an important subject area to consider when discussing the risk posed to a straw bale construction and represents the vital area of knowledge required in order to assess this subject.

## II.3-Decomposition

Although this thesis does not address the decomposition of straw directly it remains an important consideration given the uncertainty of a defined point at which decay is certain to start both in space and time. Isopleth studies represent the study of decay taking into account changing temperatures and relative humidity.

### II.3.1-Decay

Citing Viitanen's work on decay in wooden materials, Jolly (2000) warns that temperatures of -5°C and humidities of 62% are enough for some moulds to develop, but that optimum temperatures are between +20 to 28°C and relative humidity's above 95%. Summers (2003) supports this stating that at temperatures below 10°C many micro-organisms cannot survive so growth rate is low. The simultaneous availability "*over a certain period of time*" (Sedlbauer and Krus 2003, pp.1) of different parameters such as temperature, humidity, and substrate are required to stimulate biological metabolic processes.

Analysing the process of decay Summers (2003) explains the rate of $CO_2$ production of decaying straw as a potential aid to assessing a bale's deterioration together with signs of locally elevated temperatures, discolouration of the straw and the obvious smell associated with decay. The study conducted on rice straw showed a 0.009% loss in organic matter per day at 39%MC, a potential total of 3% per year suggesting that, alone humidity cannot cause significant decomposition. Summer's report does however suggest that this experiment be done again to confirm this hypothesis; the lines of best fit applied to the graphs are somewhat speculative requiring a far greater and more intense study to be conducted.

Bowen and Harper (1990) investigated fungal decomposition of wheat straw isolated from arable soils, the results suggested that plants with higher concentrations of lignin decompose more slowly, and although straw contains only around 15% lignin this is enough to protect the polysaccharides. Therefore, for the cellulose and hemicellulose to be accessed, the delignification by acid-chlorite oxidation must first occur. In Bowen and Harper's experimental findings F.culmorum and T.viride degraded only a small amount of straw over a 70 day incubation period whereas the five basidiomycetes were able to remove the lignin first before attacking the other constituent parts, resulting in Phanerochaete chrysosporium decaying 90% of the straw in 84 days. The paper concludes that these experiments, conducted at 20°C highlight two stages of kinetic decay warning of the complexity of decay kinetics and the difficulty in describing decay under parameters based on a single set of conditions, for instance by a mathematical model. The paper suggests that straw is decomposed in soil by 'microbial communities' and the extent to which basidiomycetes can compete remains unclear (Bowen and Harper 1990).

In a later paper Robinson et al. (1994) conclude that the amount of moisture, the resource size and the range of substrates is key to the colonisation patterns of fungus, explaining how the difference in structure of the leaves and the internodes of wheat straw is of importance. Robinson et al. conducted field trials subjecting internodes and leaves to buried conditions, results showed that leaves decomposed almost entirely in the 33 weeks study, comprising of soft lamina tissue, yet the internodes presented greater resilience to decomposition suggesting a: "*poor resource quality*" (Robinson et al. 1994, pp.1057). It was also noted that a high proportion of lignin remained after 33 weeks implying a lack of basidiomycetes.

Salvachúa et al. (2011) investigating the pretreatment of wheat straw for bioethanol production, traditionally using steam explosion to obtain the required cellulosic constituents, explains that biological degradation could be used to remove the lignin. The paper identifies certain complexities: “*fungal strain, culture conditions, fungal enzymatic secretion and oxidative mechanisms*” (Salvachúa et al. 2011 pp.7500). The study, using mainly white-rot fungi, aimed to identify the most effective basidiomycetes to produce the fermentable sugars needed, but concluded that a proportion of the sugars released were used by the fungi for it's own development within the first 14 days.

Although studies into degradation of straw in soil and bioethanol production are not specific to the study of straw bale construction, parallels between the investigative results can be drawn: the complexities of modelling degradation, a suggestion that the leaves are a good indicator of initial decay, and that colonies of micro-organisms are required to effectively breakdown a poorly resourced material. This alludes to a more comprehensive study into the moisture content limits advised by the straw bale industry, suggesting that a time dependence is applicable to moisture content's above 20%.

A microscopic study may reveal a previously unidentified small scale decay of the lignin elements of the straw, a preliminary colonisation of micro-organisms, allowing weaknesses to develop capitalised on by secondary and tertiary micro-organisms that are able to breakdown the more nutrient rich cellulose and hemi-cellulose. Certain experiments have been performed to provide greater clarity using Isopleth Studies to display the findings and are portrayed by a three dimensional graph plotting the temperature (x-axis), at which either mycelium develop or spores germinate, for a given relative humidity (y-axis) against time (z-axis) (Figure II.8 p70).

## II.3.2-Isopleth Studies

Isopleth Studies seek to produce a predictive model assessing the risk posed to a material, relating relative humidity and temperature to length of exposure. Holzhueter (2009) used isopleths to predict mould growth in walls of a case study based on Biglans-Pritchard's isopleth study into highly xerophilic moulds and 30 day spore germination. It concluded from analysis of hygrothermal data from the monitored building that fungus would be present; further invasive investigation confirmed this. The paper uses a third order polynomial equation (Equation II.3) developed by Bigland-Pritchard to describe mycelium growth with Equation II.4 describing spore germination. It superimposed limits of growth curves onto isopleth studies based on empirical studies conducted using multiple combinations of temperature and relative humidity in laboratory experiments conducted by Smith and Hill, and Clarke et al.

$$\varrho = -0.00083\mathrm{T}^3 + 0.08788\mathrm{T}^2 - 2.61013\mathrm{T} + 98.69800$$

$$\begin{aligned} \varrho &= \ \mathit{Relative\,Humidity}(\mathit{percentage}) \\ T &= \ \mathit{Temperature}\ \ (.^{o}C) \end{aligned}$$

*Equation II.3: Polynomial equation for mycelium growth (Holzhueter 2009)*

$$\varrho = aT^3 + bT^2 + cT + d$$

$$\begin{aligned} \varrho &= \ \mathit{Relative\,Humidity}(\mathit{percentage}) \\ a &= \ 0.0001(\ln(t))^{0.3} - 0.0007 \\ b &= \ -0.0204(\ln(t))^{0.3} + 0.1028 \\ c &= \ 0.9799(\ln(t))^{0.3} - 4.0389 \\ d &= \ -24.964(\ln(t))^{0.3} + 140.61 \\ T &= \ \mathit{Temperature}\ \ (.^{o}C) \\ t &= \ \mathit{time\,of\,germination}(\mathit{days}) \end{aligned}$$

*Equation II.4: Holzheuter (2009) polynomial equation for spore germination*

Independently, Wieland (2004) developed Figures II.7 and II.8 based on isopeth studies of Aspergillus Restrictus and Aspergillus Versicolo; two highly xerophilic moulds. Isopleths are a useful tool in predicting mould growth; from the conclusions drawn in the illustrated examples more research is required to develop the technique. Both figures plot relative humidity (Relative Feuchte y-axis) against temperature (Temperatur x-axis), Figure II.7 demonstrating the Wachstumsrate (rate of development in days) and Figures II.8 the Keimungzeit (time taken to spore germination per day).

Bronsema (2010) states that straw has a high propensity for mould growth, but acknowledges that predicting growth is difficult. Isopleth studies are one way to investigate mould growth by subjecting the straw to combinations of relative humidity and temperature. The investigation identifies time taken to spore germination, mycelium growth, and dynamic hygrothermal conditions utilising both Lower Isopleth for Mould (LIM) and Multiple Isopleths. It suggests that further work is needed on the models including a prediction of the amount of growth and dormancy during unfavourable conditions.

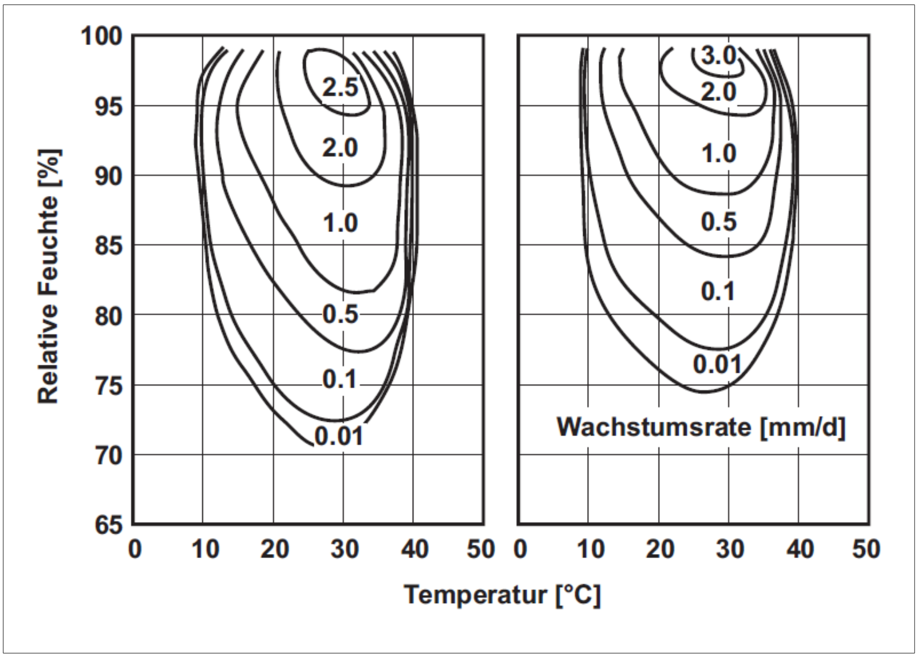


*Figure II.7: Mycelium development (Wieland 2004)*

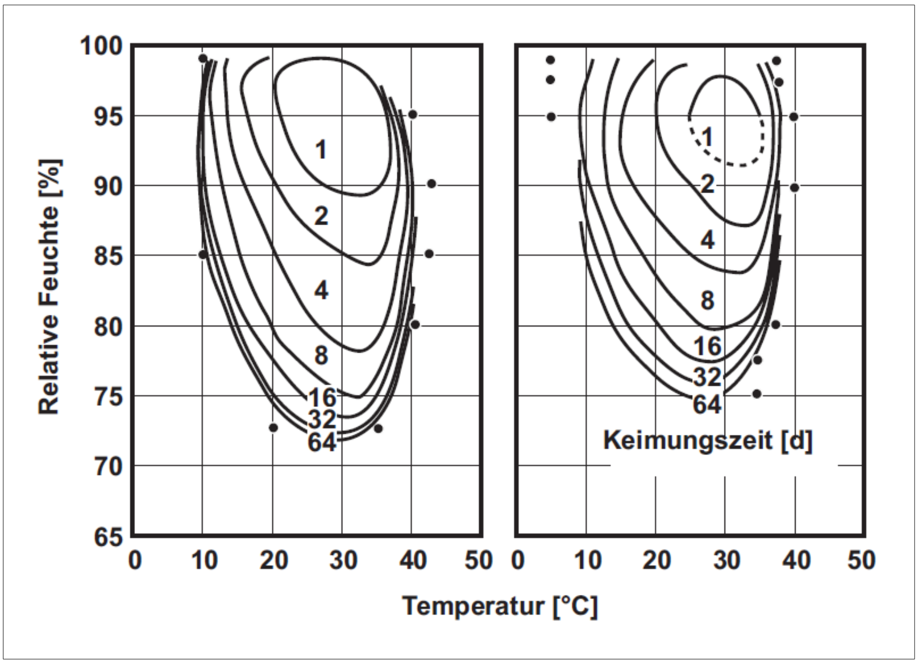


*Figure II.8: Germination of spores (Wieland 2004)*

Sedlbauer et al. (2011), utilising LIM(0), presented a traffic light system tool to aid in the assessment and identification of mould infestation bound by ranges in an isopleth study (Figure II.9) under which mould growth is likely to develop (red), cannot be completely excluded (yellow), and is unlikely to develop (green). The raw data on which the graphs are based were collected under steady state conditions, straw was placed in a wire mesh container and sterilised with gamma radiation thereby avoiding multiple spore contamination, certain spores were then introduced prior to the experiment.

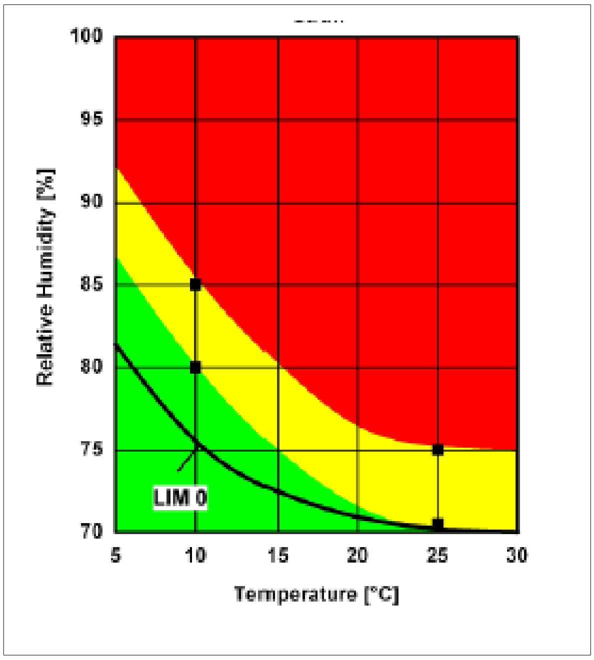


*Figure II.9: Isopleth System detailing wheat: Substrate Class I (Sedlbauer et al. 2011)*

The LIM(0) line is also shown on Figure II.9 describing the point at which, below the line, there will be no mould activity. Ambient humidity will determine the germination of spores (Sedlbauer and Krus 2003) both thermal and hygric, the LIM however, is substrate specific. The onset of decay is an important consideration when discussing the risk posed to a construction, the level at which moisture and other conditions are favourable to micro-organism development therefore requires quantifying, requiring the use of measurement devices and techniques to assess the construction's risk potential; see page 168 for examples of mould growth.

## *II.4-Moisture measurement*

The CMHC's (2000) report concludes that it would be wise given rapidly evolving construction methods, to monitor straw bale walls. There were, as of 2012, a number of monitoring methods and devices in existence, including isothermal and isopleth studies, the most common being in no particular order gravimetric analysis, resistance meters, relative humidity sensors, thermometers and Wood-block probes.

### II.4.1-Gravimetric analysis

This method offers an accurate way of obtaining the mass of moisture within a material however, it is generally confined to laboratory experiments as obtaining a sample from a wall is destructive (BS EN 14774-2:2009). The method simply involves placing a sample into the oven at 105°C and drying it until the weight is constant, Phanopoulos et al. (2000) noted during a study involving straw, evidence of changes in cell shape along with an increase in surface debris when viewed with an scanning electron microscope however, the report does not state the temperature, or duration the sample was subjected to and fails to provide any further evidence.

### II.4.2-Voltage based methods

Saïd (2007) reviewed amongst other monitoring devices the Sereda and Printed Circuit Condensation Sensor, surface moisture sensors both recording Time-Of-Wetness (TOW) measurements. The Sereda has a limited life expectancy of 1-4 years depending on the environment and uses an electrochemical cell to generate a voltage potential therefore, a wetness reading of the surface of the material can be generated; each sensor requires individual calibration. The Printed Circuit Condensation Sensor has a far shorter life of 4-6 weeks. Although these methods would produce valuable data the cost of implementation in time and expense makes this equipment impractical for long term monitoring purposes.

## II.4.3-Resistance meters

Resistance meters measure the resistance of a material across a set distance, the resultant readings depend on the material's dielectric properties together with additional temperature compensation. Jolly (2000) used a wood chip meter to assess wood-blocks placed into straw bales however, the lack of graduations in scale of the meter above 14%MC reduced the accuracy of the results. The resistance meter provides a useful 'off-the-shelf' method to check the moisture content of a material, but is not able to provide in-situ monitoring, requiring both a temperature calibration and knowledge of how to interpret the reading. The Timbermaster (Appendix Figure XI.4) and Balemaster (Appendix Figure XI.3) meters are both examples of resistance meters.

$$C_{GM}=\varrho+((20-t)*0.1)$$

$C=$ *Moisture Content* $(\%)$
$\varrho=$ *Timbermaster reading*
$t=$ *Temperature* $({}^{o}C)$

*Equation II.5: Temperature conversion for Timbermaster (EquGM) (GE Measurement & Control 2014)*

The documentation supplied with the Timbermaster (GE Measurement & Control 2014) advises that results be corrected for temperature using Equation II.5. Table II.3 shows the results for a range of temperatures with and without the GE equation. It demonstrates the potential differences that could be obtained from a meter reading.

*Table II.3: Compensated reading for display of 15%MC*

| **Temperature (°C)** | **Uncompensated reading (%MC)** | **Corrected using EquGM (%MC)** |
|---|---|---|
| 30 | 15.0 | 14.0 |
| 25 | 15.0 | 14.5 |
| 20 | 15.0 | 15.0 |
| 15 | 15.0 | 15.5 |
| 10 | 15.0 | 16.0 |
| 5 | 15.0 | 16.5 |
| 0 | 15.0 | 17 |

GE Measurement and Control also produce the Balemaster; designed to obtain a moisture level from straw via a 450mm long probe attachment. Both the Timbermaster and Balemaster have the capacity to add a thermocouple (Figure II.10).

*Figure II.10: Timbermaster, Balemaster, Balemaster Probe, Digital Thermometer and Thermocouple*

## II.4.4-Relative humidity sensors & hygrometers

As previously discussed Sorption Isotherms (Section II.2 p58) can be used to convert the relative humidity of the atmosphere in a bale to an equivalent moisture content of the straw. The study conducted by CMHC (2000) utilised hygrometers, but questioned their lifespan in damp environments. Lawrence et al. (2009a) used relative humidity/temperature sensors placed throughout the depth of a bale to measure the moisture profile. However, Carfrae (2011) specifies that a system capable of providing enough information, 'off-the-shelf', could run to a total of £8000 (Stirling); based on £100 per sensor and £2000 for the data-logger.

Wihan (2007) utilised the Lascar EL-USB-2 humidity, temperature and dew point USB data logger in the survey of various field studies. In conclusion however, the thesis reports that the relative humidity did not fully correspond to moisture content levels observed, but does provide a “*satisfactory indicator of microbial growth*” (Wihan, 2007. pp162).

Dick and Krahn (2009) placed three isolated relative humidity/temperature sensors within a perforated PVC tube at different depths of a bale to measure the inner, middle and outer conditions. The identified problems, other than the expense at implementation, included a debate concerning the ability of the sensors to describe exactly the moisture content of the straw due to the indirect method of assessment and the potential for rapidly changing relative humidities as seen at the extremities of a bale walls.

Carfrae (2011) points out that this method is unable to describe the hysteresis effect seen in cyclic isothermal studies, yet as the Forest Products Laboratory (1999) report describes: the oscillating adsorption curve can be used in certain circumstances.

There are a wide variety of relative humidity/temperature sensors with a wide range of costs attached, one type used primarily in this thesis was the Maxim 1-Wire/iButton Sensor DS1923 (Appendix XI.0.2 p324) measuring 17mm in diameter by 6mm thick. This self contained unit has a built in data-logger and has a lifespan of seven years recording at an hourly interval.

### II.4.5-Wood monitors

The CMHC (2000) gives one of the first accounts of the utilisation of wood-block sensors stating that it may be a more realistic method of monitoring based on an assumption that relative humidity changes faster than the moisture content of straw. However, no evidence is provided to support this statement. The report highlights the importance of using correction factors such as temperature compensation, warning that; some of the results may be inaccurate due to a lack of adjustment. Using the sensors to monitor the straw close to the exterior the report suggested that: "*straw bale walls do not exhibit any unique propensity for moisture retention*" (CMHC 2000, pp.4), reasoning against the need for internal vapour barriers.

Goodhew et al. (2004) modified the original wood block design opting to use a wood-disc mounted in a perforated plastic tube. The probes were calibrated prior to use in a case study and returned an accuracy of ±1%. In analysing the data for the case study a disparity between the results of the probe and the bare wood samples suggested to the researchers that the plastic tube created a barrier effect. It was noted also that an increase in temperature lead to a small increase in the moisture level of the probe.

On analysis of the case study results obtained by Goodhew et al. (2004) it was found that one corner returned a moisture content of 25% which was later confirmed when a sample of the wall was oven dried and found to be 27%; the field accuracy of the probe was thereby revised to ±2%. It concludes that the probe provides a cheap, easy to use method of evaluating the moisture content of a construction to a reasonable degree of accuracy.

The woodblock probe was further developed by Carfrae et al. (2009b) in a long-term study that removed the perforated plastic tube and put the wood-block (now bullet shaped) in direct contact with the straw. The results produced a more accurate method: “*almost exactly duplicating the readings given by the* '*Balemaster*' *and gravimetric analysis*” (Carfrae et al. 2009B, pp.5) however, the results are not displayed in the paper.

Lawrence et al. (2009a) argues for the use of relative humidity sensors, stating that straw will have different sorption isotherms to that of timber and the installation of the probes is more destructive than the implanting of relative humidity sensors. A further issue is presented by the Forest Products Laboratory (1999) suggesting that each sensor must be individually calibrated as different sections of timber may have slightly different dielectric properties; heartwood and sapwood.

### II.4.6-Temperatures

The study of temperature alone could be used to provide an assessment of a straw bale wall system as Carfrae (2011) reports that the thermal lag for a straw bale is around 12 hours. From work done by Goodhew et al. (2005), 240mm of clay straw was applied to one side of a bale and a course of bricks to the other, a time lag of 16.91 hours was recorded. Summers (2003) also proposes the use of a temperature study to assess the level of decay in a bale as micro-organisms will generate significant amounts of heat whilst decomposing the straw.

### II.4.7-Summary

The methods of analysing the risk posed to the straw from moisture, detailed above, are all valid and more so if used in combination. All methods have advantages and disadvantages however, the devices and techniques do not fully explain what is occurring within a bale, to evaluate this; the data, the restrictions of the device, and the method of analysis must first be understood before a confident assessment of risk may be made. Adopting a model to evaluate data and provide potential outcomes based on patterns of historical trends could also prove valuable in making an informed decision based on the evidence.

## II.5-Modelling

The majority of literature refers to a building physics simulation program named WUFI, developed by Fraunhofer IBP as an aid to assessing building fabrics. The program allows the simulation of an experiment through the section of a wall in one dimension, utilising different layered components of a building assembly, with the ability to adjust widths and physical properties of the material. A weather pattern may be introduced and results will demonstrate, based on set building physics criteria, the potential outcome for the construction method.

Reviewing the accuracy of WUFI Wihan (2007) describes how the results provided by the software at elevated humidities should be regarded as: "*conservative estimates*" (Wihan 2007, pp.110), referring to the 2005 Manual which warns of calculations distorting data at saturated level in straw. Wihan highlights the failure of WUFI to account for convection currents within the wall together with the effects of vapour penetration due to infiltration for inaccuracies in modelling the outside edge of the wall, identifying the need for weather data to improve accuracy. The detailed recording of weather data provides the model with greater capabilities; wind driven rain, strength of wind and temperatures may all have an effect on calculations within the simulation.

Grmela et al. (2010) conducted a review of a case study monitored with the Balemaster and Balemaster probe against the predictions of WUFI. The authors evaluation shows that WUFI presented inaccuracies in comparison to the Balemaster data. Grmela et al. reason that this may have been caused, in part, to inaccurate input parameters and the lack of climactic data with which to run the simulation. The paper concludes that the calculation of thermal resistance, heat transfer and moisture content in a straw bale wall requires a new methodology taking into account bale density, thermal gradient and moisture dependent thermal conductivity.

Bronsema (2010) suggests that WUFI should be capable of modelling a straw bale wall system provided accurate climate data including sun and rain records can be provided. The author argues for the addition of a rain gauge to be placed on the external render, thereby increasing the accuracy of the modelling software.

Other contributions to modelling include generic modelling methodologies such as Kesik and De Rose (2004) aiming to provide guidance on complexities of wall performance classification.

In summary a model may only be considered accurate once it has been applied to a real environment in order to test the theory and verify effectiveness of laboratory experiments with some degree of success. Case studies or monitoring sites, and test rigs offer a method of evaluating a model with the prospect of developing it and implementing it with confidence.

## *II.6-Case Studies (Monitoring Sites)*

Several papers and theses have utilised case studies to investigate the effects of the real world environment on straw bale construction and to compare data against laboratory experiments.

The Canadian Mortgage Housing Corporation (CMHC 2000) notes that northern walls (in the northern hemisphere) retained comparatively more moisture than other elevations. The CMHC report identified a Canadian West Coast study that showed sustained high moisture levels despite no external wetting, identifying high humidity as the likely cause. The CMHC report proposed the hypothesis based on results showing that hygrometers placed immediately behind the stucco showed levels of 95%RH, suggesting that: "*the concept of a quick moisture redistribution in bale walls is probably not valid*" (CMHC 2000, pp3). It concluded that leaks, lack of rain protection, and high humidity and precipitation environments make straw constructions more susceptible to decay.

In the analysis of nine monitoring sites Jolly (2000) noted issues of concern including inadequate protection from splash-back and precipitation, minimal exposure to solar gain, insufficient roof overhang, watering of a flowerbed situated against a wall, use of below grade bales, northern exposures, and stucco extending beyond the damp course. In a more detailed explanation than that reported in the Canadian Mortgage Housing Corporation (CMHC 2000) report, Jolly suggested that, moisture levels in the north wall of the West Coast study, were caused in part by the proximity of vegetation (forest) restricting air circulation and thereby the drying process. The report also records, in study nine, the lack of moisture build-up even though there are cracks in the interior earthen plaster; it suggests that significant ex-filtration may be the cause.

A timber frame infill building with uninsulated roof and no heating was chosen for a case study by Goodhew et al. (2004). The northern and eastern elevations were surrounded by mature trees and the humidity of the site was reported to be unusually high. The analysis demonstrated a high moisture content for the straw in the exterior of the southern wall exposed to moisture penetration from wind driven rainfall, but identified that the probe located at the same level 100mms further into the interior of the bale gave a low reading. Goodhew therefore suggests that moisture migration is slow in protected straw bales, which agrees with the findings of the CMHC (2000) and Straube (2009). The behaviour of a straw bale wall in absorbing rain, Bronsema (2010) concludes, has a strong impact on its performance and should be studied in more detail.

The results of a fault in the case study investigated by Carfrae et al's. (2009b) highlighted a trend in the drying process of a straw wall. The straw to the exterior of the wall was saturated up to 37%MC compared to 15%MC towards the interior. Over the initial five weeks, post repair, the exterior straw dried quickly to around 24%MC, yet the interior increased to around 19%MC. The author explains that vapour pressures are equalising across the wall causing the spread of moisture. After the initial five weeks there is a second trend, the moisture content continues to fall, but at a far reduced rate taking a further four months for the external to reach around 15%MC.

Lawrence et al (2009b) conducted a study into the protection of straw by exposing nine wall sections with different surface treatments to the same south westerly climate. The field trials were monitored using relative humidity sensors and converted to a comparable moisture content using the Equation II.1 (p61) proposed in Lawrence et al. (2009a). The external relative humidity varied over the 11 month study between 40-99% averaging 83% and although the trial was abandoned due to technical difficulties conclusions on surface protection could still be drawn. Deliberately damaged panels showed localised decay whereas correctly detailed ones equilibrated at 14%MC (83%RH) with no decay.

The effect of protective surfaces have also been investigated by Carfrae et al. (2009b), demonstrating that cladding can offer significant protection reducing moisture content of the straw by up to 3.8%. Concerning render, Wihan's (2007) study of a straw bale house in Brittany, France, discovered that degradation of straw was due to a failure of the lime render to carbonise due to inappropriate environmental conditions and late application, finally completed in early October. In conclusion Wihan cites wind driven rain as the main protagonist for raised moisture content conditions, solved by the addition of cladding. Poor design was also cited as a reason for the majority of problems, but the thesis does highlight that condensation from water vapour diffusion in a simple plaster-straw-plaster assembly: “*doesn't prove to be a potent enough source of moisture to cause straw decay*” (Wihan 2007, pp.167).

## ***II.7-The knowledge gap***

A fundamental requirement of any construction is to provide a healthy environment, minimising the risk posed to the occupants. The minimisation of risk posed from moisture is paramount to a constructions functionality; the presence of moisture is described by Brand (1997) as quoted in Oliver et al's book (1996) 'Dampness in Buildings':

*“The root of all evil is water. It dissolves buildings. Water is elixir to unwelcome life such as rot and insects. Water, the universal solvent, makes chemical reactions happen every place you don’t want them. It consumes wood, erodes masonry, corrodes metal, peels paint, expands destructively when it freezes, and permeates everywhere when it evaporates. It warps, swells, discolours, rusts, loosens, mildews and stinks...”*

This overtly dramatic description highlights the issues surrounding elevated moisture levels in construction of all types, not just straw, it is however, an inability to confidently assess a straw bale construction where moisture is concerned that removes confidence from the construction method (Section I.5.1 p41).

In essence the moisture content of the straw will largely be dictated to by the amount and type of protection it receives from external influences in the form of renders, plasters, cladding, topography and extraction methods; for high moisture environments such as bathrooms. A study conducted into the effect of variable thickness, application and imperfection of protection methods applied to straw bale construction, although vital, would not however address an issue of greater importance; the risk that moisture poses to the straw.

The confidence to interpret the results comes from the knowledge of how each monitoring methods works and the shortfalls of each. The resistance meter, the

Balemaster with probe attachment for instance, measures the path of least resistance between interconnected strands of straw, unlike the measure of relative humidity which provides a measure of the percentage of moisture in the atmosphere in the immediate location of the sensor depending on the temperature of the air. A wood-block probe together with a resistance meter will provide a comparable moisture content based on the assumption that wood and straw, both cellulosic materials, will demonstrate similar moisture contents and finally gravimetric analysis will provide the researcher with the total amount of moisture within a bale; the atmosphere and surface moisture combined with moisture contained within the plant's cellular structure.

This line of enquiry raises a specific question concerning how exactly results obtained by the different monitoring devices relate to the overall risk posed to a straw bale wall and thereby how the data should be interpreted. To date there has been little comparison or discussion surrounding these questions, only separate investigations. In order that these questions can be addressed it is of importance to describe how moisture occurs within the bale and, what and how that interaction with the straw takes place. If it is assumed that a straw bale varies in moisture content influenced purely by the presence of water vapour and temperature then the risk posed would be time dependant and would also rely on dew point temperatures; the requirement of water vapour condensing out of the atmosphere onto the straw surfaces, one variable measurable by an relative humidity sensor the other by a resistance meter.

The assumption should also include the external atmosphere's tendency to drop in temperature during the night and for the humidity to rise subject to a natural 24 hourly cycle notwithstanding seasonal flux. The rate at which moisture is capable of travelling through a bale compared to temperature is also significant, at the edges of the bale a high rate transfer of moisture and temperature may be seen. However, in the centre of the bale can the same hypothesis be applied confidently?

The rate of transfer of moisture and temperature through a straw bale is important as it will provide evidence to suggest the rate  at which moisture could potentially be brought to, or removed from, an internal area of the bale. Subsequently, there is a question of how the moisture interacts with the straw and whether the relative humidity is purely a reflection of the moisture content of the atmosphere rather than of the straw.

In attempting to design a building fabric simulation to investigate the moisture and thermal properties of a straw bale construction, previous studies have demonstrated, that conventional building models struggle with the unique and unconventional amalgamation of a straw bales structure (Section II.5 p79). It was concluded by the studies that detailed knowledge of weather patterns and wetting of the protective coatings applied to the straw is required to perform an accurate comparable of a case study with a computer simulation.

The gap in knowledge therefore is in an understanding of how moisture reacts with the straw and in the confidence to interpret monitoring results to a significant degree of accuracy for a simple visual system or model defining the 'Risk' posed to the construction to be created. Chapter three describes the methodological approach adopted to further progress the research.

## II.8-Summary

The research aim is to quantify and evaluate the risk posed to straw bale constructions by moisture. The following list has been drawn from the gaps in knowledge as discovered by the literature review:

1. Lack of definitive agreement concerning the risk posed to straw from moisture (Table II.1 p50).
2. An unclear definition of the term 'risk' when related to straw and moisture (Section II.1.2 p54).
3. The literature does not clarify how results produced by each monitoring device should be interpreted (Section II.4 p72-78).
4. There is a lack of critical analysis involving the relationship between the monitoring devices and the risk to straw (Section II.4 p72-78).
5. Beyond Straube's (King 2006) explanation of moisture storage regimes there is a lack of factual and researched descriptions of how moisture interacts with straw within a bale (Section II.1.1 p47).
6. The literature review failed to uncover research conducted to establish the way in which moisture transfers through a bale.

The gap in knowledge exists in part due to the youthfulness of the method of construction, and the lack of categorical research evidence. The disagreements concerning the risk posed to straw from moisture do little to promote confidence in the use of this renewable resource. The following chapter presents the methodological approach taken to address the aims and objectives (section I.1 p11) together with the subsequent questions in this summary.

# *Chapter III-Methodology*

## ***III.1-Introduction***

Quantifying and evaluating the risk posed to straw bale constructions from moisture was highlighted as a gap in knowledge (section II.7 p84). The main aim and objectives (p11) set out to: define the term 'risk', explain how moisture interacts within a bale, and to develop a basic visual identification system and model to promote confidence in the construction method.

The methodological procedure began by establishing a method of study and investigating potential boundaries utilising: critical evaluation, discussion of relevance, alternative approaches, assessment and acquisition of resources, evaluation of the design goals and the establishment of precautions, variables and limitations (Whisker 2008).

## ***III.2-Methodological Approach***

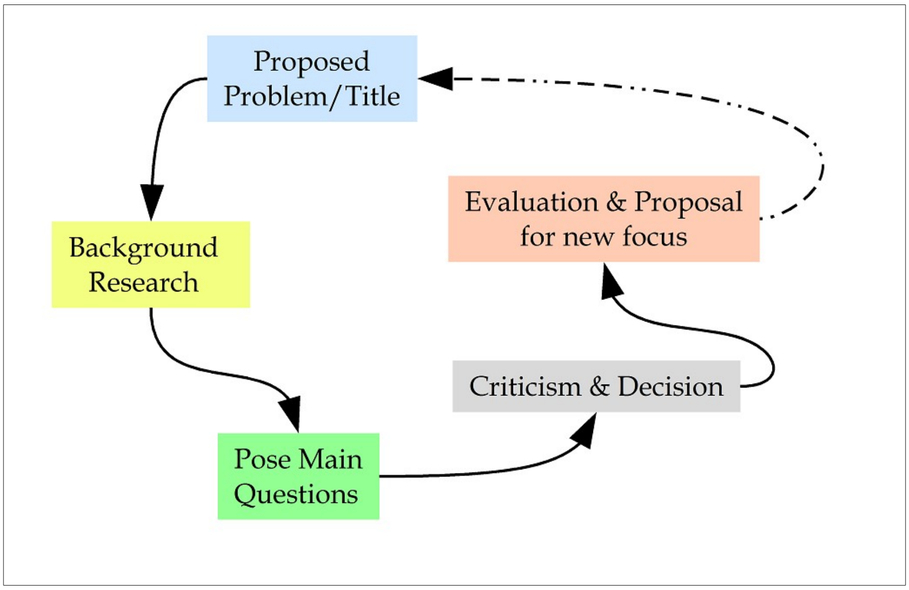
The initial research approach was designed to begin collecting data quantitatively in order to establish a contribution to knowledge. A deductive investigation was then used to explain the relationship between and apply controls to applicable variables by use of a structured research approach to scientific investigation and collection of data. Information was then transferred into a data stream creating significant sample sizes in order to provide an informed conclusion.

During the research and planning stages of each individual experiment, inevitable assumptions were identified (Clough and Nutbrown 2007). The significance of the results were then discussed and any hypothesis was accepted or rejected, terminating in a suggestion for further work.

### III.2.1-Generalised Methodological Approach

The research problem was approached using scientific method requiring the systematic collection and analysis of data in order to propose a model to reflect reality and bridge the gap in knowledge. Figure III.1 illustrates the scientific procedure adopted for each experiment.

*Figure III.1: Scientific approach*



The adopted approach (Figure III.1) generalises the thinking process behind each decision taken with the desired aim of refining an original question down to the 'One Idea'. From this principle it is possible to identify knowledge gaps, to criticise current thought and to evaluate results of the process; or discover, develop, and interpret the system.

Wisker (2008) provides a breakdown of different research approaches, this thesis initially followed an exploratory approach, extrapolating an exploratory procedure to investigate underlying subsidiary, and complex questions and variables. Support was provided by explanatory research specifically investigating the cause and effect between two or more variables culminating in a predictive stage of research.

### III.2.2-Variables

Table III.1 shows some of the variables that will be considered in this thesis although not all relate to each of the subject areas (section III.2.3 p92), or individual experiments (chapters IV to VII).

*Table III.1: A variable list*

| | | |
|---|---|---|
| Bale Density | External Climate | Pollution |
| Building faults | History of the straw | Quality of straw in bale |
| Climate bales stored in | Husbandry | Relative Humidity |
| Climate built in | Internal Bale Climate | Temperature |
| Climate crop grown in | Internal Structure Climate | Types of m-o in bale |
| Construction history | Leaks | Weather crop harvested in |
| Dust | Moisture Content | |

The highlighted variables were specifically considered throughout the research procedure however, all may have some impact on overall results and outcomes.

## III.2.3-Subject Areas

This investigation focused on five subject areas:

### *III.2.3.1-Laboratory Experiments*

Laboratory Experiments formed the basis of the investigation, providing an environment that isolated variables, thereby allowing control and accuracy over measurements. The laboratory studies also provided the ability to manipulate different scenarios in order to study cause and effect. The benefit of Laboratory Experiments is in repeatability and standardisation however, Laboratory Experiments are also simulations based in an artificial environment and must be regarded with a limitation to mimic natural reactions under true environmental conditions.

### *III.2.3.2-Monitoring Site (Case Study)*

A monitoring site (Case Study) was acquired to provide information concerning a practical environment, obtaining data and assessing conventional monitoring techniques, to be used as a comparative study and tested against modelling and descriptive techniques designed to investigate the risk posed to a straw bale construction.

#### *III.2.3.3-Test Rig*

A Test Rig provided a means of bridging the gap between the monitoring site and laboratory experiments, it presented the opportunity to perform multiple experiments and destructive testing on a straw bale construction based in a real world environment whilst allowing unlimited access to the site. The Test Rig was designed to be a cost effective solution to performing extensive research on a straw bale construction without the potential for costly failures, or inconveniencing the owners of a property.

#### *III.2.3.4-Monitoring Techniques and Methods*

The development and assessment of Monitoring Techniques and Methods was used to describe the risk posed to a straw bale construction, performed together with the above subject areas, it provides comparative and descriptive information that is utilised by the model.

#### *III.2.3.5-The Model*

The Model was designed as an evaluation tool; according to Epstein (2008) a model illuminates uncertainties in current procedures, offering crisis options based on comparative data and estimations, it educates and trains, and amongst other goals reveals the complexity of an apparently simple solution. The goal of the model is not to predict when a wall will decompose, but to suggest the possible outcome of certain scenarios, together with an evaluation of historical records.

The subject areas are interrelated and interlinked: methods of modelling, descriptive, comparative, and experimental approaches were used to address scientifically the knowledge gaps.

## III.2.4-Areas of research discounted

Certain areas of research were not covered as part of this thesis due to the design scope, methodological approach and time constraints. Each area however, may have an influence on a straw bale construction to varying degrees.

### *III.2.4.1-Wheat strains*

A none specified wheat strain was used in the research: one sourced batch of straw bales was used exclusively. It remains unclear how different crops, strains, or cultivation methods would affect the results obtained in the project however, this area may be addressed in future work.

### *III.2.4.2-Varieties of straw*

Evans et al. (1981) identified the differences in varieties of straw inherent in the husbandry, geographical location the crop was grown, and the types of straw used. In order to investigate the optimum type of straw to use in straw bale construction, a large scale research project beyond the scope of this study would have been required.

### *III.2.4.3-Decay*

The identification of different microbial species is also outside the remit of this study as it encompasses not only too larger study, but also represents the bane of which the study aims to avoid and of which moisture is one of the known catalysts. If mould takes hold in a wall then for that section the risk is already too great and all affected bales must be replaced. Section V.6 (p167) of the Preliminary Results chapter does however investigate differences between decay of straw subjected to a continuous liquid phase and another to high relative humidities. The experiments were conducted to demonstrate the general differences in mould development not in specific identification.

#### *III.2.4.4-Climate*

The investigation into alternate climates was restricted by the research approach to climatic conditions that affect the UK; which has a Maritime climate. It is unclear whether the resultant data and model will be applicable in other regions of the world.

#### *III.2.4.5-Renders and cladding*

The knowledge and effect of renders and cladding, although recognised as important to moisture transition in a straw bale construction, represents an advanced stage of research, secondary to the importance of the interaction of moisture with straw. It is argued here that the effect and influence of moisture on straw within a bale must be understood prior to investigating protective remedies. Although the later stages of the thesis, Section VII.4.1 page 257, evaluate the application of render and cladding no further investigation concerning the topic was undertaken.

## *III.3-Defining the Research Problem*

The main problem with identifying the risk posed to straw is the uncertainty surrounding the point at which straw becomes susceptible to decay (Table II.1 p50) and thus, the method by which monitoring should be conducted (Steen et al. 1994, CMHC 2000, Goodhew et al. 2010, Lawrence et al. 2009a).

### III.3.1-Risk

'Risk' in the context of the thesis relates to the vulnerability of the straw within a walling system that is subject to change. It requires the definition of a system from which there is a lack of knowledge and unknown outcomes. Risk therefore requires an understanding of the uncertainties (Section II.1.2 p49) and the analysis of known probabilities (Hansson 2011).

A wall at 'No Risk' would constitute one that is free from the potential for decay and one that is functioning both efficiently and effectively. Alternatively, a wall 'At Risk' may be considered in degrees of Risk exhibiting symptoms of: reduced functionality, a drop in U-values, or a rise in 'decay potential', leading to concerns over structural stability and occupant health. Spengler and Chen (2000) raise concerns over the public's perception of risk in a paper reporting on air quality, therefore Risk requires categorisation to further explain the concept.

In diagnosing the Risk to a straw bale construction information concerning applicable variables as shown in Table III.1 (p92) must be collected and analysed; a reading of 35%MC at a certain position in a wall may be considered by the majority of literature as at 'High Risk'. However, if further variables are known:

- '*the reading of 35%MC was taken during the winter period and was sustained for over two months at which time the temperature did not rise above 5°C*' [scenario example].

From the scenario example above; a conclusion of 'Low Risk' to decay may be assumed based on isopleth studies and empirical data (Wieland 2004, Holzhueter 2009). However, the question remains: is the allocation of 'Low Risk' a fair assessment of the situation?

An increased moisture content will affect the thermal insulation capabilities of straw bales (Grmela et al. 2010 and Goodhew et al. 2005) and a drop in thermal efficiency may have a 'knock on impact', the rate at which the wall losses or gains heat will affect the internal temperature of the building. The occupants may therefore attempt to compensate for this by using heaters or air conditioning, if the method of compensation is produced from a non-renewable or polluting resource then, there is a secondary environmental impact. The evaluation of Risk in this case requires clarification or contextualisation; a construction rated at 'Low Risk' still requires an amount of consideration if it potentially causes undesirable secondary impacts.

The scenario example depends also upon the decay potential; the potential for the moisture content and temperature to rise or fall within a set amount of time relating to the ranges of decay (Wieland 2004). For instance, in the given scenario, if temperatures rose with the onset of spring or the residents compensated for the loss of heat by increasing the heating output, the Wieland's isopleth studies (Figures II.7 and II.8 p70) would warn of a dangerous potential for highly xerophilic fungi to colonise the straw; spores may germinate within eight days at temperatures of 15°C and 35%MC (92%RH). This would then indicate a review of the categorisation to 'High Risk', therefore Risk must also be defined with respect to the potential for changing conditions.

In order to describe the risk posed to a straw bale wall the generation of a model with the capability for prediction based upon previous data and known responses to variables was required. It has to be intelligent enough to extrapolate different scenarios based on assumed future events taking into account worst case scenarios and normal trends; for instance, a worst case scenario may include a sudden warm wet spell unusual for the time of year.

Thermal efficiency of a wall will decrease with increased moisture content due to temperature transfer through moisture migration (Stone, 2003 and McCabe, 1993) and isopleth studies provide an account for decay (Holzheuter, 2009 and Wieland, 2004). Risk may therefore be divided into 'No Risk', no potential for decay, and 'At Risk', potential for decreased efficiency or onset of decay. The potential for decay is time and scenario dependant; Figure III.2 demonstrates a basic evaluation of the Risk to a straw bale construction from moisture and temperature as ascertained from various sources in the literature review (Table II.1 p50 and Figure II.2 p52).

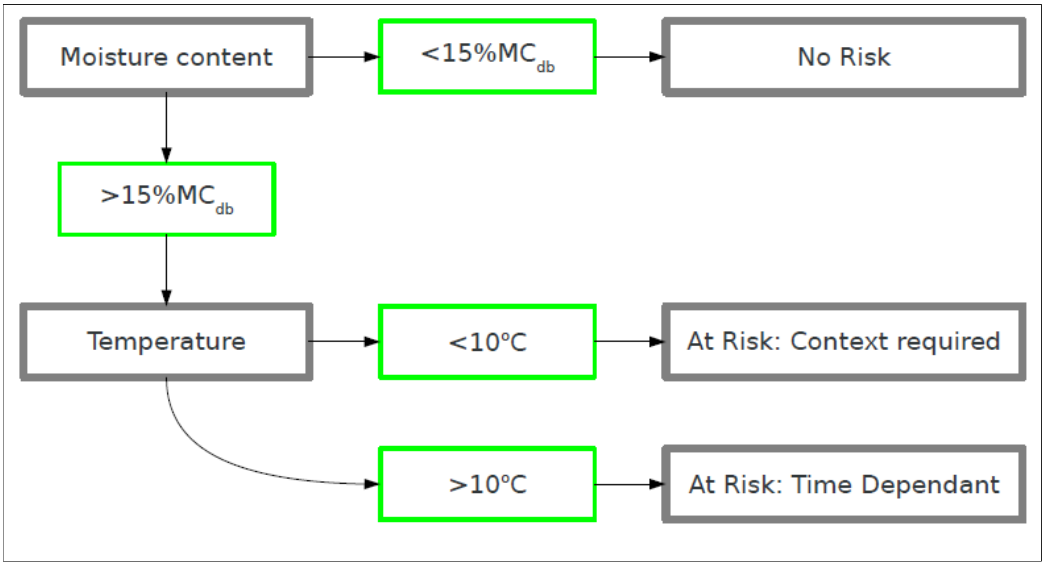


*Figure III.2: Risk decision*

The level of moisture within a straw bale wall is of primary concern, if kept below 15%MC, the monitoring of other variables will be rendered null and void as the moisture level is below that for biological activity (Summers, 2003). Above 15%MC, concern over the risk to straw increases with respect to efficiency and decay potential, temperature becomes the second variable to be of concern with relation to the moisture level; at temperatures over 10°C micro-organisms can develop (Summers, 2003).

Figure III.2 however could not be used as a stand-alone model due to the simplistic nature, evaluating Risk not only involves the calculation of results, but also the effective combination of a descriptive terminology combined with an understanding of the data. The further development of a model to describe Risk must deal with a complex input data stream and present a simplified assessment that may be understood by a lay person (Spengler and Chen 2000).

### **III.3.2-Defining a solution**

Under conditions of excessive moisture and if other criteria are met micro-organisms will begin to colonise straw and cause degradation. The overriding aim of a construction is to avoid conditions that promote decay, therefore a study to examine the exact point in which decay begins could be considered important. There is however a lack of agreement surrounding the issue (Table II.1 p50), it may be prudent therefore to simplify the argument and suggest a colour coded method of assessment that encompasses the lack of agreement within broader terms (Figure III.3).

⬛ **No Risk {Below 15%}**
Regarded by most as the maximum level by which no decay will affect the straw

🟪 **Low Risk {15-20%}**
Recommend close monitoring

🟧 **Medium Risk {20-25%}**
Warning; prolonged exposure may lead to decay

🟨 **High Risk {Above 25%}**
Danger; this level of moisture can be damaging

*Figure III.3: Visual identification for Risk Assessment System based on moisture content only*

Figure III.3 represents the precursor development to the overall model, the colours chosen to be printable in monochrome without loosing distinction. The Risk Assessment System relies on the correct interpretation of results in order to produce a simple analytical technique to diagnose the risk posed to a wall and thereby can be used to illustrate issues relating to structural stability and occupant health. The majority of literature states that a moisture content of below 15% is safe and therefore poses 'No Risk'. The system however puts in place a method of warning:

1. A measurement of between 15 and 20%MC suggests that greater vigilance is required.
2. At moisture contents above 20%  there is an elevated potential for decay and is classified at 'Medium Risk' and therefore represents greater urgency in discovering the cause of the elevated moisture level.

3. The classification of 'High Risk', although dependant on other factors (Figure III.2 p98), signals the potential onset of decay and the need for a detailed assessment to verify the risk posed to the construction.

In conclusion a reading of 35%MC would be viewed as at High Risk in Figure III.3, yet if the temperature was below 5°C there is less risk for decay and the remedial action required will be different to that of a warmer temperature measurement. If the cause for the high moisture content can be discovered and dealt with prior to the onset of a temperature rise the demolition of the wall may be averted; this analysis method is key to evaluating the risk posed to a straw bale wall.

## III.3.3-Potential benefits

The development of a monitoring technique or model will benefit all parties involved in straw bale construction projects. The ability to provide an accurate assessment concerning the risk posed to straw combined with historical trends and future predictions gives rise to confidence for investors, builders and owner/occupiers to embrace this method of construction, and for engineers, designers and architects to consider effective protection strategies.

Figure III.3 (p100)presented a basic visual identification method to define risk showing that excessive moisture will increase the potential for mould development, the model therefore relies upon accurate data from monitoring devices together with correct interpretation.

## III.4- Summary

From the gaps in knowledge identified by the literature review (Section II.7 p84), the methodology chapter discusses the method employed to critically evaluate and quantify the risk posed to straw bale construction from moisture. The summary of the literature chapter (Section II.8 p87) was investigated, identifying five subject areas (Section III.2.3 p92) allowing the application of descriptive, comparative, experimental and modelling methods to the research approach. The experimental phase of the research program was divided into three sections:

### III.4.1-Preliminary Investigation – Part I

The preliminary investigation sought to establish a platform on which to base initial investigative research. Designed to answer the main aim of the thesis, to quantify the risk posed to straw bale constructions from moisture, the investigative method began by aiming to compare the assessment of multiple case studies utilising wood-block probes as the moisture monitoring method of choice.

### III.4.2-Preliminary Investigation – Part II

Part II of the Preliminary investigation represented a change in the original research approach due to the laboratory experiments revealing an issue of response rate of the wood-block probes. The original research approach to study multiple case studies utilising wood-block probes was changed to encompass a study involving a monitoring site, laboratory experiments, and the construction and analysis of a test rig (section III.2.3 p92).

The aims and objectives of the study remained unaffected and led to the design of two new monitoring devices. The assessment of the test rig highlighted several other limitations concerning moisture measurement with resistance meters; temperature and density.

## III.4.3-Focussed Investigation

The third phase, the Focussed Investigation, sort to refine and analyse in detail the problems identified in the Preliminary Investigations (Parts I and II) using the data and knowledge gathered to advance the contribution to knowledge. The aim of the third phase of the investigative research was to verify the correct interpretation of results, and establish how each monitoring device relays information and to what that measurement relates; by further advancing this knowledge an accurate and reliable model could be produced.

The main problem with identifying the risk posed to straw bale construction stems from the uncertainty over the point at which straw will degrade in the presence of moisture (Table II.1 p50) and other influencing variables such as type of straw (Section I.1.4 p18) or husbandry (Table III.1 p92). In defining a solution Figure III.3 (p100) introduced a Risk Assessment System as a visual identification method grouping moisture contents into classifications of 'Risk'. However, Figure III.3 relies upon the collection and correct interpretation of accurate monitoring data, yet is not inclusive of other potentially critical variables (Table III.1 p92) of which a model of risk was proposed in Figure III.2 (p98).

# Chapter IV-Preliminary Investigation – Part I

## *IV.1-Introduction*

The literature review highlighted certain gaps in knowledge concerning the lack of definitive agreement over the risk moisture poses to straw. The importance of the research is to provide interested parties with the confidence to proceed with straw bale construction given the potential for the social, economic and environmental benefits (Bigland-Pritchard and Pitts 2006, Kennedy et al. 2002 and Atkinson 2010). The acceptance of straw bale construction as a mainstream option would also provide sustainable housing for a growing population (NHPAU 2007 and UN 2013). Therefore, the monitoring of multiple case studies would provide a comparative and contrasting analysis of this method of construction, similar to the studies conducted by Jolly (2000) and Bronsema (2010). Jolly (2000), Goodhew et al. (2004), Carfrae et al. (2009b) and Wihan (2007) used case studies as part of the research method and highlighted the following areas of concern: sheltered sections of wall, northern exposures, and moisture penetration from wind driven rain.

With careful systematic evaluation, the research sought to address the identified gaps in knowledge and produce a conclusion based upon field work. The study of multiple case studies offer an opportunity to consider and explore fully an in-depth situation acknowledging the inherent limitations, and adopting scientific rigour (Wisker 2008).

## IV.2-Preliminary Case Study

The boundary conditions set for the Preliminary Case Study focused exclusively on the evaluation of the wood-block probes (section II.4.5 p76) as a monitoring solution and the use of one case study (section II.6 p81). The Preliminary Case Study would therefore be used, from an exploratory context, to gather information concerning certain variables (Wisker 2008) with the overall aim to inform and advise upon the establishment of further case studies.

The aim of the preliminary case study was to justify the use of wood-block probes as a monitoring device to reflect the moisture content of walls in a real world environment. The objectives were defined thus:

1. wood-block probes to establish moisture related problems within a construction.
2. To identify reasons for data disparities between individual monitoring devices.

The research was designed to collect fieldwork data, the analysis of which would justify the continued progression into the analysis of multiple case studies.

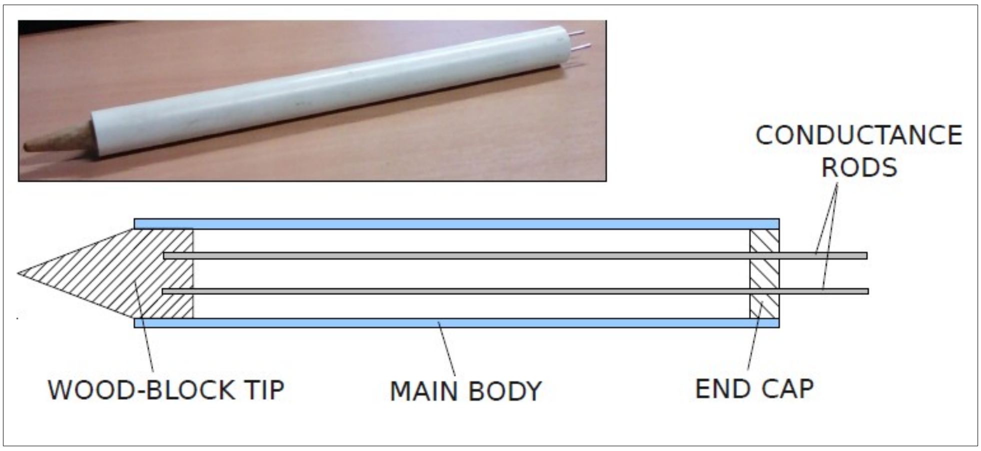


*Figure IV.1: Wood-Block Probe*

The design of the probe (Figure IV.1) was taken from Carfrae's work which refers to them as bullet tip probes, but for a historical context and the purpose of this thesis will remain as wood-block probes. The probes utilised oak as the timber of choice for the wood block tips and the assembly consists of a main plastic body (PTFE tubing) and end cap (nylon), with two metal rods protruding 10mm from the cap running the length of the body to penetrate the wood-block tip to a depth of 10mm's; the space between the tip and end cap is a void.

The home of Wendy Graham, located on the banks of Loch Tey, Perthshire, Scotland, was secured as the Preliminary Case Study site in late 2009. 14 wood-block probes were installed prior to this; wood-block probes at the time offered the best monitoring solution from a perspective of: cost, ease of use, robustness and track record (Carfrae et al. 2009b, Goodhew et al. 2004).

Previous studies conducted by Goodhew et al. (2004) concluded from a field study that wood-block probes offered an accuracy of ±2, with slight variations for temperature. Carfrae et al. (2009b) found that results from wood-block probes closely matched that of gravimetric analysis and the Balemaster readings. Timber probes have undergone several different modifications over recent years from the basic block methods used by the CMHC (2000) culminating in the bullet shaped probe developed by Carfrae. This provided the thesis with a base on which to begin addressing the research problem and identifying the risk posed to straw from moisture in a real world environment by using wood-block probes as the monitoring device.

The house (Figures IV.2 and IV.3) was constructed in the summer of 2008, it has a large overhanging roof, bales raised one foot above ground level, is rendered with lime both internally and externally, and has undergone a lime wash once every year. There is little protection afforded to the house by the local topography; to the north-east there is another house within a distance of six meters, the north-west wall faces a 20 meter wide courtyard, rising slightly, leading to a single story barn conversion. The majority of the south-eastern wall (Figure IV.2) is glazed and the whole of the south-west wall is timber clad; added protection is provided to the south-west ground floor wall by a lean-too (Figure IV.3).

*Figure IV.2: View of South-east façade*

*Figure IV.3: View of north-west and clad south-west façades*

The house (Figure IV.4) is heated by a solitary wood burner located in the living room which opens up into the spacious kitchen; both rooms providing a south-easterly view across the loch. The larder adjoins the kitchen and the door is kept shut to maintain a low temperature, the study also remains cool being north facing and removed from the heat source. The roof is insulated by 200mm of solid foam and southern facing double glazed skylights offer additional heat gain.

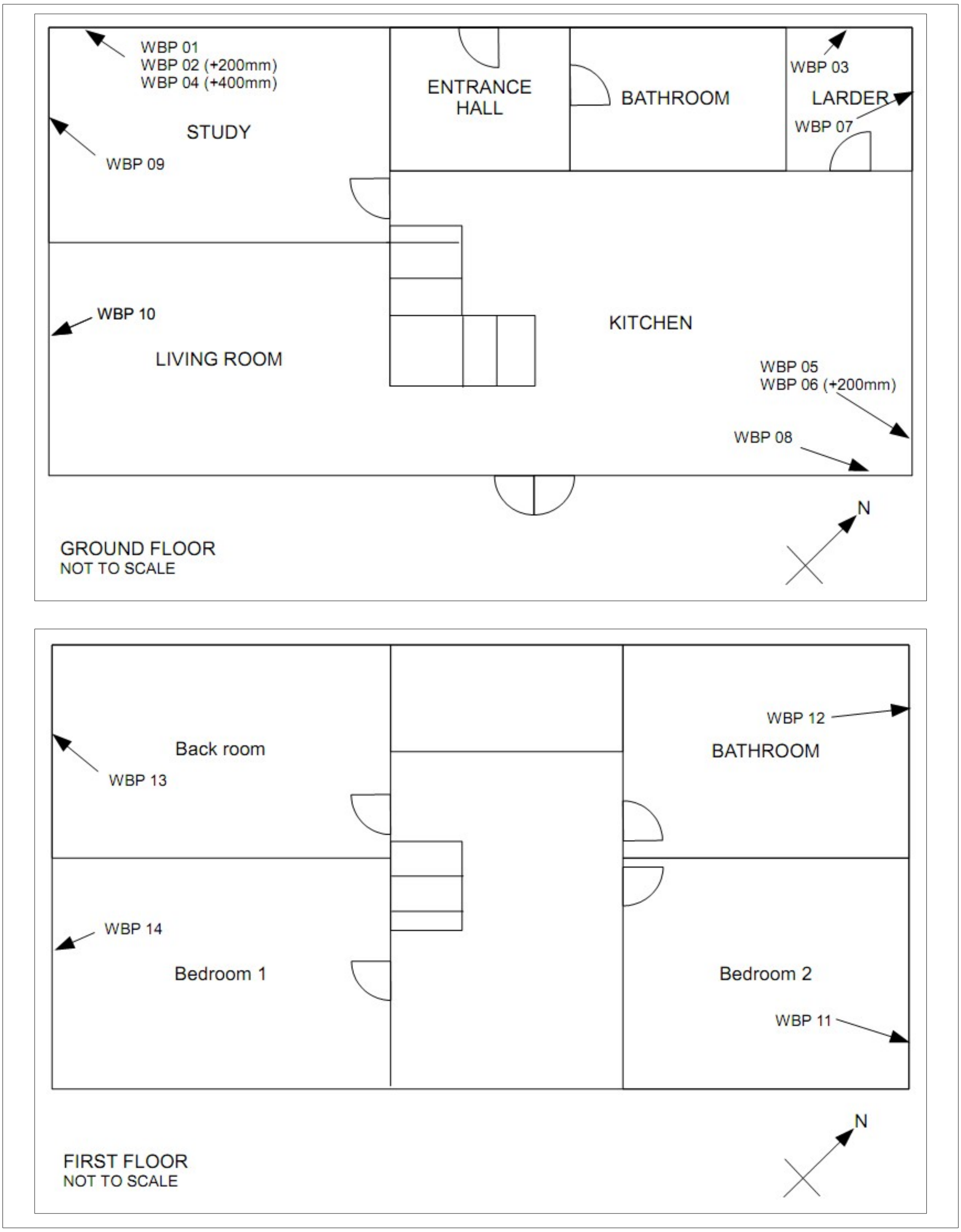


*Figure IV.4: Plan view of house at Loch Tay showing approximate locations of wood-block probes*

Figure IV.4 also shows the approximate locations of the 14 probes, identified as potential places of weakness in the building design, all of which are located 200mm from floor level except probes 2, 4 and 6 located vertically above probes 1 and 5 at 200mm increments. The results from these probes were collected monthly using a Timbermaster meter (reading set at group A); without thermocouple attachment. The generated data could then be entered into a computer and analysed being flagged if the moisture content rose over 15%, the point at which the majority of literature agrees that there is no risk of degradation (Figure II.2).

The aim of the case study was to evaluate the benefits of using wood-block probes to monitor moisture levels within the walls of straw bale constructions, however, as the case study site is a home there were two limiting factors inherent in the research: the inability to perform destructive testing on wall sections, and secondly to make detailed routine assessments of the site. It was therefore decided to allow the monitoring of the house to continue with minimal disturbance to the residents. Other restrictions imposed by the method of study are by the confounding variables such as: weather patterns, heat and moisture generation from within the construction, and the time scale. There was a time limit imposed on the initial research as a decision was to be made on progression to the next stage; involving the investigation of multiple case studies.

The assumptions for the investigation were, that timber is capable of reflecting the moisture content of straw, and that the south-western wall would exhibit a lower moisture reading than the north-western as it had been afforded extra protection in the form of timber cladding (Carfrae et al. 2009b and Wihan 2007).

At the end of each month the data was collected and analysed in a graphical format that would highlight areas deemed to be 'At Risk'. The format plotted the moisture content of each probe against the date; it was therefore possible to identify disparities between monitoring devices and to evaluate the benefit of using wood-block probes to monitor the condition of a construction.

In summary the preliminary case study analysed, in a dynamic field study environment, the response of the wood-block probes to the conditions of a straw bale construction. If it was demonstrated that the wood-block probes provided an effective method of monitoring, then multiple case study assessment would be undertaken, alternatively further more rigorous assessment would be required.

## IV.2.1-Results: Preliminary Case Study

Figures IV.5 to IV.8 present the preliminary results, the moisture content (y-axis) plotted against the date (x-axis), aiming to establish the effectiveness of the wood-block probes as a monitoring tool in reflecting the moisture content of the case study walls. The results also identify any disparity between individual probes.

The overall trend of data suggests a rise in moisture content in early 2009, immediately post construction, followed by a drop in the moisture level of all the probes to a permanent record of under 15%MC by January 2010. The results demonstrated that there were no problems inherent within the construction at the positions monitored, and although wood-block probes 09 and 10 did not surpass 13%MC or show a rise and fall, as illustrated by the other wood-block probes (Figure IV.7), there were no distinct disparities between the individual monitoring devices.

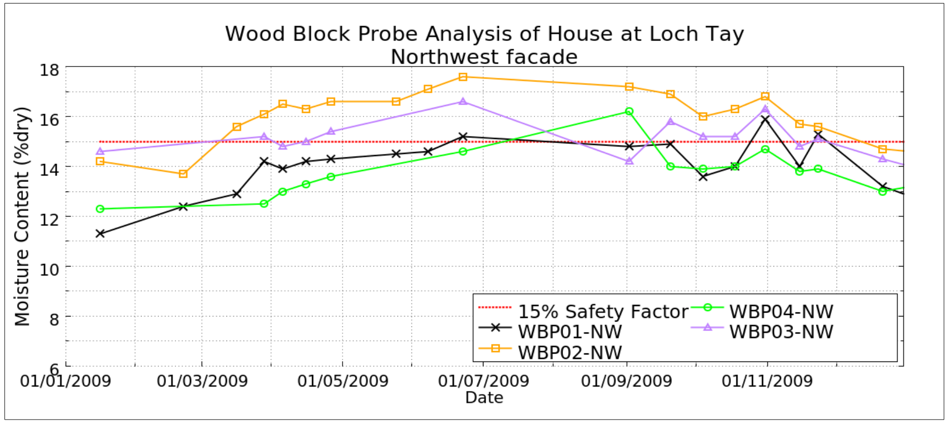


*Figure IV.5:North-west Façade Preliminary Results*

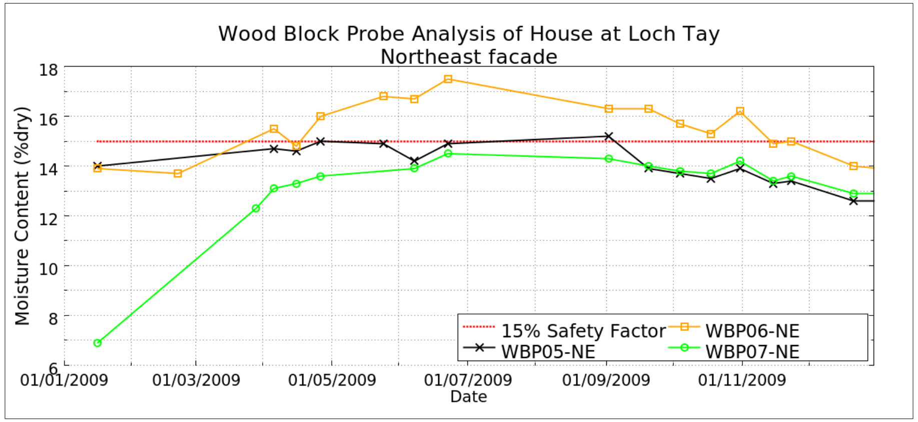


*Figure IV.6: North-east Façade Preliminary Results*

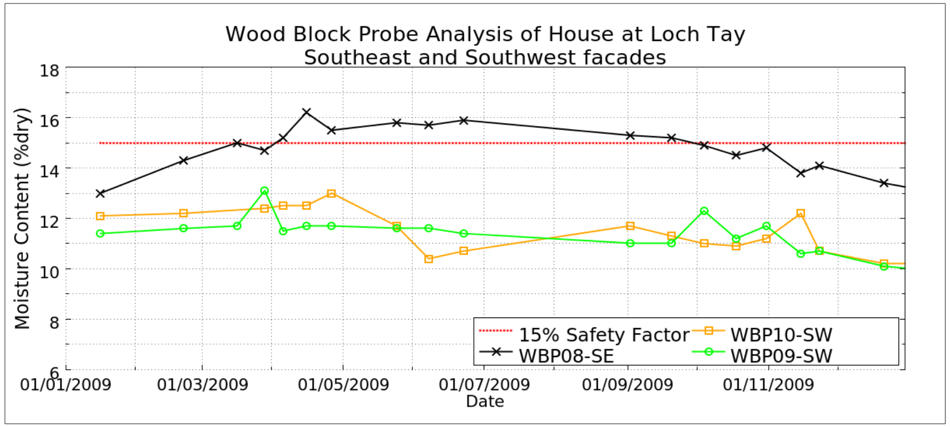


*Figure IV.7: South-west and South-east Façade Preliminary Results*

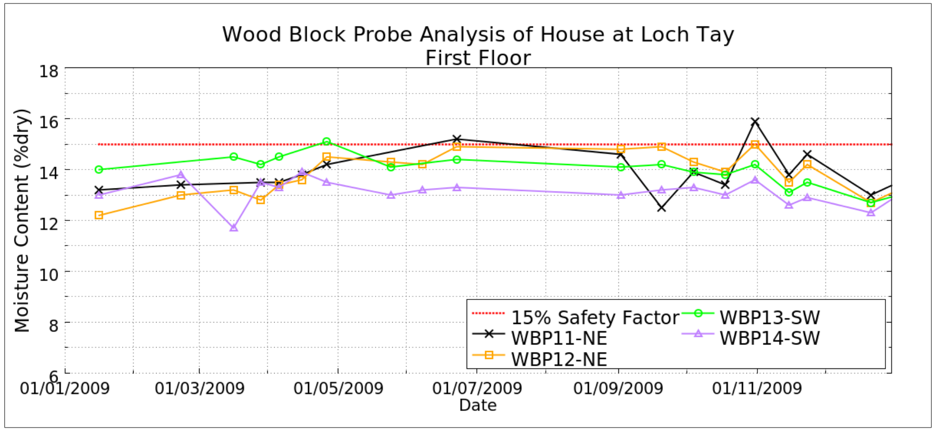


*Figure IV.8: First Floor Preliminary Results*

Upon evaluation the results of the year's study failed to demonstrate a need to progress with the analysis of multiple case studies. As the Preliminary Case Study could not be defined as being 'At Risk'. It was argued therefore that as a construction should in theory be designed against moisture penetration any case study undertaken would potentially provide no evidence on evaluating the Risk posed to straw bale construction from moisture.

The investigations limiting factors included the inability to perform destructive testing to verify the ability of the wood-block probes to reflect the moisture content of straw, or to control certain variables such as weather. The limiting factors would provide uncertainty for future research study results, the chance that multiple case studies would provide inconclusive data, not progress into areas considered to be 'at Risk', or that action would be taken on a section of wall without the ability to study prolonged effects of a high moisture environment gave doubt to the progression of this research course. It was therefore concluded that the investigation continue monitoring the preliminary case study and explore in a laboratory environment the effectiveness of the wood-block probes to changing conditions.

## IV.3-Wood-Block Probes

The ability to describe the risk posed to a construction, especially if the material is susceptible to degradation, is clearly important and requires an effective monitoring system. The preliminary results chapter investigates, based on the findings of the literature review and the reasoning promoted by the methodology, wood-block probes as a cheap reliable form of monitoring device.

The Preliminary Case Study highlighted several inherent limitations and confounding variables that restricted the gathering of informative data, such as the limited control afforded over relative humidity and temperature. A series of laboratory experiments was therefore devised utilising an environmental chamber to assess the reaction of timber in the probes to a sudden change in environment. Previous literature (CMHC 2000, Goodhew et al. 2004, Carfrae et al. 2009b) assumed that timber has the ability to reflect the moisture content of straw, but this was questioned by Lawrence et al. (2009a).

To build upon established research into wood-block probes the experiments were devised to verify Goodhew et al's. (2004) findings of a ±2MC accuracy, possibly a difference promoted by the differing dielectric properties inherent in different sections of timber (Forest Laboratory Products 1999), and the ability of timber to provide an accurate measurement of straw moisture content.

### IV.3.1-Wood-Block Probes Experiment 1

In exploring the functionality of the wood-block probes it was of importance (section III.3.3 p101) to know how the monitoring devices reacted to certain changes in conditions thus providing a level of confidence in the data being analysed. An empirical experiment was designed to investigate the effect of dramatic humidity change on the wood-block probes; achievable in an environmental chamber. There was no published literature at the time concerning the effect however, Carfrae et al. (2009b) eluded to Ramin providing better response times than oak.

The experiment was to subject multiple wood-block probes to varying relative humidity's at a set temperature. The moisture content of the test samples were determined by gravimetric analysis and by use of a Protimeter Timbermaster resistance meter. The experiment's aim was to discover the effect of varying humidity on the wood-block probes readings but did not attempt to compare moisture content of the probes with straw moisture content at this stage of the study.

A number of the probes were manufactured to gain an understanding of how moisture interacts with the wood under sudden changes in humidity; nine individual probe tips, minus the bodies (Figure IV.1 p106), were used for a comparative study isolating any influence from the probe body and rods.

The tip's dry mass was obtained, as described in Section II.4.1 (p72), and then placed in an environmental chamber at a constant temperature of 23°C. The probe tips were subjected to a dramatic increase in humidity followed by several smaller sharp drops to simulate a dramatic changing environment. The relative humidity was set to 85% and held for one month, it was then adjusted to 80% until the moisture content readings had stabilised then reduced further to 70% for the remainder of the experiment.

Each probe tip was removed individually from the environmental chamber and the mass was obtained followed by the resistance meter reading in which two metal conductance rods were firmly placed into the holes located at the butt end of the tip. It was assumed that based on the literature of Goodhew et al. (2004) and Carfrae et al. (2009b) the probe tips would all have demonstrated similar moisture contents of ±2 with respect to each other. This accuracy was to be confirmed by analysing the nine probe tips and obtaining the statistical analysis between each; if confirmed then the average of the moisture content would be taken and compared to the changes in humidity.

The limitation to the experiment was perceived to be in time restraints, as the confirmation of the wood-block probes response was to provide evidence to support the continued design method analysing multiple case studies. Therefore, if a null hypotheses were returned then the study would have undergone further expansion to encompass multiple case studies. The availability of multiple case studies would in turn provide a greater pool of results together with justification for further laboratory tests analysing the relationship between timber and straw; alternatively further laboratory experiments would have been required and the expansion of the case study portfolio would have had to be put on hold.

#### *IV.3.1.1-Wood-Block Probes Experiment 1 - Results*

Figure IV.9 compares the gravimetric analysis and resistance meter readings for the wood block probe tips; days (x-axis) plotted against the moisture content results (left y-axis) and humidity of the chamber (right y-axis). The results are depicted as an average for the nine wood-block tips which demonstrated, as highlighted by Goodhew et al. (2004) and Carfrae et al. (2009b), an accuracy of ±1%MC (See Appendix A : Additional Data Figures X.1 p313 and X.2 p313).

Figure IV.9 shows that the individual wood-block tips (minus probe bodies) took less than six days to stabilise from a 10% drop in humidity from 80%. It is also worth noting that a different degrees of pressure exerted on the contact rods produced differing readings, therefore to maintain a degree of consistency the exerted pressure was enough to bend the rods slightly thus confirming an adequate connection. In earlier experiments (not presented) it was found that the gravimetric analysis and resistance meter results could differ individually by up to -3%MC with less force applied to the rods.

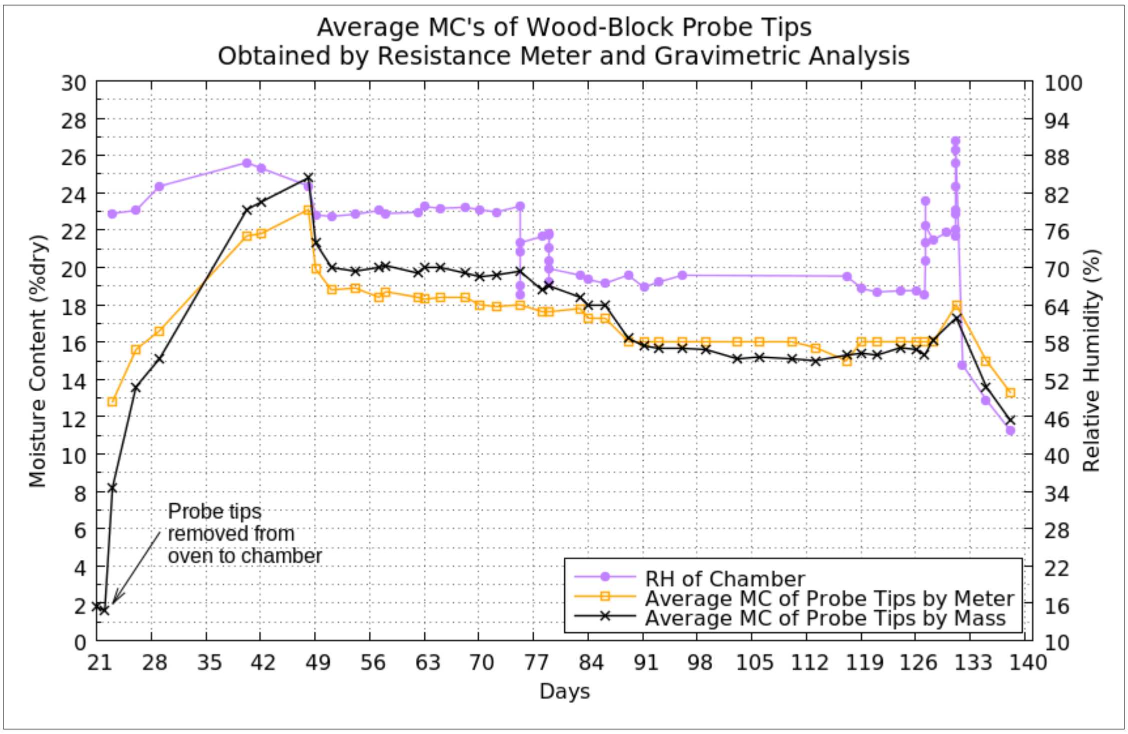


*Figure IV.9: Probe tip moisture content recorded by gravimetric analysis and resistance meter*

Although the results are based on averaged data for the nine wood-blocks and have not been repeated for confirmation, they indicate a lag effect inherent in the wood-block tip. Regarding the differences between the gravimetric analysis and resistance meter results; the gravimetric analysis read 2%MC higher than the resistance meter results at 80%RH, dropping to a similar result at 70%RH. The resistance meter relays a figure reflective of the path of least resistance, therefore as moisture is adsorbed and then absorbed into the wood-block from the external atmosphere a gradient of moisture content will develop, dependant on the time taken to bring the core of the block to equilibrium, thus skewing the mass measurement. After a change in humidity, the first few millimetres of the surface of the block will react to the external humidity at a faster rate than the core, thus the resistance meter measurement of the exposed surface may be considered as to be of greater accuracy. Further evaluation was therefore needed to assess the application of the wood-block probes.

## IV.3.2-Wood-Block Probes Experiment 2

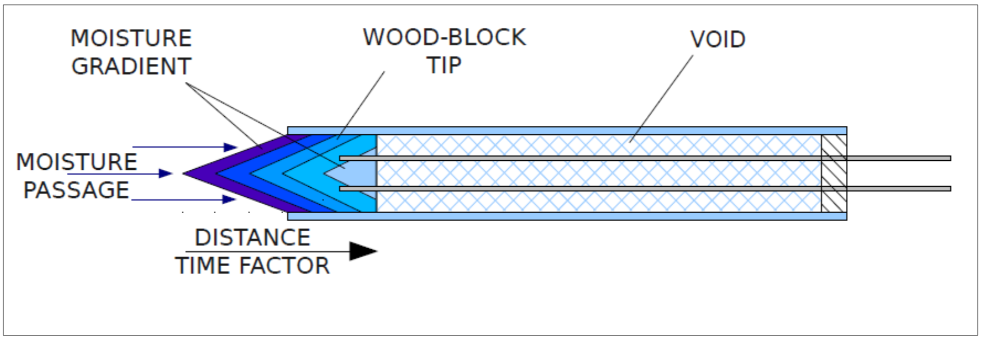
Experiment 1, essentially a calibration exercise, confirmed that the wood-block probes fell within the ±2MC accuracy threshold however, the alternative hypothesis was accepted as a concern was raised by the probe tips response rate to dramatic changes in humidity. The concern with a slow response to rapid changing conditions within a bale may promote the potential for the onset of degradation, whereas a rapid response warning may give interested parties sufficient time to assess the cause of a problem before it either escalates or causes damage.

The first experiment focused on the wood-block tips and did not test the reaction of straw to the changes in humidity, therefore the aim of the second experiment was to compare the reaction to changes between readings for straw and timber. The experimental design was devised to answer the following objectives:

1. Compare the response rate of straw, wood-block tips and fully assembled wood-block probes to a dramatic change in humidity.
2. Determine if timber should be used to accurately reflect the moisture content of straw.

The design of the experiments focused on addressing the issue of response rate. It was hypothesised that the fully assembled wood-block probes may have an inherent time lag issue. The concern was with the rate at which moisture can pass from the external probe surface to the point of measurement in the probe tip (Figure IV.10), therefore applying a moisture gradient within the internal cellular structure of the timber. A moisture gradient may, under conditions that have not been equilibrated, provide errors in resistance meter and gravimetric analysis readings.

*Figure IV.10: Moisture passage through probe tip*



The second experiment therefore undertook an empirical study based on previous observations and a predictive theoretical framework concerning moisture gradients. Straw samples (two bundles, measuring 200x120x80mm, bound with polypropylene string and placed in individual aluminium containers) were placed in the environmental chamber together with four fully assembled probes, and the individual probe tips from Experiment 1. The straw, wood-block probes and wood-block tips were spaced equally over the shelf in the centre of the chamber to ensure even exposure to the surrounding mechanically generated atmosphere. The straw had been stabilised in the laboratory environment at around 55%RH 23°C for three months beforehand. As there was some uncertainty as to the effects on drying straw to 0%MC (Phanopoulos et al. 2000), the gravimetric analysis was conducted at the end of the experiment.

Two of the wood-block probes were submerged in water prior to the experiment, the remaining two were equilibrated to laboratory conditions (55%RH at 23°C); all were weighed in their entirety to obtain the gravimetric analysis reading. In detail the experiment was designed to observe the difference in moisture content readings of each of the materials and methods, and to demonstrate the difference between adsorption and desorption rates. The experiment ran for one month at 75%RH and 23°C.

The approach of submerging the probes was to obtain a supersaturated regime from which to observe a recovery to a state of internal capillary condensation

(Figure II.2 p52), and similarly from a low starting moisture content. The experiment would then assess the time taken to reach the set relative humidity dictated to by the chamber. The straw bundle represented the control for the experiment thereby a measure by which to gauge respective response times and corresponding accuracies.

The full body probes were used as a comparative to the probe tips due in part to the concern raised regarding the potential for time lag promoted by the body of the probe (Figure IV.10). Data was acquired by removing each individual experiment sample from the environmental chamber separately before obtaining the mass, and in the case of the timber materials the resistance meter measurement. Care was taken to minimise the amount of time each sample spent out of the chamber.

The limitations to the study are in the subjection of the samples to a constant unchanging environment that does not reflect the dynamic extremes experienced in the real world. However, the research remains valid as it removes confounding variables and satisfies the requirement of the aims and objectives that could only be achieved through prolonged exposure to a stable environment.

Further question raised by this experiment included the definition of what a reasonable response rate was and about a concern raised by the potential effect from the void space within the wood-block probes relating to additional buffering.

The first hypothesis of the experiment to be tested was the response rate, if adequate in both the desorption and adsorption phases with respect to the straw sample, then the original aim of the thesis, to assess multiple case studies, would stand. The second criteria for acceptance of the original aim was that the wood-block probes and the wood-block tips should accurately reflect the straw moisture content to within ±2. The alternative to either of these failing would be to develop a new monitoring system maintaining all the advantages of the wood-block probes and removing any of the observed issues.

In relation to quantifying the risk associated with response rate this may depend on the potential for damage, the difference between the time taken for a straw bale to reach over 25%MC and the time for the monitor to reflect it with the included complication of the bale temperature. The problem associated with the potential time that it takes for a monitoring device to relate to the surrounding straw, in an ideal world this should be instantaneous, the delay of even a two days in the case of highly xerophilic mould spores coming to germination under relative humidities of 90% and 20°C (Figure II.8 p70) could signify the difference between large scale remedial action removing sections of a wall, or a less destructive option of fixing the cause.

#### *IV.3.2.1-Wood-Block Probes Experiment 2 - Results*

Two straw bundles (the densities unconfirmed) were placed into the chamber to equilibrate whilst Wood-Block Probes 1 and 3 were left to equilibrate under laboratory conditions (55%RH 23°C), Probes 4 and 5 were submerged in water (after equilibrating with Probes 1 and 3 for several weeks). The individual probe tips remained in the chamber at 85%RH 23°C. Probes 4 ,1 and 3 were placed into the chamber on day 72 however, Probe 5 was left to dry in the laboratory atmosphere for a further two days before being placed in the chamber to compare the rate of moisture loss with Probe 4. It was of interest to note the dimensional difference between the submerged timber and the laboratory dried, a difference of up to 20mm diameter adjustment.

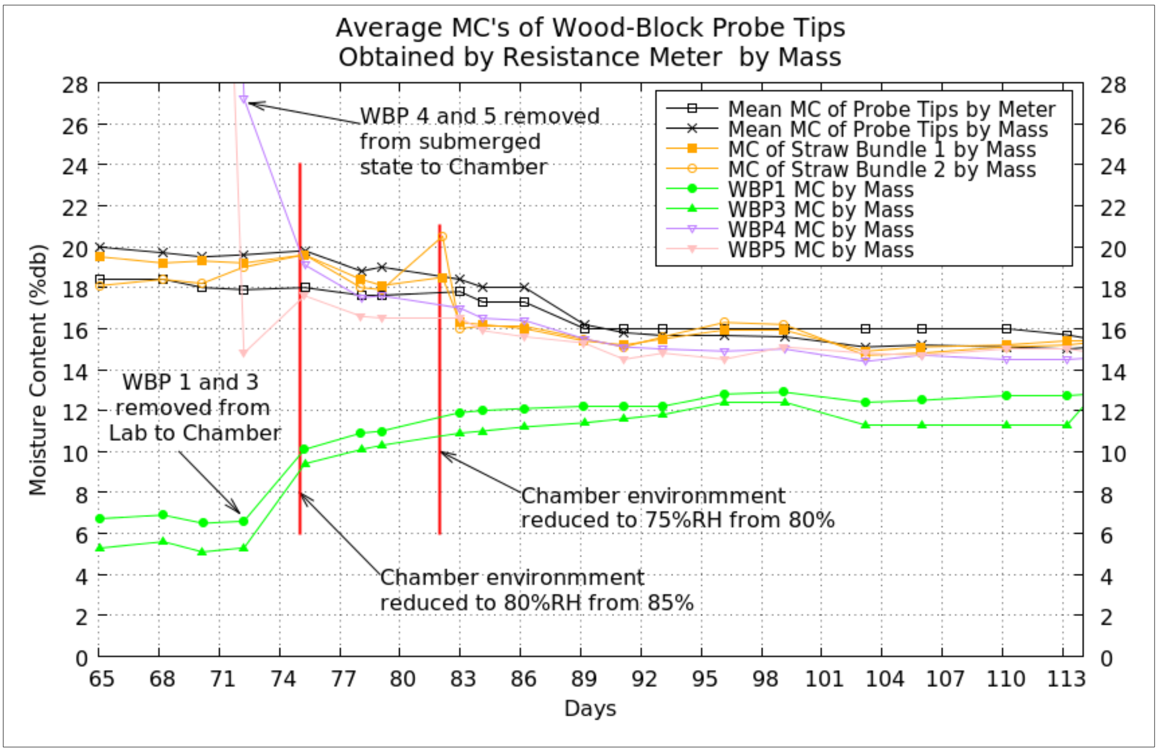


*Figure IV.11: Comparison of wood-block probes, straw and probe tips*

Figure IV.11 shows that the individual probe tips reflected the moisture content of the straw bundles to within ±1 and that Probes 4 and 5 dropped rapidly in moisture content from 70%MC (not shown) equilibrating to ±1 within five days. Probes 1 and 3 showed a far slower rate of change; after 1 month both return a gravimetric analysis of between 2-4%MC negative to the straw bundle moisture content. The results continued to rise to within 2-3%MC, 1.5 months after the start of the experiment (not shown). The results are supported by the data presented by Carfrae et al's. (2010 pp.163) study investigating the walls of the case study (Figure IV.12).

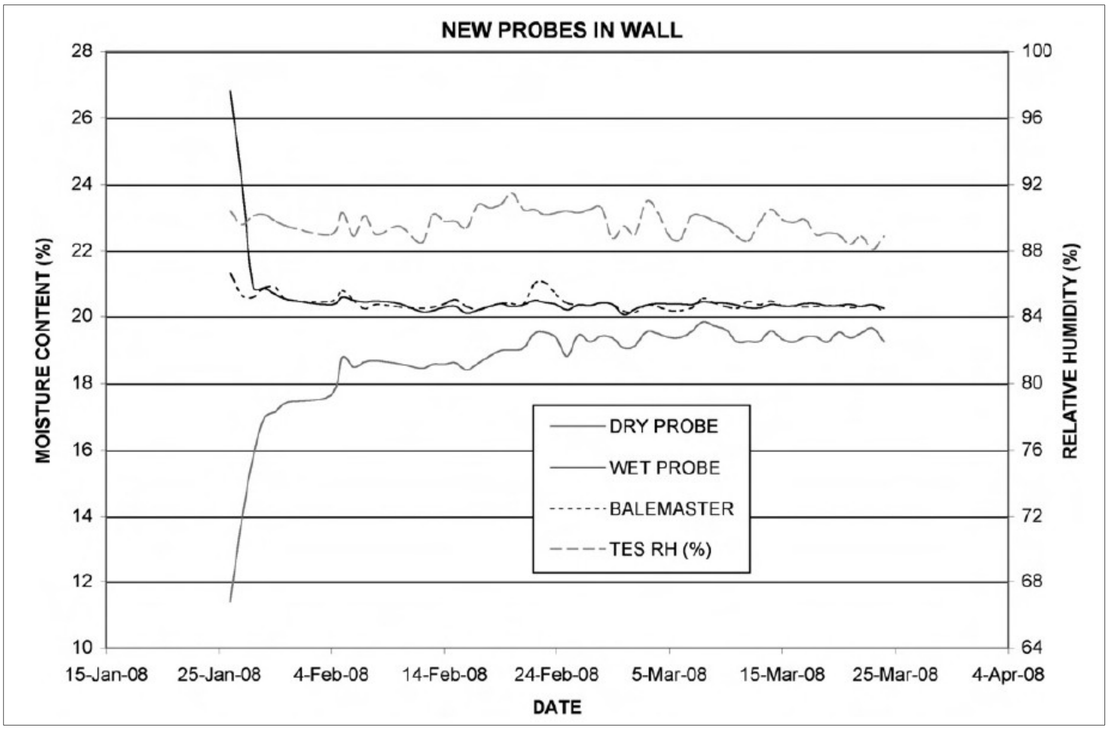


*Figure IV.12: Results From Carfrae et al (2010)*

The results from both Figures IV.11 and IV.12 suggested that there is a time lag inherent within the absorption phase of the wood-block probes (Figure IV.10). An example of moisture gain, with respect to the physical reaction rate, within the probe tip and straw bundle can be seen earlier in the experiment, Figure IV.13 shows straw bundles 1 and 2 increasing in moisture content within 12 days by around 10% from an equilibrated 20% and 17% respectfully. Although no data was recorded between days 30 to 40 the results indicate that oak probe tips gain moisture at a far slower rate than the straw. Probe tip 14 also exhibits a slower increase in moisture content compared to the averaged tips that have been dried in the oven suggesting, that the drier the core of the timber the greater the potential for absorption and therefore an increased response rate is noted.

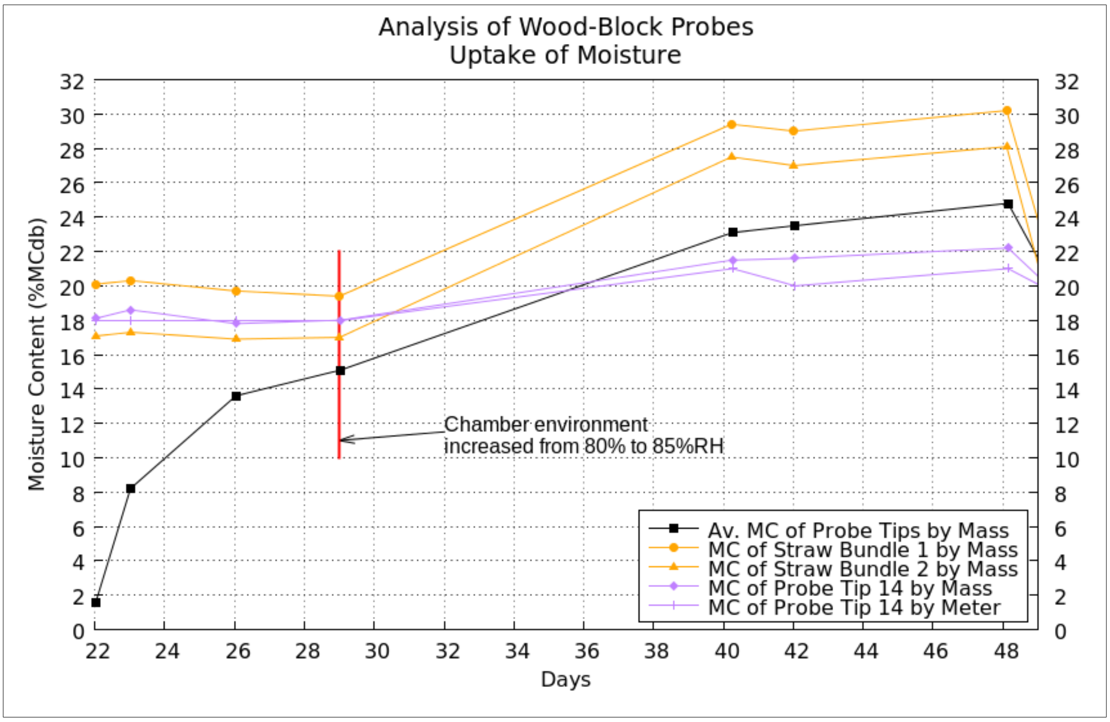


*Figure IV.13: Effect of increasing moisture content*

The results suggested that straw is more responsive to changes in external humidity due to it's structure, greater surface area and proportionally less core material, than timber block, in effect reducing the time to equilibrate. By day 48, 19 days after the experiment started, the chamber was set to 85%RH, the wood-block tips continue to equilibrate (results not shown), suggesting that the type of wood and size of tip may inhibit results. In reference to the sorption isotherm studies (Figure II.5 p60), 85%RH equates to around 25%MC.

In monitoring a construction for moisture content the rate at which the monitoring system reacts could be of great importance in notifying interested parties of any potential problems. Figure V.18 shows the rate at which the probe tips and straw bundles reacted to a decrease in humidity from 85% to 80% demonstrating the mass gained or lost in %MC per day (left y-axis). The results show that straw bundles lost moisture at twice the rate of the tips and that after the initial desorption phase, the moisture content loss rate (right y-axis) settled to show the same results.

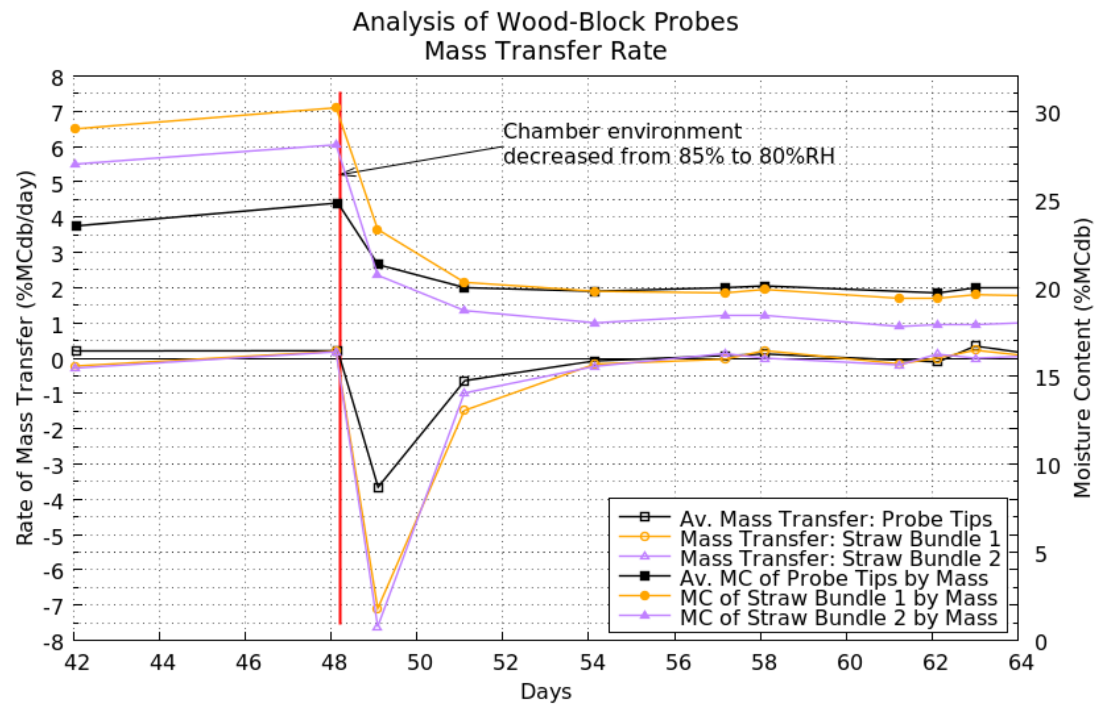


*Figure IV.14: Transfer of mass*

The comparative analysis shows that wood-block probes and individual tips react quickly during desorption, demonstrated by Figure IV.11, however, this rate is not reflected in the adsorption/absorption phase, arguably the more significant of the two phases when relating to moisture monitoring; probes 1 and 3 (Figure IV.11) and tip 14 (Figure IV.13) show evidence of this.

The results in Experiment 2 cast doubt on the validity of using the wood-block probes to reflect the risk posed to the straw, not for accuracy as demonstrated by other authors and within this thesis, but the rate at which the probe can adjust to it's surroundings. After this investigation was conducted Carfrae et al (2010) published a paper suggesting that a reduction in the time lag may be attained by using Ramin as the timber of choice; the influence of the void space within the assembled probe however, remains an unconfirmed potential for error.

## ***IV.4-Summary***

In conclusion a monitoring device should accurately reflect the surrounding environment instantaneously, the results obtained by this study cast doubt on the use of oak tipped wood-block probes as a viable method of monitoring. The response and accuracy of the wood-block probes in the desorption phase poses no cause for concern, yet it is advised that an additional 4% moisture content be added to results obtained by the wood-block probes in the adsorption phase. A model could potentially be used to compensate for a change in the moisture content of wood-block probes in the adsorption phase to predict the rate of straw moisture content increase; an area marked for future study together with the investigation of probe tip size reduction.

The associated risk with wood-block probes concerned not only the response rate relating to the adsorption phase, but also in the restriction to one monitoring point within a bale. The concern with monitoring one location in the width of a bale could only be appeased by introducing multiple probes at different depths in the same area of measurement; a point eluded to by Lawrence (2009a). Based on the results obtained during this experiment the first hypothesis was rejected and the alternative, to design a new monitoring device, was established. The results also dismissed the ability to confidently proceed with the research objective of assessing and comparing multiple case studies. The lack of certainty concerning the response rate of the wood-block probes together with the uncertainty of relevant and useful results being established during the study signified a change in the research procedure.

# Chapter V- Preliminary Investigation – Part II

## ***V.1-Introduction***

The results from the Preliminary Investigation (Part I) signified a change in research procedure, altering the original methodological approach to resolve the specified aims, objectives (section I.1 p11) and gaps in knowledge (section II.7 p84).

The concern with the wood-block probe's rate of response to changing moisture conditions, Experiment 2 (Section IV.3.2.1 p121), is restricted to the absorption phase which in the monitoring of a construction is the phase of most importance to interested parties. A sudden and unexpected rise in moisture content requires an immediate notification. This was noted by Carfrae et al. (2009b) who changed the type of timber to Ramin confirming increased response times however, this information was not acquired until after the experiments were completed.

Preliminary Investigation (Part II) began by investigating two new monitoring device concepts, one utilising the dimensional adjustments in timber, the second removing the use of alien materials and utilising straw as the measurement medium.

## *V.2-Timber Dimensional Adjustment*

An observation made whilst conducting Experiment 2 (section IV.3.2.1 p121) lead to the design of a new monitoring device, the physical difference between the swollen submerged probe tip diameter and the shrunken air dried probe tip.

### V.2.1-Timber Dimensional Adjustment – Method

The experiment aim therefore targeted the dimensional adjustment, as a result of the moisture content, to develop a new monitoring device under the following objectives:

1. Determine how stable the relationship between the dimensions of a probe tip are compared to the moisture content.
2. Investigate the relationship between the dimensional adjustment and the straw moisture content.
3. Assess the potential validity of using such a device in field trials.

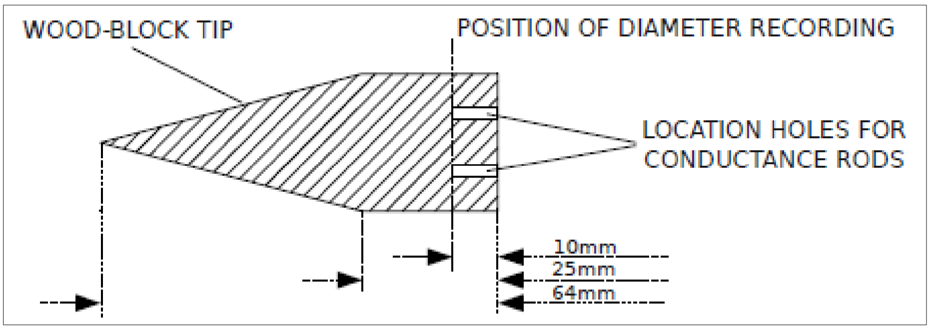


*Figure V.1: Wood Block Tip dimensions*

The preliminary investigation recorded the dimensions of three of the wood-blocks as they were subjected to changing relative humidities. A digital micrometer recorded the variations in diameter of the tips (Figure V.1); it transpired that the measurement along the grain, opposed to across it, gave a higher degree of accuracy and was therefore chosen to demonstrate the data. Two of the tips were exposed to changing environments within the environmental chamber, the third tip was extracted from the chamber and exposed to the air, prior to being oven dried until the mass remained constant, and returned to laboratory room conditions; the chamber and laboratory were maintained at stable 23°C and the oven 105°C. Care was taken to measure the diameter in the same position every time (Figure V.1) and the mass and resistance meter measurements were obtained also.

If the diameter of the probe tip reflected both the straw and the timber moisture content then a null hypothesis would be accepted leading to further development of the monitoring device. The development of this method would include the fabrication of oak discs, thin enough to reduce the effect of the time-lag and increase response times, a conclusion drawn from the wood-block probe experiments (section IV.3.2.1 p121). The alternative hypothesis would require the development of a different monitoring method.

## V.2.2-Timber Dimensional Adjustment - Results

Figure V.2 shows the moisture content (y-axis) plotted against measured diameters of the wood-block tips (x-axis) comparing the dimensional change of the timber.

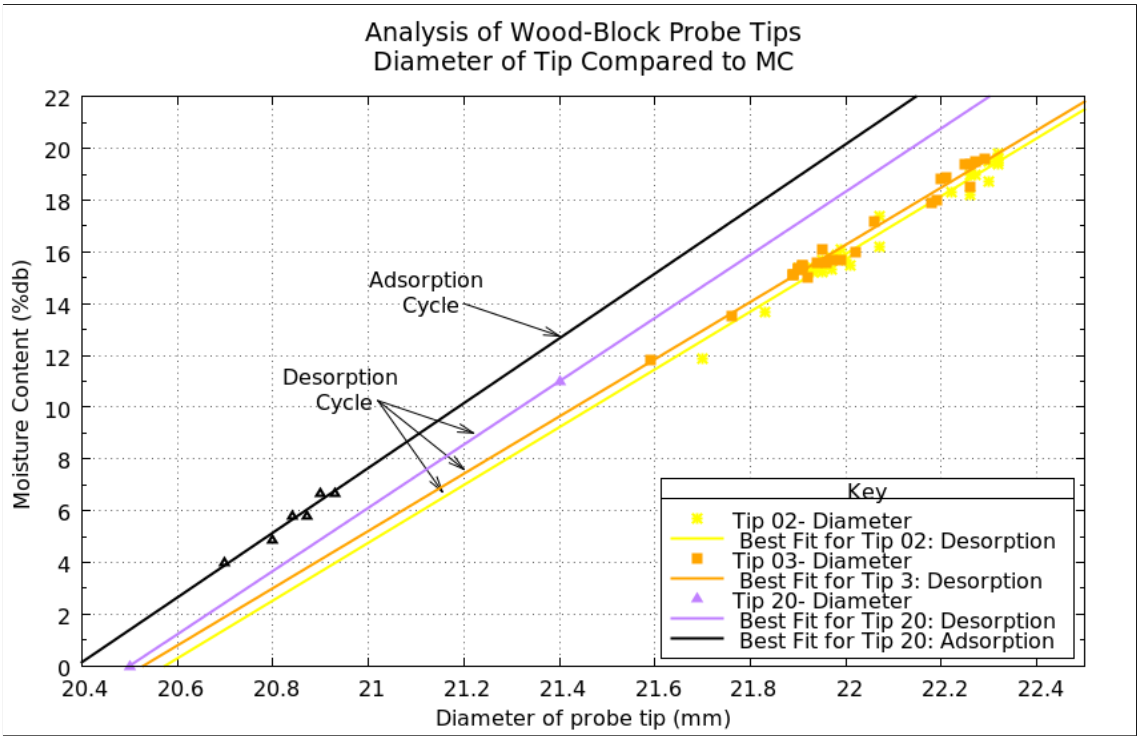


*Figure V.2: Measuring dimension of probe tip against moisture content*

The investigation conducted on probe tips 2, 3 and 20 show a stable correlation between diameter of the tip and the moisture content. Lines of best fit were applied to the data to illustrate the potential for a model based on the results. Probe tip 2 showed an error of 3.4% (rms 0.362) whilst Probe tip 3 showed an error of 2.9% (rms 0.298); both probes were subject to a change in relative humidity from 85% through 80% to 75%. The results obtained from the results of probe tip 20, maintained at laboratory conditions then oven dried over a two day period before being returned to the laboratory, indicated the effect of hysteresis (Figures II.1 p48 and II.4 p59).

The hysteresis effect indicates the importance of knowing which phase the results are displayed under; a diameter of 22.1mm could imply an moisture content (Risk) of either 19.5% (Low Risk – Figure III.3 p100) or 21.5% (Medium Risk) dependant on the desorption and adsorption phases respectfully. In conclusion the dimensional stability reflected the moisture content of the timber under a stable temperature; the effect of varying temperature however was not assessed.

The following stage, in order to develop this monitoring method further, was to consider the method of application. A wood block would have to be in contact with the straw and allow for the relaying of information regarding the change in dimension. Applying a strain gauge to a 2mm thick wood disc would provide this ability and ensure a reduction in the time lag however, this does not bridge the disadvantages observed with the relative humidity sensors, the requirement of expensive data logging software and the potential loss of sensor connection, or that it remains as a single point analytical technique. Subsequent research was halted in favour of the compressed straw probes which are able to transcend these issues.

## V.3-Compressed Straw Probe

Although the initial trial of the dimensional adjustment in timber relating to moisture content (section V.2 p129) was successful, further development, not documented here within, found that the method of measurement was impractical unless a strain gauge was attached to the timber disc inflating the cost of the monitoring device with the additional requirement for data-logging equipment. There was also concern over the effect of temperature on the results which was not researched.

### V.3.1-Compressed Straw Probe - Method

By using straw as the measurement medium the assumption of timber reflecting the moisture content of straw could be eliminated together with other cellulosic materials. A similar method had already been suggested by the CMHC, but is criticised by Lawrence et al. (2009b) as being cumbersome with limited usability in a building due to the visual invasiveness and the possibility of compromising the integrity of the wall. However, the literature review failed to unearth any further mention of this method and therefore the avenue was investigated.

The development of a compressed straw probe was therefore investigated in a laboratory environment empirically, comparing the results to the wood-block probes and straw sample as described in Experiment 2 (Section IV.3.2.1 p121). The aim of the compressed straw probe was to provide a cheap, robust, easy to use and install, reliable and accurate way to assess the moisture content of a bale. The objective was therefore to determine if the compressed straw probe would be an effective tool in evaluating the risk posed to a straw bale construction from moisture.

The first prototype compressed straw probe unit, carefully packed with 4.1g of straw (dry weight), consisted of a hydrophobic plastic cylinder with 1mm diameter holes drilled at 5mm spacings beginning 50mm from the top of the cylinder, and an interference fit cap; also hydrophobic. Two 1.5mm welding rods were inserted into the straw down opposite sides of the cylinder (Figure V.3) 3mm in from the edge and to within 10mm of the cylinders base (also drilled with holes). Lengths of straw stem, air dried at 50%RH 23°C, were selected to be inserted into the probe if certain criteria were met: stems were longer than the cylinder, contained no breaks, and were stripped of leaves. The stems would then be slid into the cylinder manually until tightly packed.

The compressed straw probe, it was reasoned, would be able to provide a complete overview of a section of straw wall with the ability to check results based both on mass and resistance meter readings; enforced by the ability to remove the probe from the wall and visually inspect the straw for signs of damage.

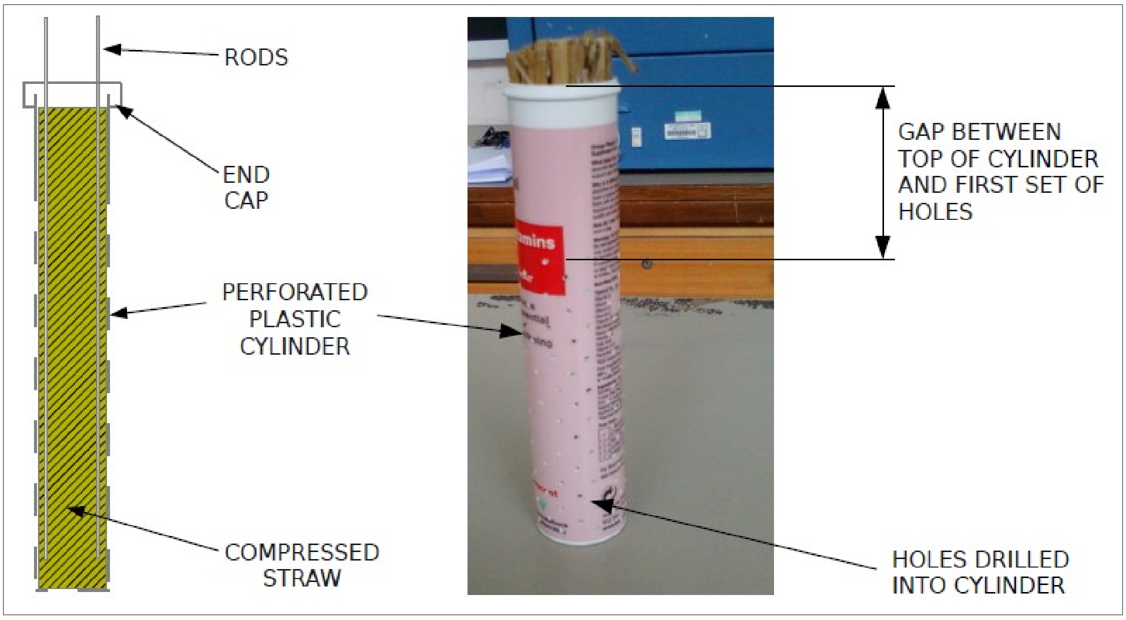


*Figure V.3: Compressed straw probe Prototype 01*

The probe was to be placed in the environmental chamber together with the wood-block probes as per Experiment 1 (section IV.3.1 p114), reducing the chamber from 85%RH through 80% to 70%. The probe would then be extracted to obtain a mass measurement, the entirety of probe, along with a resistance meter reading using the conductance rods, the dry mass of the straw in the probe was established at the end of the experiment. One limitation to the experiment was in the distribution and size of the holes drilled into the cylinder thus creating a perforated container.

If the compressed straw probe accurately reflected the moisture content of the straw sample in the environmental chamber together with an adequate response rate further investigative studies could be suggested however, the direction of the thesis had now been altered, from a comparative study of multiple case studies due in part to the uncertainty of the accuracy of available cheap monitoring devices. The problem had therefore evolved to require an explanation and understanding of how each individual monitoring system works and how the data should be interpreted.

## V.3.2-Compressed Straw Probe - Results

Figure V.4 demonstrates the findings of an 11 week study conducted in the environmental chamber at 23°C, the days shown in weekly cycles (x-axis) against dry moisture content (y-axis), the results are displayed together with WBP1 and Straw Bundle 1.

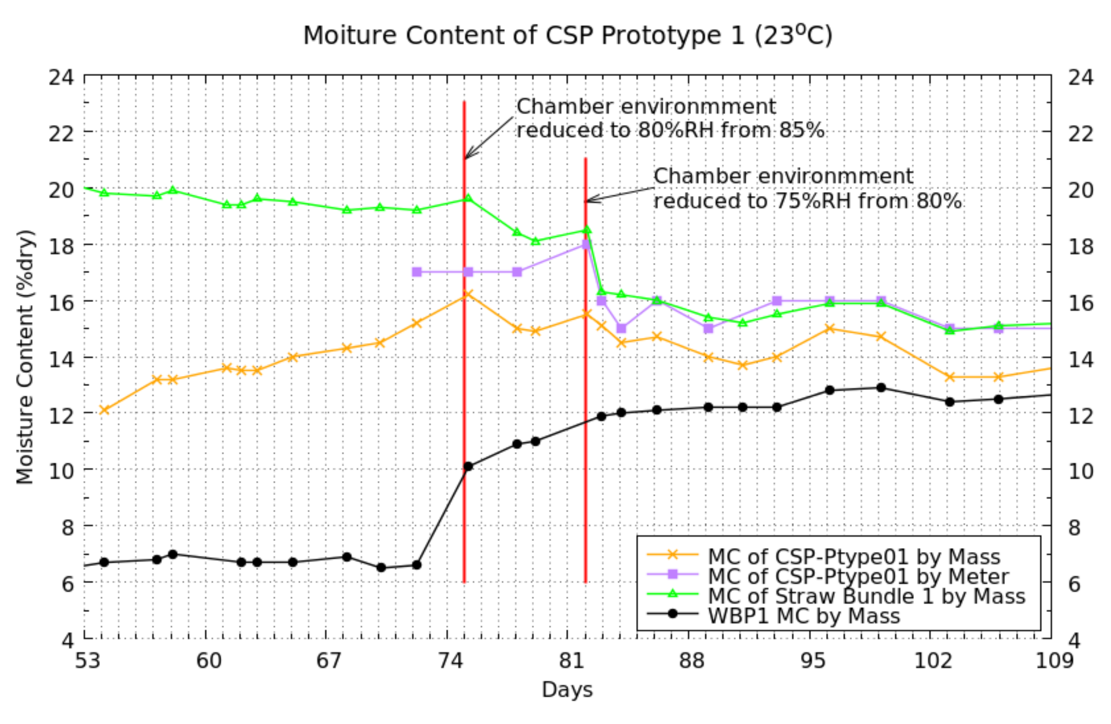


*Figure V.4: Compressed straw probe Prototype 01 trial*

The compressed straw probe is capable of providing two types of reading: the measurable changes in mass (gravimetric analysis section II.4.1 p72) and the meter reading (resistance meter section II.4.3 p73). The compressed straw probe results by mass in Figure V.4 showed that the moisture level had not increased to the level expected taking over 20 days to gain 5%MC. This result cast doubt on the initial viability of the monitoring device, yet could be explained by the limitation of perforation hole size and distribution.

Other possible explanations to the reduced rate of moisture uptake included the dead space at the top of the cylinder, straw at the top of the cylinder does not have direct access (Figure V.3) to gain moisture directly as the perforations do not continue for the length, the moisture must enter the cylinder lower down and be transferred up which may reduce the efficiency of the process. Another alternative explanation was in the straw sample containing moisture that was locked into the structure of the straw whereas, the probe freshly introduced to the atmosphere of 85%RH from laboratory conditions reflects the initial and rapid deployment of moisture on the surface of the straw, hence the compressed straw probe-meter results, with a lag effect as the internal structure of the straw remains comparatively unaffected.

If the xylem are still active then this will determine the rate of osmosis and cohesive tendencies (Section I.3.1 p28) within the structure and thereby the rate at which moisture may be adsorbed into the plant tissue. It may also be feasible that the straw in the probe is slightly more protected from unstable humidities and air movement generated by the chamber, and exposure when removed from the chamber for measurement.

One observation in response rate was noted on day 91, an increase in moisture content of the Straw Bundle which is replicated immediately by the compressed straw probe, both by gravimetric analysis and resistance meter, the wood-block probes however does not respond to this increase for a further two days. The initial results demonstrated that the compressed straw probe had the potential to be an effective monitoring system conforming to the aims laid out in section V.3.1 (p133) concerning the requirement for a cheap, robust, easy to use and install, reliable and accurate monitoring device.

Subsequently an investigation was designed to assess the validity of this monitoring method more rigorously; focussing on response rate, accuracy, implications of straw density, differences between the gravimetric analysis and resistance meter measurements, adaptation of analytical methods and ultimately the ease of use and comparison with other methods.

The removal of evaluative and comparative multiple case studies from the research program combined with the unresolved issue concerning wood-block probes and development of the compressed straw probe highlighted a potential gap in the research study; the detailed and rigorous testing of a dynamic environment. In order to address this concern a test rig was designed and constructed.

## ***V.4-Test Rig***

The construction of a Test Rig was commissioned in the summer of 2010 was to represent a worst case scenario, built entirely by unskilled labour with limited construction experience, it was to be unheated, inadequately insulated and suffer from a lack of maintenance.

### V.4.1-Test Rig - Method

The importance of the Test Rig (Figures V.5 to V.10) was: in the unimpeded access to the data stream, the ability to perform destructive testing if necessary, and to allow the risk of degradation to develop within the walls into advanced stages without compromising occupant health or safety. The rig provided a platform on which to test multiple experiments and monitoring of devices in a dynamic environment.

*Figure V.5: Location of rig construction*

*Figure V.6: Car tyre foundations, flooring, with 3 half bale loaded Blocks*

*Figure V.7: Erection of Blocks (note bales are place vertically)*

*Figure V.8 Application of second layer of render*

*Figure V.9: Rig construction finished view from NW*

*Figure V.10: Rig construction finished view from East*

The research conducted on the test rig involved empirical investigations, comparing and contrasting findings as part of an exploratory study of observation and experimentation. The overall aim of the Preliminary Study into the Test Rig investigation was to establish the benefits and disadvantages of using the Protimeter Balemaster as a reliable monitoring method and to assess the use of the proposed Risk Assessment Method (Figure III.3 p100) in a real world environment.

The Rig (Figure V.11) consists of twelve modular straw blocks, seven on the lower level and five on the upper, two window blocks and one door (Figure V.12). Constructed from OSB3 (Oriented Strand Board) each modular block comprises of three ½ bales (1100x330x225mm) laid vertically and compressed into place. The module blocks were light enough for two people to carry into position and could therefore be constructed and stored off-site whilst being protected from the elements and consequently minimising on-site construction time.

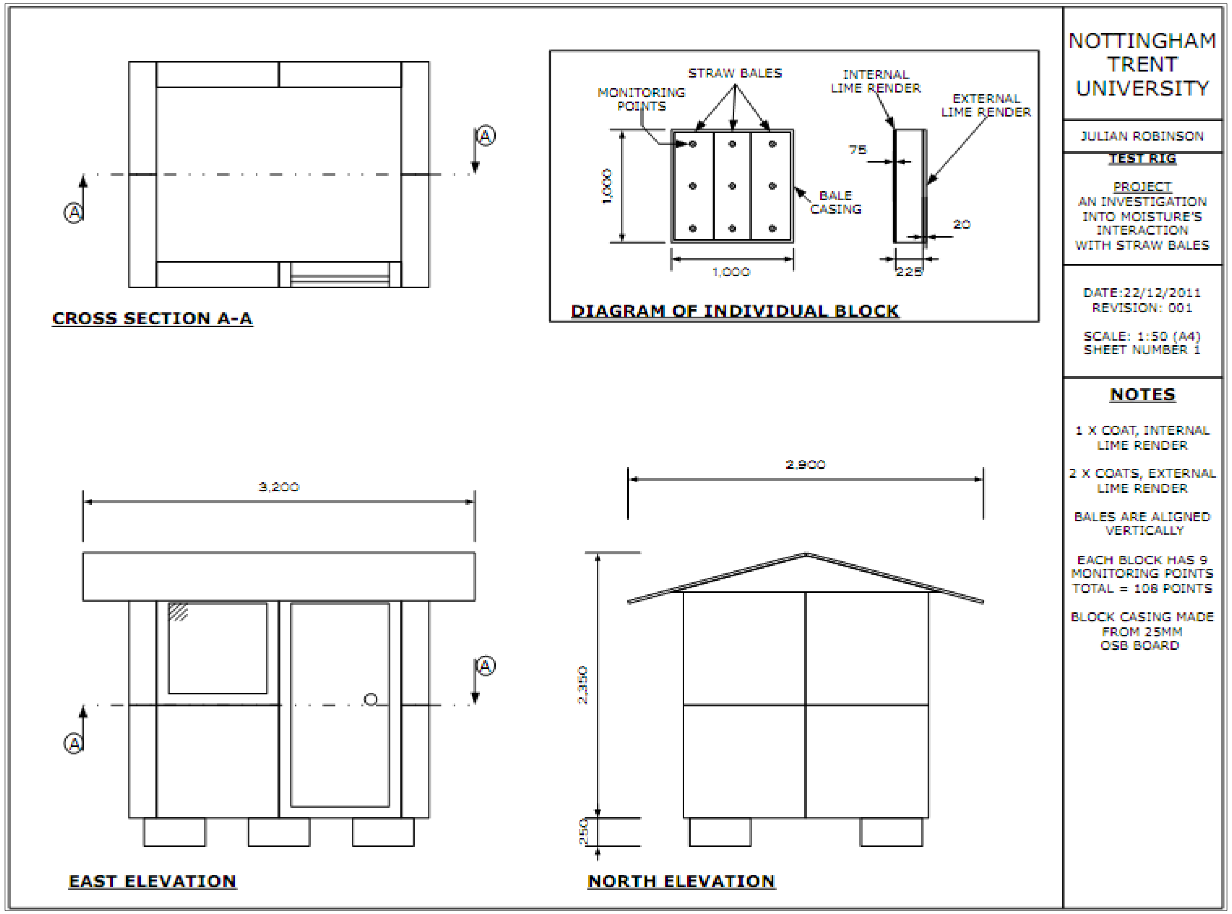


*Figure V.11: Schematic of Test Rig*

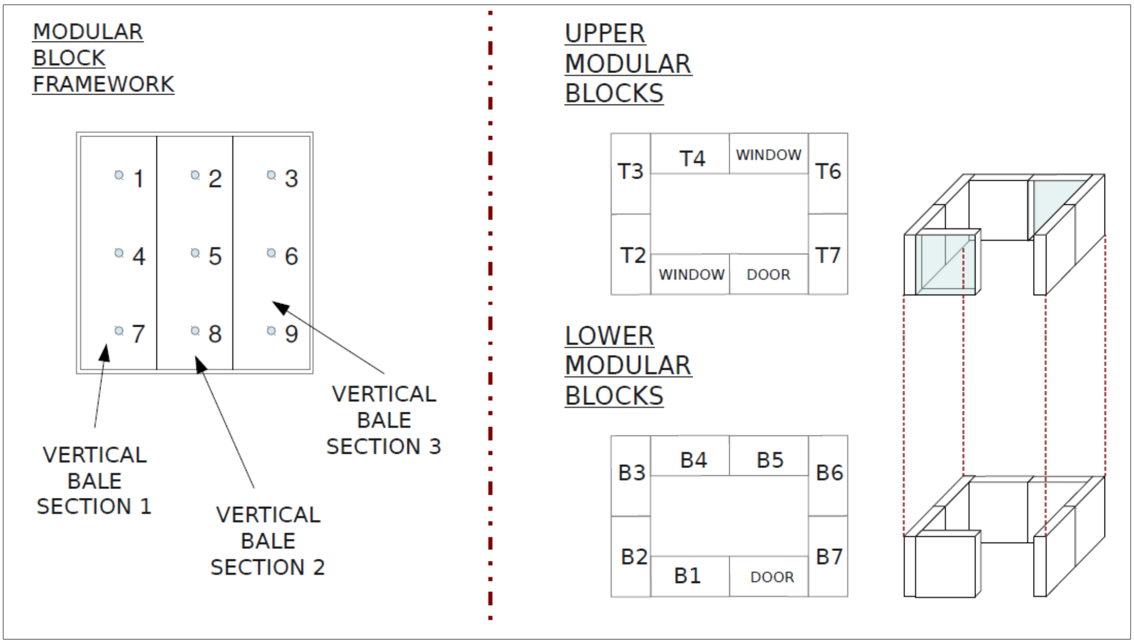


*Figure V.12: Test Rig block diagram*

The Modular-Blocks were labelled clockwise from the door '1' to '7' (Figure V.12), with the addition of 'B' to represent the lower blocks or 'T' the upper blocks. The monitoring point for the insertion of the Balemaster with probe, to a depth of 112 mm (half the wall thickness) totalling 108 positions in all, are shown in Figure V.14 as viewed from the interior of the rig. From this it is possible to describe via notation the location of each monitoring position; B5.3 would be the lower level straw block opposite the door and would represent the top right monitoring position at the top of the third bale in the block as viewed from the interior of the rig.

The rig was mounted on rammed earth car tires, the OSB3 floor was thereby raised 250mm from ground level onto which the individual blocks could be placed followed by a single skin roof, overhanging each side by 500mm, with an underlay of breathable polypropylene membrane and coated with a protective rubber solution. The offcuts of OSB3 board were then used to create a sacrificial skirt that ran around the bottom of the rig, masking the car tires and protecting the underneath of the rig from splash-back (Figures V.5 to V.10). The rig was not designed to be air tight and therefore has major air leakage paths due to the ill fitting windows and door. The east facing window consisting of two sections of transparent plastic sheeting, the west a shutter made from OSB3, and the door (incorrectly hung) was fabricated from single skin pine slats. The door, floor and roof remained uninsulated for the entirety of the investigation.

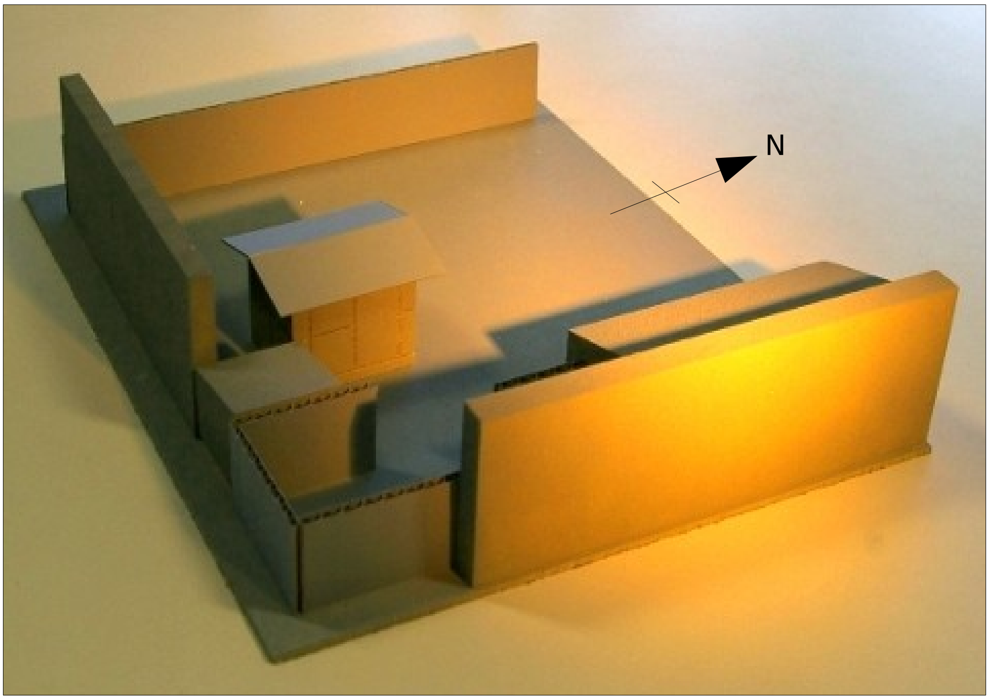


*Figure V.13: Model of Test Rig location*

The Test Rig (Figure V.13) was constructed in the garden of a house near Grantham, Lincolnshire, exposed to the north, shadowed by a large farm building four meters to the east, a three meter high hedge to the south (two meters away), and within the proximity of an aged apple tree located in a sheltered section of garden to the west. The east façade of the rig butts up to a concrete path, the other walls are surrounded by vegetation.

The Test Rig would be subject to confounding variables: the atmosphere, weather patterns, seasonal variations that would have an uncontrollable effect on the experiment. The design of the rig assumed that the reduction in thickness of the bale, to half thickness (225mm), would have little impact on the passage of moisture or temperature through the bale compared to a full width bale and was reasoned that a a faster reacting dynamic situation would be promoted; the reduction in thickness was necessary due to space constraints.

The monitoring of the rig was initiated on completion of the structure, the rendering was undertaken over the following month incorporating two external applications of lime render and one internal application leaving the nine monitoring points (Figure V.12) in each of the Modular-Blocks without render and therefore accessible from the interior of the rig with the Balemaster probe (Figure V.14).

*Figure V.14: Monitoring of Module-block with Balemaster showing holes to interior side of render*

The data obtained from the Balemaster with probe was to be presented graphically, taking advantage of the suggested Risk Assessment Method (Figure III.3 p100) to display a meaningful visual account of the preliminary study. The results would also be analysed statistically using standard deviation plotted against moisture content thus describing the historical progression of moisture throughout the walls.

The Balemaster with probe was used during the entirety of the preliminary study phase of the test rig as it provided the most convenient way to record data directly from the straw, obtaining an instantaneous assessment at multiple positions throughout the rig without the need to install 108 individual monitoring devices. Another assumption made at the beginning of the study was that nine measuring positions in each Block (Figure V.12) would provide enough data about each bale without impacting on time management and the generation of similar data from monitoring positions located close to each other, or a lack of relating data if the proximity was too distant.

The experiment plan was to assess the straw with as little disturbance, and with as fewer alternative materials and devices as possible. The use of the Balemaster with probe created an inherent confounding variable; the straw was exposed to the internal atmosphere of the Test Rig at the point of measurement to allow for the insertion of the probe (Figures V.15 and V.16). It was assumed that the influence of this exposure would be negligible due to the protection from the external atmosphere; namely wind driven rain.

Figure V.15: Holes marked for insertion of Balemaster probe from rig interior.

Figure V.16: Hole for insertion of BM probe.

A weather station was also erected to provide additional analytical benefits allowing the direct comparison of atmospheric conditions, both internal and external, and the resulting moisture content of the straw. In addition to the empirical weather data study, a theoretical and explanatory investigation was carried out in order to assess the maximum amount of direct sunlight affecting each of the blocks. A scale model of the rig and surrounding area was fabricated and placed on a heliodome table (Figure V.13). From this it was possible to measure the maximum amount of time direct sunlight came into contact with each individual Block throughout the year corresponding with the approximate time. This would in turn provide a comparative assessment method to describing observations and results. The weather station was placed to the north of the rig (Figure V.13) in an unsheltered area and was set to log readings every 30 minutes ensuring an adequate amount of data was collected compared to the capacity for data storage; moisture content results were taken weekly based on the assumption that, barring dramatic failure, moisture would not be transferred through the bale at a fast enough rate to justify additional monitoring (Goodhew et al., 2004).

The construction of the rig provided the ability to perform extensive testing in a dynamic environment. The overall assessment of the Balemaster with probe, weather station and Heliodome survey provided direction and instruction as to how to progress the thesis. The Heliodome table was set to 53° Latitude and the amount of sunlight on each module block was noted at every hour for every month of the year.

## V.4.2-Test Rig - Results

The Test Rig was constructed to address the gap in limitations of both the laboratory experiments and the monitoring site. The aim of the preliminary investigation into the Test Rig was to assess the 'Risk' posed to the straw from moisture, using a weather station and Balemaster with Balemaster probe attachment.

### V.4.2.1-Risk Posed to T4 & B4

Figures V.18 and V.19 show the history of Blocks T4 and B4 respectfully(Figure V.12 p143 for relative positions), plotted as contour graphs and showing the combined analysis of the three vertical bales within each module-block. Figure V.17 describes how to use the contour plots; once the monitoring position has been selected from the Modular-Block (i.e. position 4) the results can be analysed by looking at the y-axis (Step 1). The results extent from the y-axis along the x-axis (elapsed time period) under Step 2, Step 3 (z-axis) then provides the application of the Risk Assessment Method (Figure III.3 p100). The application of the render is shown by Step 4 as a vertical drop down line, and Step 5 details the day a reading was taken.

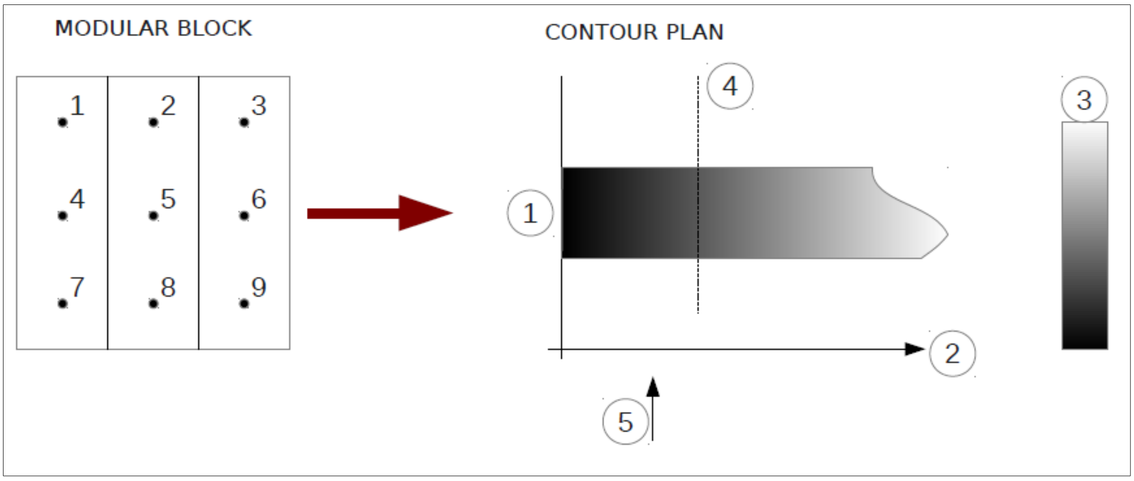


*Figure V.17: How to read the contour plot*

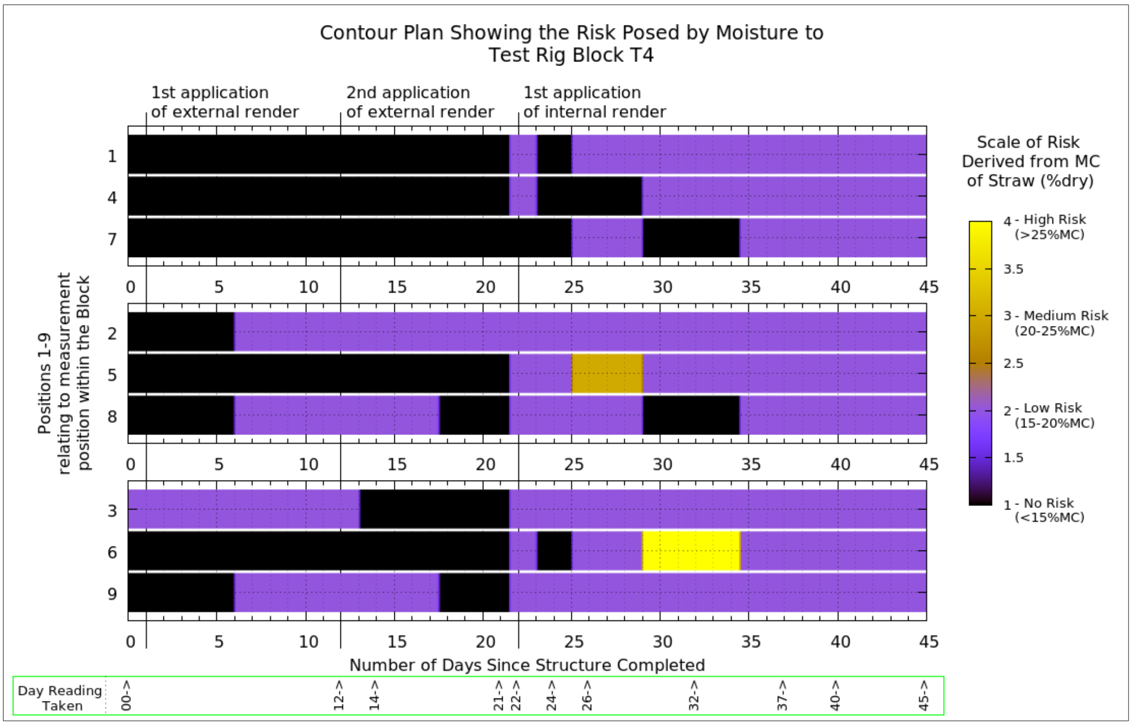


*Figure V.18: Test Rig Block T4 moisture content*

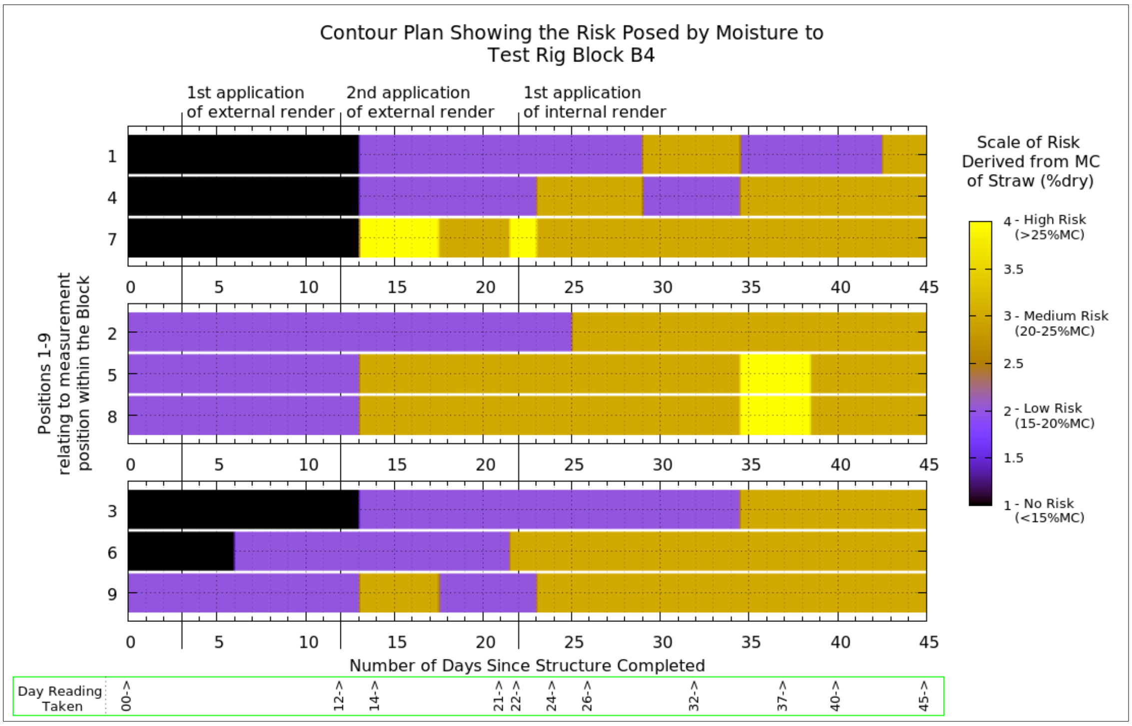


*Figure V.19: Test Rig Block B4 moisture content*

The first vertical bale section (positions 1,4,7) in Block B4 (Figure V.19) shows a progression from '*No Risk*' to '*Medium Risk*' suggesting that closer observation may be needed regarding the risk posed to the straw. The second (2,5,8) and third sections (3,6,9) also indicate a level of concern, yet positions 5 and 6 show spikes into levels considered '*High Risk*'. The results have been interpolated, therefore a spike in the data stream is often overemphasised as demonstrated by positions 5 and 6 between day 35 and 38. The dangerous spike is somewhat misleading and is due to contamination of the probe tip from the wet render applied 14 days previously. A comparison between the other blocks can be made from the data shown in Chapter X- Figures X.4 to X.15, displayed in the same format, demonstrating  other errors in records caused by wet render in contact with the Balemaster probe.

Comparing the Upper Blocks to the Lower, B4 (Figure V.19) and T4 (Figure V.18), B2 (Figure X.6 p316) and T2 (Figure X.7), and B3 (Figure X.8) and T3 (Figure X.9) all exhibited higher moisture content's in the Lower blocks than the Upper. B6 (Figure X.12) and T6 (Figure X.13), and B7 (Figure X.14) and T7 (Figure X.15) remained however at similar moisture levels. At this stage there was little conclusive evidence to indicate any conclusion other than to suggest that the application of the render did not appear to have any immediate effect on the moisture content of the straw. It remains unclear however why position B4.7, on day 14 shows at '*High Risk*' elevated and can only be explained by an error in data acquisition.

In conjunction with the Contour graphs, which offer a general overview of the data, comparative bar charts, Figures V.20 and V.21, show the risk posed to all the blocks grouped into the Risk Assessment Method (Figure III.3 p100) and separated into Upper and Lower Blocks. The contour plots were produced to provide greater clarity in reviewing all blocks simultaneously; plotting the number of occurrences of the moisture content ranges on the y-axis against the days the readings were taken (x-axis).

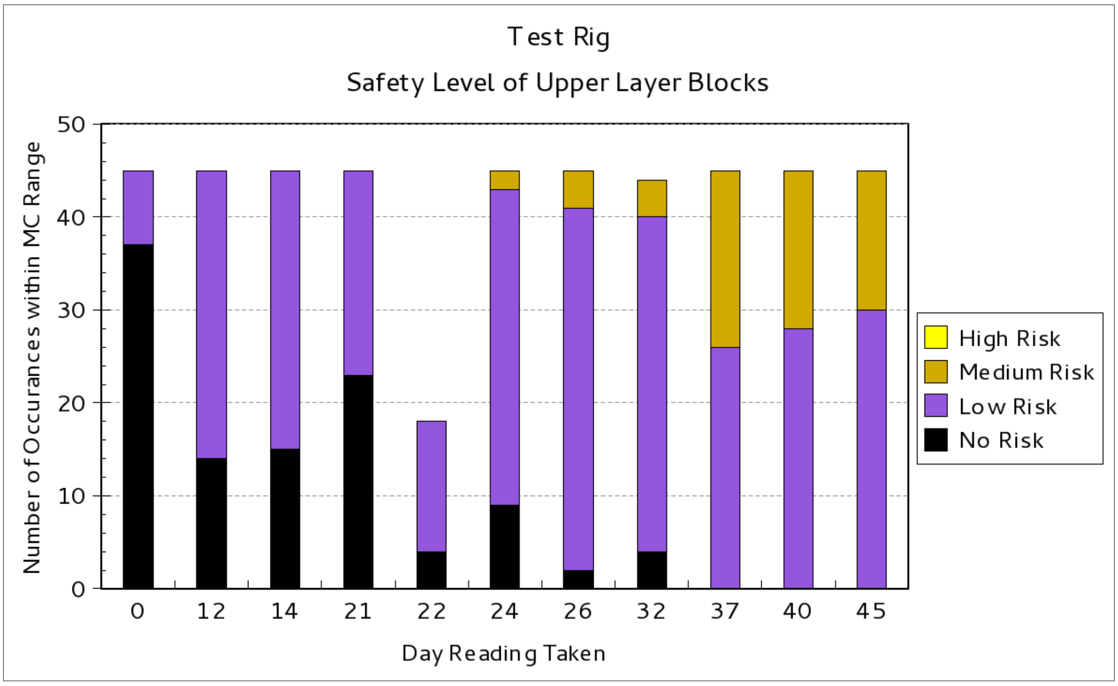


*Figure V.20: Health of the Upper Blocks*

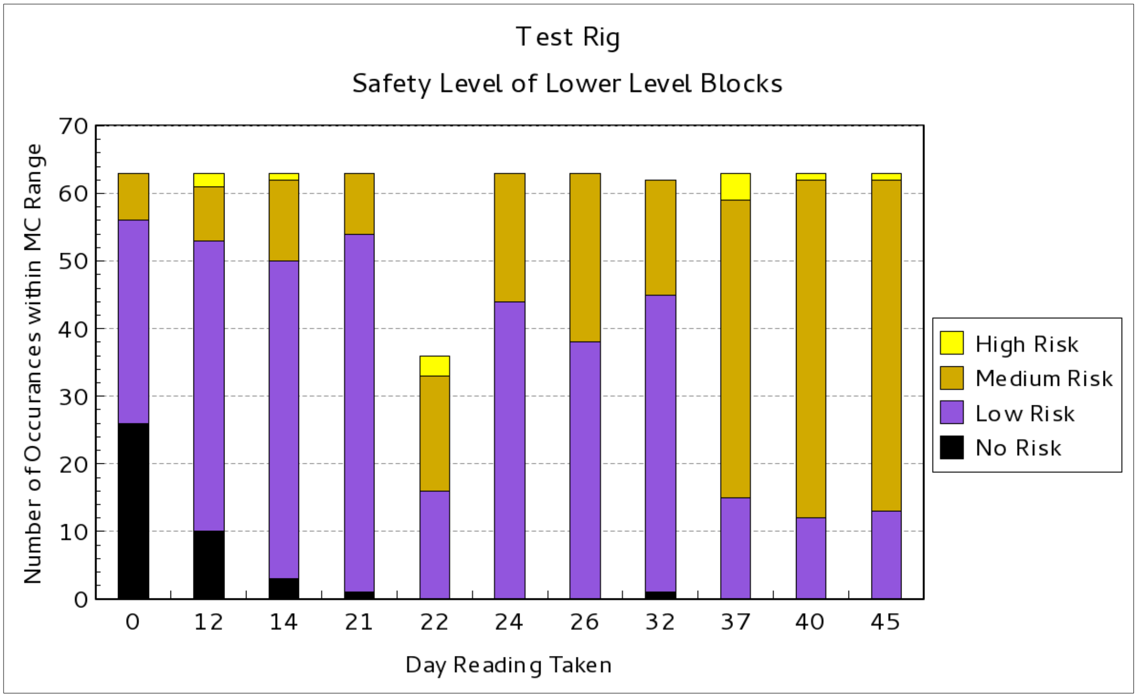


*Figure V.21: Health of the Lower Blocks*

Both graphs show an increase in 'Risk' of the straw over the 45 day time period; the Upper Block (Figure V.20) results indicate that after 32 days no results are recorded below 15% moisture content, yet there is a significant rise in the number of cases of results at 'Medium Risk' from 4 to 19 occurrences. No readings are made below 15% moisture in the straw of the Lower Blocks (Figure V.21) after 21 days, the majority of results descending into the allocation of 'Medium Risk'. On day 22 there was some data loss hence the drop in the number of occurrences.

The main observation made when analysing the results was a difference in the starting moisture contents of each bale and in some cases of the moisture content between each position within the same bale. It had previously been assumed that each of the bales used would have had very similar moisture contents, having been stored in the same dry environment for several months. The analysis of the starting moisture content's on Day 0 for the Upper Blocks produced an arithmetic mean of 16.2%MC with standard deviation of 2.838, a maximum reading of 23.9 and a minimum of 12.5. The incorrect assumption regarding the equality of starting moisture contents of the bales lead to a questions of accuracy, and of cause and effect. It was hypothesised that the variations were due to confounding variables, for example: temperature, density and naturally different starting moisture contents highlighting a further gap in knowledge requiring further in depth investigations.

### *V.4.2.2-Further Investigations of Risk*

In analysing the statistical results for the preliminary study of the Test Rig Figures V.22 and V.23 were produced to show the standard deviation for the data obtained from the mean moisture content (y-axis) plotted against the individual readings of moisture content (x-axis) presented for each day the readings were taken. This provides a detailed visualisation of the statistics for the data stream; when a comparison between V.22 (the Upper Blocks) and V.23 (the Lower) is made the results illustrate the differences in progression of the moisture content. Designed to show the mean moisture content (standard deviation of zero), maximum and minimums and the moisture content at each standard deviation and concentration of data, the graphs also demonstrate the increase in moisture content of the straw over the 45 day period, and any outliers that may have affected the results.

Figure V.22 shows that on Day 0 the mean moisture content was 13.8% with a range of 5% (minimum of 11%) and a standard deviation of ±1.8 ignoring one outlier. Conversely Day 45 shows a mean of 19.2%, range of 7.8% (minimum of 15.2%) and a deviation of ±1.9 ignoring two outliers. It shows that there was little moisture gained between the 12th and 21st, the 26th and 32nd, and the 37th and 45th. This suggests that the first application of external render may have had an effect on the moisture content of the straw, with a less noticeable effect after the second application. The application of the internal render after day 21 also provides evidence of an effect, raising the moisture level of the interstitial bale.

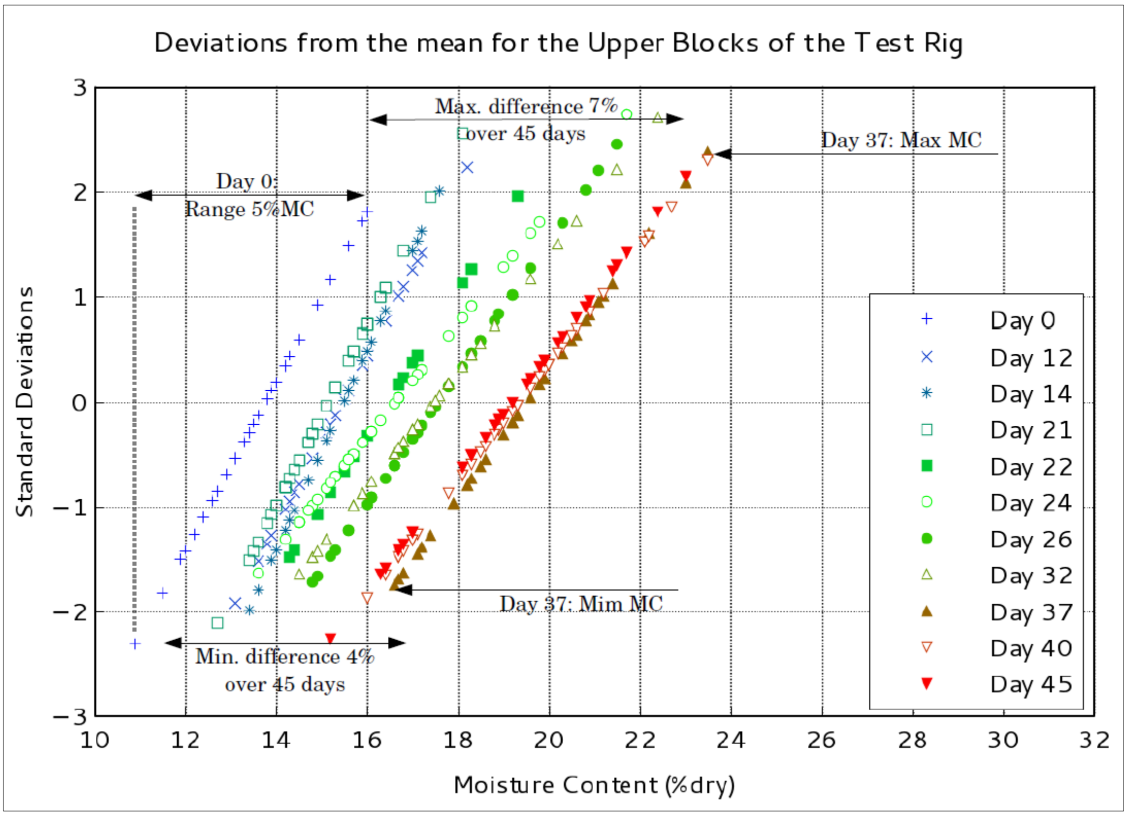


*Figure V.22: Statistical analysis of Upper Blocks*

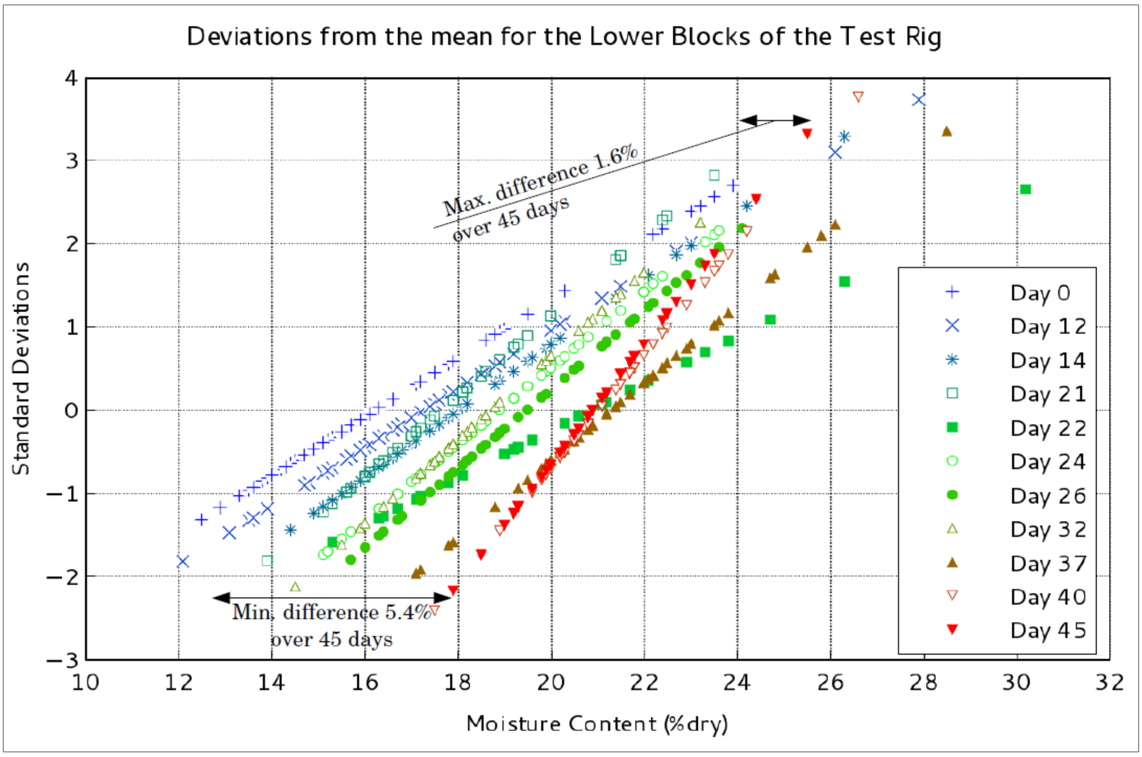


*Figure V.23: Statistical analysis of Lower Blocks*

The range of moisture content of the straw increases over a 45 day period together with a disparity in the maximum and minimum readings, the difference between Days 0 and 45 for the minimum moisture content's is 4% opposed to the maximum readings of around 7%, this suggests that the moisture contents were not stabilising and an equilibrium moisture content was not being obtained. This has highlighted the need for more detailed analysis to be conducted as the difference in the readings at the start of the study was 11% between the maximum and minimum values compared to 19.2% after 45 days.

The results shown by Figure V.23 suggest the emergence of a different pattern; the disparity appears to be at the minimum end of the moisture content range a difference of around 5.4% opposed to 1.6% difference in the maximum moisture content. This suggests that around 16% (±1 s.d = 68% of distribution) of readings changed little in moisture content over the 45 day period.

The majority of the results are documented as reading below 25%MC. An important observation is that on Day 0 the readings obtained above 22% are exhibited by different bales; this suggested that another variable was affecting the results as the moisture content of each individual bale was expected to be the same at the beginning of the data acquisition.

The only rainfall in this 45 day period was from the north and west on light winds of less than 5m/s; totalling 13ml. Therefore, the rain during this period was deemed unlikely to have had a significant affect on the overall increase in moisture content of the bales, leaving humidity, temperature and the drying render as the possible causes. As the render cures it will absorb $CO_2$ and expel water which will raise the moisture content of the straw; the changes in gradient and moisture content of the results on day 22 and 37 can be explained by contamination of the Balemaster probe by the recently applied render.

### *V.4.2.3-Environmental Factors*

The analysis of temperature and relative humidity in Figure V.24 provides a greater degree of explanation when assessing the Risk posed to the straw. Upon initial examination the moisture content appears unaffected by temperature however, the literature (GESensing 2006) states that a thermocouple be used to provide a more accurate assessment; a drop of 5°C could equate to a reading 1%MC greater than the displayed moisture content (Equation II.5 p73).

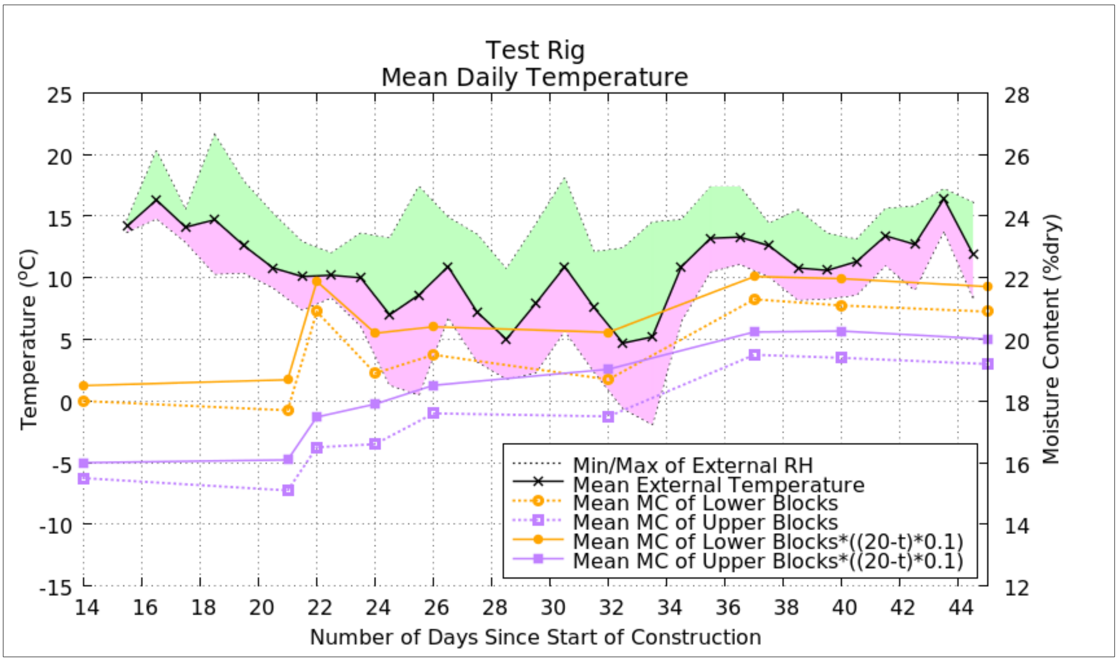


*Figure V.24: Temperature affecting bale moisture content*

Adjustments of the results for the external temperature (t) can be seen in Figure V.24, the mean lower block reading on the 32nd day potentially reading 1.6% lower than stated (equivalent to 20.2%MC) whereas the reading on the 37th read 0.8% lower, equating to a potential result of 22.1%MC. The use of the external temperature to modify the raw data leads to the generation of another error; the temperature of the bale in the centre will be different to the external temperature. The internal bale temperature was not available to this set of data and therefore it was suggested that future measuring techniques be adjusted to incorporate this.

Factoring temperatures into the results would produce the results as illustrated for the moisture content against relative humidity in Figure V.25. The adjusted results show that the moisture content rises at a rapid rate stabilising within the estimates of Lawrence's equation; a relative humidity between 80% and 85% equating to an moisture content of between 19% and 22.5%. The application of the internal render may produce an effect apparent in the results, post 20 days, as the straw is sealed from both sides and the moisture content of the straw is raised.

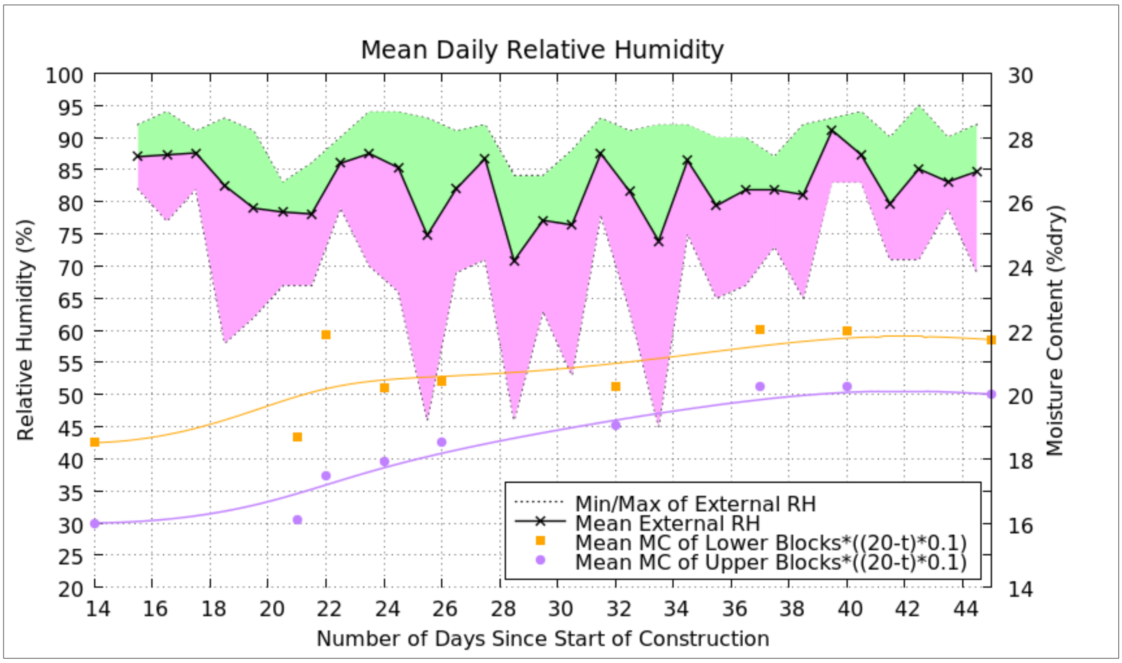


*Figure V.25: Relative humidity affecting bale moisture content*

The use of external temperature to produce the corrected moisture content is an estimate of the real bale temperature, and has been used to demonstrate the effect of the correction. The temperature of the bale was not obtained during this stage of the study and is likely to be cooler than the external temperatures used when obtained in the morning. The temperature and relative humidity used in Figure V.25 is the average over a 24 hour period, but the maximum and minimum data is included to demonstrate the extremes reached within the time-frame.

### *V.4.2.4-Sunlight Factor*

The study of direct sunlight on the render was also of interest to the study, yet was not measured in real time, but obtained by measuring the path of the sun projected onto a scale model by a Heliodome (Figure V.13 p144). Table V.1 shows the maximum amount of direct sunlight affecting the render over a year detailing the range of times at which each module-block is exposed. Module-block's 6 and 7 have two phases of direct sunlight, early morning and late evening.

*Table V.1: Average amount of sunlight per module-block per year*

| **Module Block** | **Average hrs/yr sunlight** | **Phase 1** | | **Phase 2** | |
|---|---|---|---|---|---|
| B1 | 27 | 07:00 | 11:00 | - | - |
| B2 | 34 | 08:00 | 16:00 | - | - |
| B3 | 33 | 08:00 | 16:00 | - | - |
| B4 | 32 | 12:00 | 19:00 | - | - |
| B5 | 36 | 13:00 | 19:00 | - | - |
| B6 | 7 | 06:00 | 07:00 | 17:00 | 19:00 |
| B7 | 7 | 06:00 | 07:00 | 17:00 | 19:00 |
| T2 | 33 | 08:00 | 16:00 | - | - |
| T3 | 26 | 08:00 | 16:00 | - | - |
| T4 | 29 | 14:00 | 19:00 | - | - |
| T6 | 10 | 06:00 | 07:00 | 17:00 | 19:00 |
| T7 | 8 | 06:00 | 06:00 | 18:00 | 19:00 |

The study demonstrates how much effect the direct sunlight could potentially have on the construction in one year, naturally a share of these hours may be under cloud cover and the intensity of the sunlight will be different at midday than for the first few or last hours of the day. In conclusion the North facing module-blocks 6 and 7 will have not only a reduced amount of direct sunlight but the solar gain will also be at a lower intensity.

## V.4.3-Block B5

During construction of the Test Rig it was discovered that one of the half bales had experienced elevated moisture levels whilst in storage, although there was no apparent degradation visible to the surface of the straw a decision was made to investigate the effect of retaining the bale in the construction. Advice given by literature and general practice is to disregard any bales of elevated moisture levels. The elevated bale was located in the first vertical position of Block B5 (positions 1, 4 and 7; Figure V.12 p143).

### V.4.3.1-Block B5 - Method

It was hypothesised that the inclusion of a bale with a high starting moisture content would create an area of weakness in the building, and potentially an area for degradation to begin forcing a critical failure within the construction. It was of interest to the study how this inclusion would affect other bales contained within the same block, addressing another important issue concerning the spread and effect of primary mould cultures leading to further colonisation.

The method of data collection was not altered from the method described in Section V.4.1 (p139) however, it was assumed that the straw would maintain a high level of moisture increasing the risk to degradation post the application of the render relative to the other bales in the test rig. The inability to inspect the straw visually was a limitation to the experiment, the method was therefore reliant on moisture content and temperature analysis to evaluate any signs of microbial activity.

### V.4.3.2-Block B5 - Results

Figure V.26 shows the results obtained from Block B5 positions 1, 4 and 7, demonstrating levels of moisture considered at 'High Risk' that could not be attributed to render contamination of the Balemaster, with probe attachment, as observed in Section V.4.2.2 (p153), and may have seen elevated temperatures above 10ºC for extended periods of time. The effect of the Risk Assessment System (Figure III.3 p100) is demonstrated by the contour plot, Figure V.26, indicating that a problem exists and that further analysis and possible rectification was required.

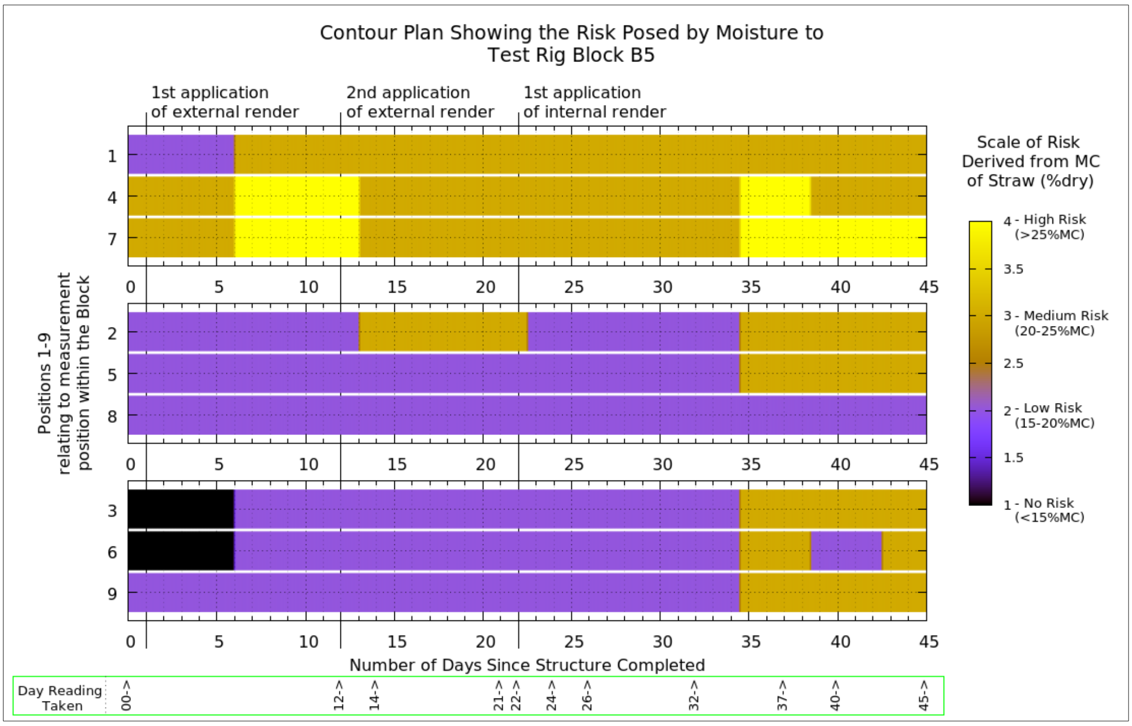


*Figure V.26: Block B5*

Positions 4 and 7 (Figure V.26) exhibit higher readings throughout the study however, the distinction between the exact levels of moisture is unclear from the contour plot; the difference between the results from Day 34 of Position 2 cannot be distinguished from a moisture content reading of either 24.9% or 20.1%. Figure V.27 shows a detailed breakdown of Positions 2, 4 and 7 illustrating the differences and the limitations of the contour plot. It illustrates also the High Risk moisture levels recorded during the study at days 12 and 37.

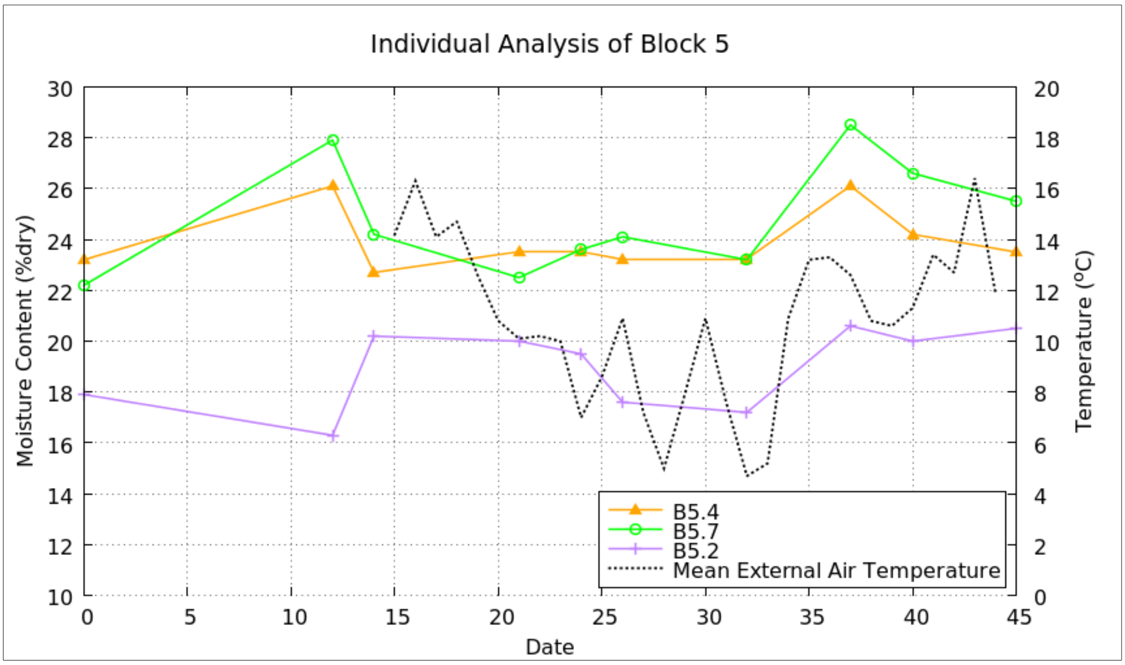


*Figure V.27: Detailed analysis of Block B5*

The recorded mean air temperature was of concern during the monitoring of the Block reaching above 10°C at moisture levels in excess of 25% however, after the 45 day study a compressed straw probe was prepared for insertion into Position B5.7 thereby providing a medium on which degradation could potentially spread and be observed. In order to insert the compressed straw probe a hole was drilled into the wall and the extracted straw was collected and inspected for signs of decay. The extracted straw had no smell synonymous with the decay of straw and provided no visual sign of mould or rot.

In conclusion the study suggested that the inclusion of a bale of high starting moisture content did not provide an observable area of weakness however, it maintained a level of high moisture in comparison to the other monitoring points and therefore qualified for further investigation utilising the compressed straw probe as an alternative to demolition of the wall section.

### *V.4.4-Test Rig Summary*

The combination of the Risk Assessment System (Figure III.3 p100) and contour plot demonstrate a quick reference and highly visual guide to viewing the data. Although the plots do not demonstrate intricate data for each measurement point, the plots do highlight potential problems which may be analysed in greater detail at a later date (Figure V.27).

The use of the Balemaster represents a quick method of obtaining a moisture content reading from the straw, but disadvantages include: temperature calibration, effect of straw density, and the requirement to leave a gap in the render for insertion of the probe. The observations made during the overall initial study have demonstrated that further research is required concerning other variables including density of the straw at the point of measurement, and the effect of using a straw bale with a raised moisture level placed inside a construction’s walling system.

## V.5-Test Rig Resistance Meter study

The documentation provided with the Timbermaster resistance meter suggests a compensation factor for temperature (Equation II.5 p73) however, an experiment was performed on the test rig to verify the capability of the equation for the Balemaster and Timbermaster both with and without thermocouple measurements.

### V.5.1-Test Rig Resistance Meter study: Method

Equation II.5 was developed for timber therefore, the accuracy of the equation required confirmation when applied to straw. An empirical study was conducted in the Test Rig; the interstitial bale readings were taken (Figure V.28) from position five within each Modular-Block, a temperature reading was obtained from the point of measurement by use of the digital thermometer, and the resistance meter thermocouple was inserted into the wall; it is important to note however, that it is restricted to a depth of around 50mm and was therefore unable to acquire the temperature at the point of measurement. The diagram (Figure V.28) also shows the position of a relative humidity sensor which was utilised in later experiments.

One hour prior to the commencement of the study the Balemaster probe was inserted into the wall starting at position B1.5; this was done to ensure equilibration with the internal bale temperature. The Timbermaster was connected to the probe and a moisture content measurement recorded, the thermocouple was then plugged into the Timbermaster and the reading noted, the process was then repeated for the Balemaster taking note of the digital thermometer temperature and care was taken not to disturb the probe during the analysis. The measurement procedure was then repeated for each of the Blocks every hour for 20 hours.

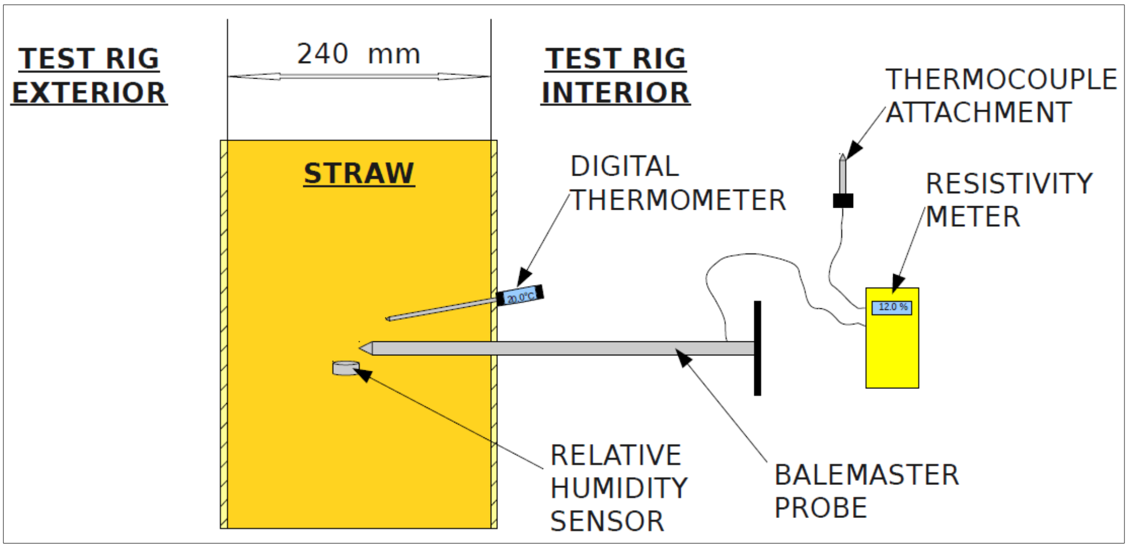


*Figure V.28: Test Rig monitoring diagram*

There was a duel aim to the experiment: firstly to compare the Balemaster and Timbermaster results, both with and without the thermocouple, and to assess the change in moisture content of the interstitial bale moisture level over a 24 hour period. The second aim was an exploratory study to assess moisture transfer within the construction's walls which highlighted a limitation: the Test Rig is subject to a dynamic environment with confounding variables such as temperatures.

## V.5.2-Test Rig Resistance Meter study: Results

In light of utilising different resistance meter combinations throughout the study an experiment was conducted on the Test Rig to compare the differences between the resistance meter's. The results (Figure V.29) of the resistance meters omitting the thermocouples have been corrected using the GM equation (Equation II.5 p73) for straw, plotting moisture content (y-axis) against the digital thermometer temperature (x-axis).

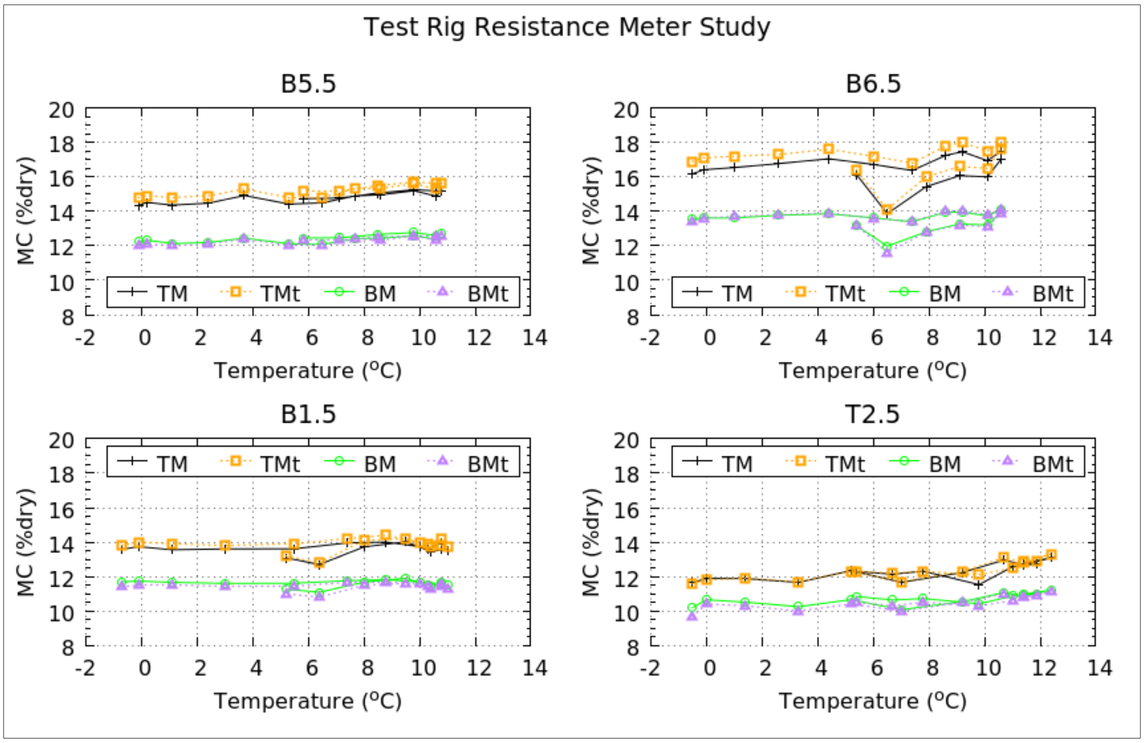


*Figure V.29: Raw data from resistance meter study with probe attachment*

The moisture levels results recorded during the experiment for T1.5 and B6.5 offer the minimum and maximum recorded moisture levels respectfully. The results as demonstrated in Section V.4 of this chapter show that the lower module-blocks have a higher moisture content than the upper blocks, as confirmed by Figures V.22 and V.23 (p154).

From Figure V.29 it can be noted that the moisture content increases during the measurement phase; the slight increase could be a result of an increase availability of moisture to the straw as the temperature increases at the external straw/render interface. The temperature increase drives humid air further into the bale, which then condenses at the cooler interstitial section; below the dew point temperature. This may be due to a product of: inaccurate conversion by the GM equation (Equation II.5), an unidentified variable, the observation of moisture transfer through the bale, or a combination of these.

Another observation includes the switch from heating to cooling of the straw and the effect it has on the moisture content reading. The results indicate the development of a cyclic pattern or hysteresis; the straw cools at a lower moisture content and does not retrace the original moisture content path. This evidence suggested that further work may be required in a laboratory environment investigating the cyclic pattern together with a repeat investigation conducted on the Test Rig at higher temperatures. The study also casts doubt on the ability for the GM equation to accurately correct the raw data; the graph appears to demonstrate the straw gaining moisture, albeit very slightly, as the temperature increases. The difference in readings between the Balemaster and Timbermaster is also apparent.

## V.6-Straw and Degradation

In quantifying the risk to straw posed by moisture and based on the findings of Block B5 a small scale investigation was undertaken to assess the affects of elevated levels of moisture on straw.

### V.6.1-Straw and degradation: Method

The investigation consisted of two experiments, one subjected a sample of straw to a relative humidity in excess of 90% at temperatures of 23°C, whilst the second submerged a straw stem in water for a fortnight at 20°C.

The aim of the experiment was to compare the differences between straw affected by a continuous layer of water and one subjected to high humidity (Section II.1.1 p47). The investigation findings were required to instruct in the identification of different base types of degradation thus enabling the cause of deterioration of straw within a bale to be explained. A photographic record of condition was conducted in order to track different situations and devise explanations for potential outcomes.

### V.6.2-Straw and degradation: Results

In determining the risk posed to a straw bale construction the thesis initially examined the effects of a worst case scenario, straw subjected firstly to a significantly elevated humid environment and then to a continuous liquid phase. Figures V.30 to V.32 show the extent of decay and mycelium development from the first experiment, subjecting the straw sample to a relative humidity of 90% at 23°C, the selected straw stem showed development of spores photographed in Figure V.32.

*Figure V.30: Mould development on stem*

*Figure V.31: Mycelium development on stem*

*Figure V.32: Spore development*

*Figure V.33: Submerged straw*

Figure V.33 shows two stages and types of decay present in the submerged straw stem, the 50mm stem section immersed in water developed a black rot and gelatinous slime over the two week period whilst, the section protruding 5mm above the surface of the water developed a white mycellium growth. Both experiments demonstrated what is to be avoided during the life of a straw bale construction, high humidities and constant wetting of the straw.

This study does not encompass a total investigation into mould development and this initial research provided a base set of knowledge in order to describe the cause of deterioration dependant on a constant liquid phase or high relative humidity level. During the experiments another observation that is not mentioned in the covered literature was made, straw's external surface is hygroscopic containing pores that will pool liquid water in favourable conditions, but it also has a waxy coating that causes a hydrophobic effect as demonstrated in Figure V.34. A small amount of water dropped onto the stem will bead due to the polar nature of the water; this is how straw is thought of.

*Figure V.34: External surface of straw. Water bead: hydrophobic nature*

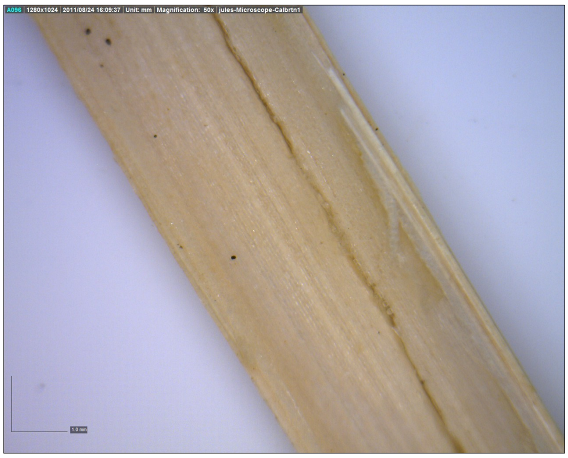


*Figure V.35: Internal surface of straw. Water absorbed: hydrophilic nature*

The internal surface (Figure V.35) however, is not commented on in literature; straw stems are hollow structures but do not exhibit the same properties as the external surface, a similar amount of water added to the internal will immediately be absorbed into the structure. As a crop the internal structure of the stem is protected however, once the stem is cut the external atmosphere will penetrate and due to the hydrophilic nature of the internal structure this will equilibrate with the humidity of the atmosphere differently to the external surface. There will also be a restriction to air flow in the hollow stem, which may cause a lag effect acting as a buffer for the previous level of humidity. The monitoring of moisture's interaction with straw and the understanding of the obtained readings is therefore of importance with relation to this effect. This challenges Summer's (2009) assumption that straw does not effectively wick water; this argument may hold for the external surface of the straw, but not for the internal.

## ***V.7-Density***

During the construction of the Test Rig it was observed that there were significant variances between the densities of not only each bale, but also at different points within a bale.

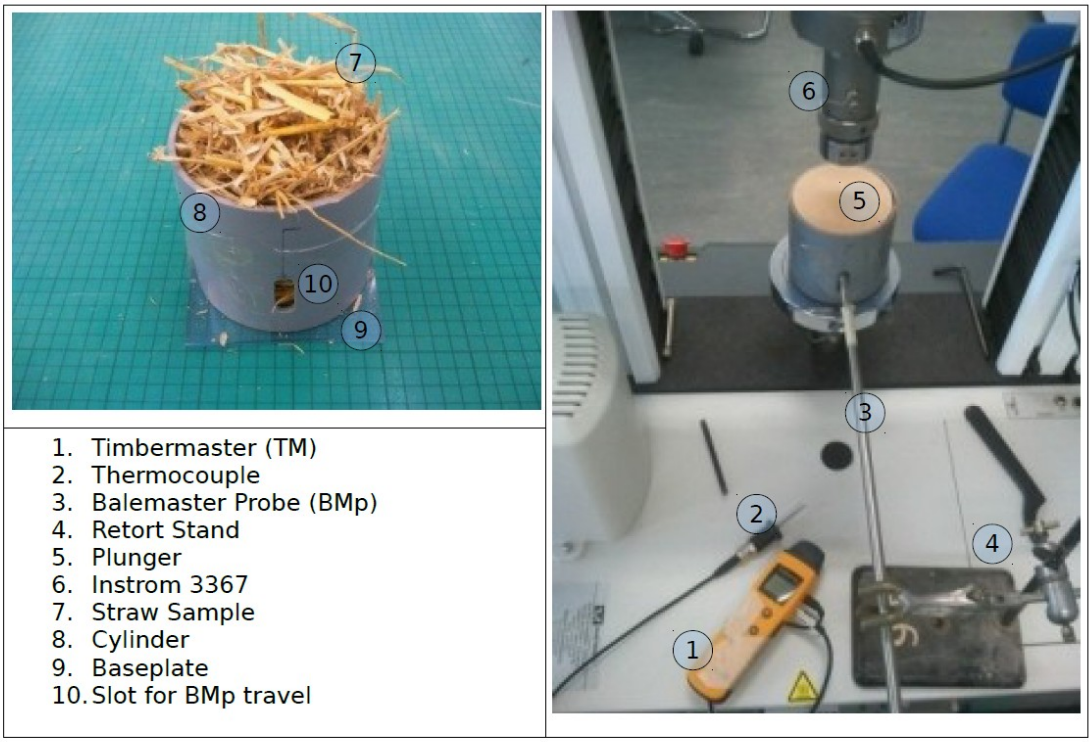
### V.7.1-Density: Method

The questions over the effect of density on the readings for the resistance meter with the Balemaster with probe attachment were highlighted in the early stages of the Test Rig monitoring (Section V.4.2 p147). Bales that were kept under the same storage conditions for several months, at the same temperatures, exhibited discrepancies in readings. One possible cause for the discrepancies was the difference in densities of each monitoring point and the subsequent pressure placed against the probe.

So far there has been little discussion concerning the topic of bale density relating to moisture measurement. Goodhew et al. (2004) suggested further work was needed to assess the effect of density on moisture and thermal performance whilst Carfrae (2011) offers the only published study. Other authors are concerned only with thermal conductivity relating to density (Stone 2003, Bronsema 2010).

The aim of this experiment was to demonstrate the effect of bale density on readings obtained with the Timbermaster and Balemaster probe attachment. The importance of this research is to contribute to an understanding of how resistance monitors work and to highlight any discrepancies between results. The objectives of this section were therefore to determine the significance of straw density relating to meter readings, demonstrate the effect of density when samples are subjected to extremes in moisture levels, and of obtaining readings at various densities with standardised straw samples.

GEsensing claims, of the Balemaster, that “*The instrument is calibrated for wheat straw and may be used to take relative measurements in other baled products*” (GE Measurement & Control 2014). However, as demonstrated by Carfrae (2011) there are certain unconsidered limitations regarding the meter's software and the adopted operation technique. It is worth noting that the exact density of a bale in a building may not be known at any one specific point, within a bale therefore, results of an investigative study into a real building conducted with a resistance meter and Balemaster probe attachment may generate uncertainty. At this point in the overall research agenda the use of the Balemaster had given way to the Timbermaster, as the Timbermaster represented a closer reading to dry density and therefore involved less complexity of written code within the computer software used to analyse the data.



1. Timbermaster (TM)
2. Thermocouple
3. Balemaster Probe (BMp)
4. Retort Stand
5. Plunger
6. Instrom 3367
7. Straw Sample
8. Cylinder
9. Baseplate
10. Slot for BMp travel

*Figure V.36: Compression tests of straw*

The design of the experiment consisted of an empirical study using a cylindrical plastic pipe of diameter 104mm and 90mm depth (internal dimensions) with a wooden plunger cut to provide a maximum clearance tolerance of 1mm, a base plate adhered to the end of the cylinder and a slot cut into the cylinder to allow the Balemaster probe unimpeded travel as the straw was compressed (Figure V.36). A small sample size was chosen in order to minimise the issue of void space and unequal loading as experienced in Carfrae's work. The reading would be taken from the centre of the sample to minimise edge effects and the straw would be laid carefully into the cylinder to simulate the section of a bale.

A sample of straw was stored under laboratory conditions (50%RH and 23°C) for several months before being loaded into the cylinder to a depth of 80mm and the mass obtained. The cylinder was then placed centrally under the compressive piston of a compaction machine (Instrom 3367), the Balemaster probe inserted into the cylinder and supported at the centre of balance by a retort stand to minimise any further loading effect, and finally the Instrom machine applied a vertical load in five millimetre increments up to a maximum of 40mm. Readings were normalised for 20°C with the attachment of the thermocouple; the laboratory was maintained at a constant 23°C.

By applying a load in the design of the experiment the difference in moisture content of the straw could be plotted against the effective load and the density of the straw. The experiment was also deigned to be repeatable. It was assumed that the sample, carefully packed into the cylinder, would replicate a bale, in addition it was assumed that the act of compression would not impact on the results. The limitations of the exercise were in dimensional constraints however, a larger sample may have been subject to uneven loading.

## V.7.2-Density: Results

The disparity in results observed during the preliminary Test Rig investigations (Figures V.22 and V.23 p154) indicate straw density as a potential factor in the promotion of inaccuracies within readings obtained by the resistance meter with Balemaster probe attachment. To a lesser degree, yet a similar context, the wood-block probes are not immune from the issue of density as the pressure exerted on the rods inserted into the wood-block tips caused variations within the results (Section IV.3.1 p114).

The study measured  a sample of straw of 50.4 grams (wet weight), previously stored in the laboratory at a stable 50%RH and 23°C for three months, then packed into the cylinder (Figure V.36) to undergo the first run of the inquiry. The straw was then saturated with water under the tap and left to drain in the laboratory (encapsulated by the cylinder) for a further seven days before the second run was undertaken. On inspection the straw had started to develop mould prior to the second run, and felt damp to touch.

Prior to, and after each run, the straw and cylinder were weighed to confirm the moisture content level had remained constant throughout the experiment; the gravimetric analysis was confirmed at the end of the experiment, as per the reservations concerning oven drying the straw prior to experimentation.

Figure V.37 illustrates the findings of both runs, the first run (detailed results shown in Figure X.3 p314) compressing the straw from 52 to 102 $kg/m^3_d$ (dry density), the meter readings altered by 0.9% from 6.8%MC however, it failed to reach the 7.9%MC reading obtained by gravimetric analysis. In contrast the second run shows moisture increasing by 63%, from an initial level of 32%MC, over an increasing density of 50 $kg/m^3_d$. It is important to note however, that the straw had succumb to slight mould growth between the two runs which may have affected both the gravimetric analysis results and the second run resistance meter moisture measurements.

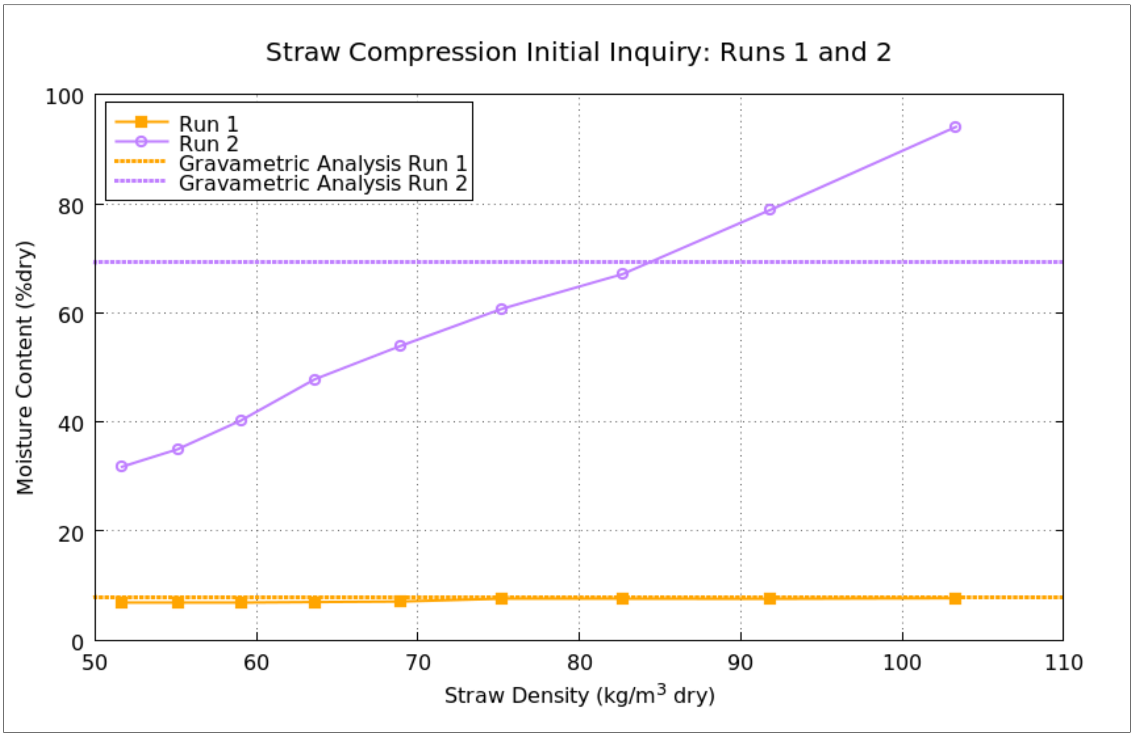


*Figure V.37: Comparative results*

The results of Run 1 show a spike in the moisture reading at 75 kg/m$^3{}_d$, one possible explanation was that a void in the straw collapsed giving an elevated reading (Figure X.3). This however would have been matched by a drop in the load applied, the load remained constant throughout the experiment and therefore the reason remains unexplained.

In observing the results presented in Figure V.37 a 'Fan' effect was proposed; low levels of straw moisture content generating lines of shallow gradient, increasing in gradient with increasing moisture content. Figure V.38 illustrates the 'fan' effect hypothesis in which it is proposed that the gradient will plateau at the point where the moisture content reaches a maximum level for the resistance of the straw; the intersect. From these initial results it was proposed that a model could be developed using the 'fan' effect however, further detailed investigation would therefore be required to address the inconsistencies and weaknesses identified during the Initial Inquiry.

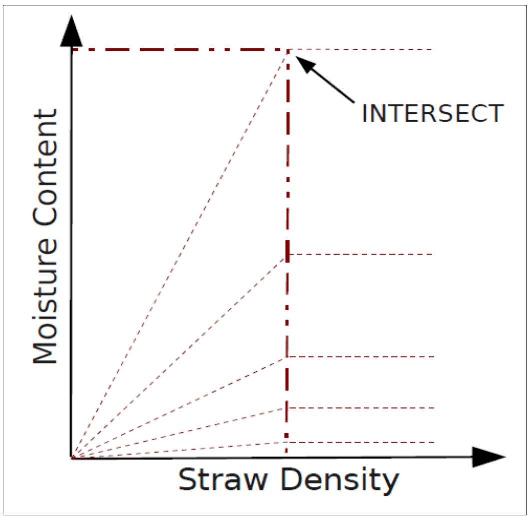


*Figure V.38: Fan Effect*

This part of the investigation represented an initial inquiry into an area as yet unexplored in previous literature and provides part of the thesis's Contribution to Knowledge. One important implication emerging from the inquiry was, that data is only comparable once the results have been calculated for the equivalent dry density, this then provides a standardisation of the results. The results of Run 2 suggest that free water may be forming as the moisture is compressed from the straw, thereby decreasing the resistivity illustrated by Straube's (King, 2006) moisture storage regime graph, Figure II.2 (p52).

In summary the experiment showed the importance of investigating density when relying on resistance meter readings to assess moisture levels and the requirement to develop a method of investigation to reduce uncertainty. The extremes of moisture content investigated during this experiment illustrated the effect of straw density and limit of the Balemaster compared to the Timbermaster. The moisture contents were out of range of the Balemaster and have therefore not been investigated further.

## V.8-Summary

The Preliminary Case Study (Section IV.1 p105) aimed to investigate the ability of the wood-block probes to reflect the moisture content of straw and to identify disparities between readings however, the study was inconclusive causing a change in the initial research direction of multiple case study investigation towards a test rig with greater freedom to perform experimentation.

The development of an alternative monitoring device measuring the dimensional variations of timber with respect to moisture content (Section V.2.2 p131) achieved initial success, yet was rejected on the grounds of cost for strain gauges and data logging software. A second monitoring device was developed, the compressed straw probe (Section V.3 p133), which provided the ability to record a change in mass of the straw and obtain a resistance meter reading. The prototype compressed straw probe met the criteria for a cheap probe that is robust, reliable, easy to install and accurate.

The results from the test rig demonstrated the Risk Assessment System (Figure III.3 p100) in the format of a Contour plot (Section V.4.2.1 p148) illustrating the 'Risk' posed to the construction from moisture. The results show that although the bales had been stored in the same environment the initial moisture consents varied. The effect of render application (Section V.4.2.2 p153) was also noted; raising the straw's moisture level together with the potential effect of direct sunlight on the render surface (Table V.1 p158) and the introduction of a bale that had suffered moisture damage into the construction (Section V.4.3 p159).

A comparison of resistance meters was conducted in Section V.5 (p165), due to the use in the test rig, suggesting potential inaccuracies of the temperature compensation equation supplied with the meters (Equation II.5 p73) and evidence of a cyclic pattern (Figure V.29 p165) as an effect of temperature variations within the bale. A preliminary investigation was conducted into the effect of density on resistance meter readings demonstrating that higher moisture contents of straw produce greater variations in readings as load is applied.

The overriding concern highlighted within the Preliminary Results was one of moisture's interaction with straw. This represents the fundamental basis on which further work must be conducted, with this knowledge the data provided by a monitoring device can be clearly interpreted and understood providing interested parties with confidence. It was identified in Section V.6 (Figures V.34 and V.35 p169) that a straw stem has both an internal hygroscopic surface and an external hydrophobic surface affecting the materials interaction with moisture, one side able to wick water, the other forcing it to bead. In the formation of a bale the straw may therefore promote unconventional behaviour when compared to mainstream construction materials.

Overall the Preliminary Results chapters (Parts I and II) established a basis for further research to be conducted, raising various questions concerning: the accuracy and interpretation of monitoring device data, the intensity by which readings should be conducted to obtain a categoric evaluation of a construction, and of the factors affecting a construction. The next chapter, Focussed Results, therefore begins by addressing the issue of density and in developing a compensation factor for the resistance meters, before explaining moisture transfer through a bale.

# Chapter VI-Focussed Results

## VI.1-Introduction

The results of the investigations in the Preliminary Investigations chapter (Part II) identified significant gaps in knowledge concerning monitoring of moisture and the association with risk. The main weaknesses exposed, encompass an inability to define an accurate moisture measurement in a construction when utilising resistance meters, due, in part to temperature (section V.5.2 p165) and density effects (section V.7.2 p174). The technique of moisture data acquisition utilising different monitoring methods (section V.4.2 p147) is also an area of concern.

The development of the compressed straw probe offers a way in which to obtain a known density and record the temperature of the straw at the point of measurement. The Focussed Results chapter details the adoption of different techniques used to acquire accurate moisture related data, the research of which highlights the need to explain moisture transfer through a straw bale.

## *VI.2-Focussed Density*

The focused density experiments represent a refinement of the Preliminary Investigation (Section V.7 p171) utilising two independent straw samples held at constant moisture contents. The Balemaster results were inconclusive at the lower moisture levels and have not been included in the study.

### VI.2.1-Focussed Density: Method

The preliminary investigation into density was limited by a lack of repeatability and the analysis of two extreme parameters from which the effect of density was demonstrated, but could not be quantified. The focussed method ensured that the straw was carefully placed into the cylinder thereby averting voids which may promote errors and was packed to a starting density of no less than 80 $kg/m^3_d$ (dry density) thereby conforming to construction densities of between 100-120$kg/m^3$ (Atkinson, 2010 p38). Another change encompassed multiple runs on the same sample to check for repeatability and consistency, together with the final change that set an upper moisture limit at which the straw could be held for a sustained period of time in laboratory conditions without promoting mould growth.

A modified restructuring of the method of data collection was therefore required; two independent samples of straw were prepared and placed in salt chambers for one month, the first chamber containing Magnesium Chloride (MgCl) and second Sodium Chloride (NaCl) giving atmospheres of approximatively 33% RH and 75% RH at 23°C respectfully. This would provide the straw samples with, when converted with EquLaw, a moisture content of around 7.1% and 16.8%. To ensure that the moisture remained the same during exposure to the laboratory environment, the loaded cylinder was weighed immediately prior and after each experiment run; each run was restricted to a maximum of 45 minutes to minimise interaction with the laboratory atmosphere.

## VI.2.2-Focussed Density - Results

The aim of the experiment was to obtain information concerning moisture levels posing no more than a 'Low Risk' to the straw whilst demonstrating the proposed 'fan' effect presented under the Preliminary Results; Figure V.37 (p175).

### *VI.2.2.1-MgCl (Magnesium Chloride)*

Figure VI.1 illustrates the results obtained during the compression of the straw sample for runs conducted on the 23rd, 24th and 29th of May 2012; dry density (x-axis) versus moisture content (y-axis). It can be seen that the straw 'stabilises' under repeated loading cycling, the Timbermaster with Balemaster Probe and thermocouple attachment returned a measure of 8.9%MC, at a density of 81 kg/m$^3$ on the 23rd, dropping to stabilise at around 7.3% by the fourth compression cycle (Run 1 on the 24th).

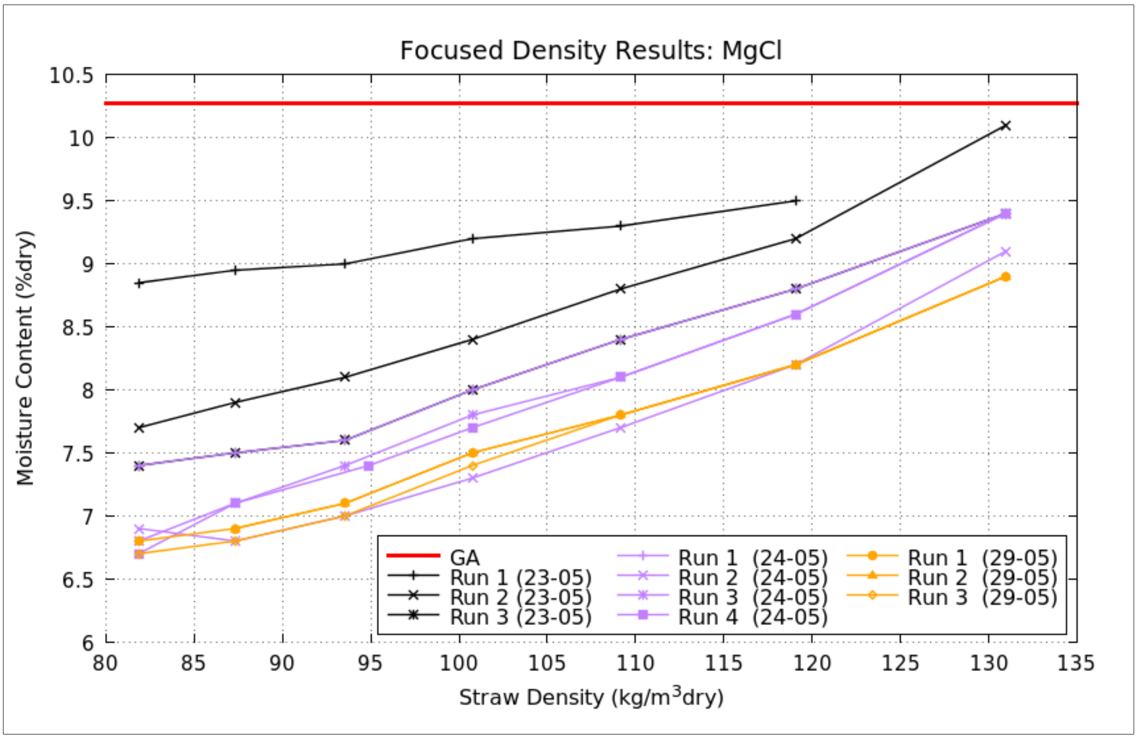


*Figure VI.1: Straw from MgCl environment*

A drop in moisture content of 0.5% (0.4 grams), due to moisture loss, was observed between the 24th and 29th and is reflected by the results. The gravimetric analysis returned a result of 10.3%MC for the straw sample, as shown in Figure VI.1, yet all the runs fail to reach this level, falling 1.3% short on the penultimate 'stabilised' readings at 131 $kg/m^3_d$.

### *VI.2.2.2-NaCl (Sodium Chloride)*

Figure VI.2 provides the results of the straw sample held in an atmosphere of 75%RH and 23°C, a similar pattern to the MgCl emerges showing the straw moisture content 'stabilising' during the initial compression runs. One unanticipated finding was demonstrated on the final run when a decision was made to compress the straw beyond 145$kg/m^3$; once the Balemaster probe had reached its maximum travel on the final compression cycle it was removed and reinserted back at the top of the slot. In order to check that that this extension of the run had not disturbed the experiment significantly the last two densities were repeated. The results, as shown by the gradients of the moisture content readings, demonstrated that densities of between 90 and 145 $kg/m^3_d$ produced a constant rate of increase however, as the density increases beyond 145$kg/m^3$ the rate decreases tending possibly towards a plateau as hypothesised in the Preliminary Results chapter (Figure V.38 p176).

One issue that emerged from the findings concerns the first run of the experiment, straw that had not undergone any compressive cycle returns an artificially high reading that is reduced by subsequent loading cycles until a 'stabilised' environment is met. This gives rise to questions of straw bale density in a real construction; how is an assessment of density to be made at a particular position in any randomly selected bale, secondly at what stage has the straw in a bale 'stabilised', and thirdly is the act of compressing a straw sample an accurate reflection of a bale, or does the act of compression with the Instrom alter readings significantly?

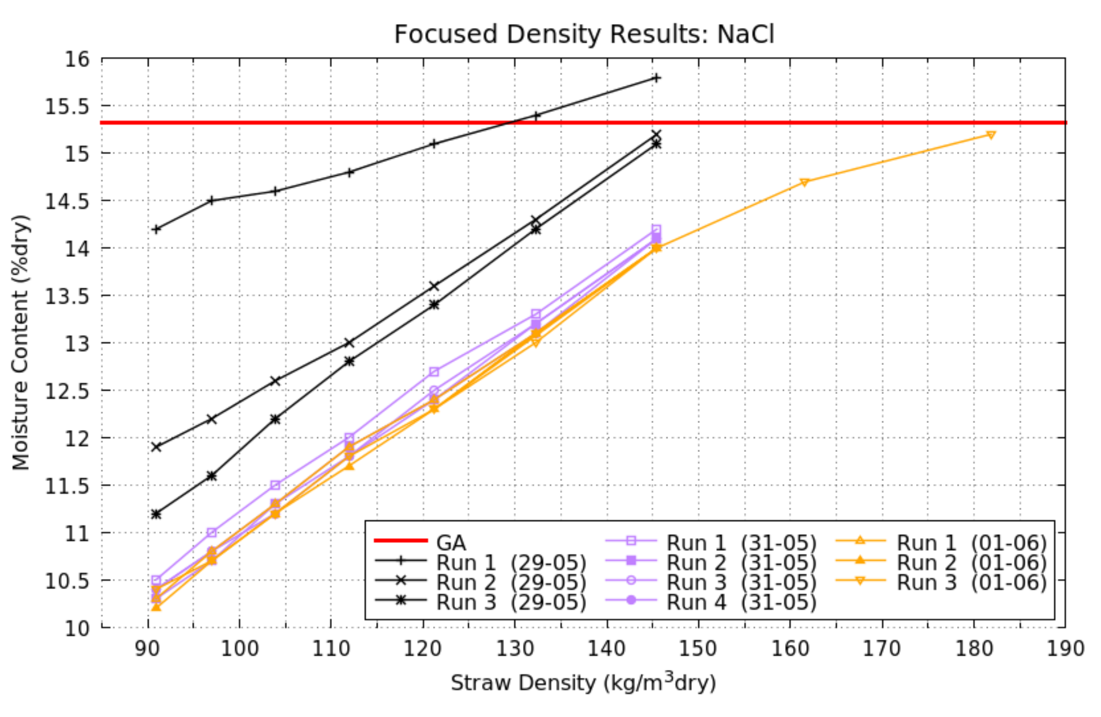


*Figure VI.2: Straw from NaCl environment*

From the variance in readings of these results a conclusion was drawn, that the direct use of a resistance meter with Balemaster probe attachment for the purposes of monitoring a construction can not generate the assurances required to confidently describe the risk posed to a straw bale construction from moisture. A reading of 13%MC from a resistance meter in an unknown bale density could be an under or over estimate of the true moisture value of the straw. If however, the straw could be standardised for density, as with the compressed straw probe, this confounding variable would be eliminated and the resistance meter would require further research as prescribed in the previous chapter (Section V.7 p171).

## ***VI.3-Focused Resistance Meter Study***

The limitations of the resistance meter with respect to temperature, as discovered during the Preliminary Investigation (Section V.5.2 p165), required a more systematic study to identify how different temperature scenarios affect the results for straw. A series of experiments were therefore conducted utilising the compressed straw probe as the measurement medium.

The compressed straw probe has the advantage of a known density of straw, the ability to gain a resistance meter reading, to observe temperature changes from the measuring point, and due to standardisation can be interchanged with real or laboratory environments.

The verification of: the GM equation (Equation II.5 p73), temperature calibration, ability for the Timbermaster to reflect straw's moisture content, and the conversion of a Balemaster reading to a dry basis, or equivalent Timbermaster results, is detrimental to the development of not only the compressed straw probe, but for the wood-block probes and surveys conducted using the Balemaster Probe.

Resistance meters offer a easy and robust method of obtaining an instantaneous moisture measurement however, as the Preliminary Test Rig resistance meter study (Section V.5 p163) indicated, the temperature calibration requires further verification together with clarification as to the conversion of a Balemaster to a Timbermaster reading. The Balemaster is not shipped with any warnings of error bounds and the literature provided does not highlight the potential need for temperature calibration.

### VI.3.1-Static temperature test

In order to assess the Timbermaster's ability to cope with variable temperature ranges an empirical experiment was devised. A pre-calibrated compressed straw probe was subjected to a constant temperature cocooned by an insulation blanket, whilst the thermocouple was placed in a water bath and the temperature varied. The moisture content was then recorded by the Timbermaster both with and without the thermocouple attached. The experiment consists of two tests holding the compressed straw probe at 4.0°C and then at 30°C both temperature extremes likely to occur in a real world environment.

The aim of the experiment was to demonstrate under extreme circumstances why the measurement of temperature must be obtained from the point of the resistance measurement and how effective the calibration equation is.

#### *VI.3.1.1-Static temperature test: Results*

Assessing the effect of varying the thermocouple temperature for a straw sample held at constant temperature gave rise to the results presented in Figure VI.3. Table VI.1 shows that the temperature increased slightly over the course of the experiment due to inadequate insulation provided by the blanket. However, this does not alter the results significantly; it can be seen that results with the thermocouple attachment give rise to an error as the conversion software receives an incorrect reading and adjusts it appropriately.

Applying the GM equation (Equation II.5 p73) to Test 1 readings (left hand side) taken without the thermocouple suggests that the straw had a moisture content of 16.5%; the gravimetric analysis of the compressed straw probe however, returns a moisture content of 21.0%.

Raising the temperature of the compressed straw probe to 30°C (Test 2, Table VI.2) gives a modified Timbermaster reading of 19.5% when Equation II.5 is applied. It can therefore be concluded that the Timbermaster in combination with the GM equation for temperature adjustment does not reflect the moisture content of the straw. The results with the thermocouple attached also show that the temperature at the point of measurement in a straw bale wall is critical in providing an accurate assessment of the straw and the potential for errors when adopting an incorrect method of measurement.

*Table VI.1: Static Temperature Test 1*

| **CSP Temp** | **TMt** | **TM** | **Thrmcpl Temp** |
|---|---|---|---|
| 3.3 | 15.6 | 14.8 | 14.0 |
| 4.1 | 14.9 | 14.8 | 20.0 |
| 5.4 | 13.0 | 14.9 | 33.7 |
| 6.0 | 14.7 | 15.0 | 21.9 |
| | | | |

*Table VI.2: Static Temperature Test 2*

| **CSP Temp** | **TMt** | **TM** | **Thrmcpl Temp** |
|---|---|---|---|
| 30.0 | 23.1 | 20.6 | 7.6 |
| 30.0 | 21.1 | 20.6 | 13.8 |
| 30.0 | 20.7 | 20.6 | 17.9 |
| 30.0 | 18.0 | 20.6 | 28.2 |
| 30.0 | 18.4 | 20.6 | 30.3 |

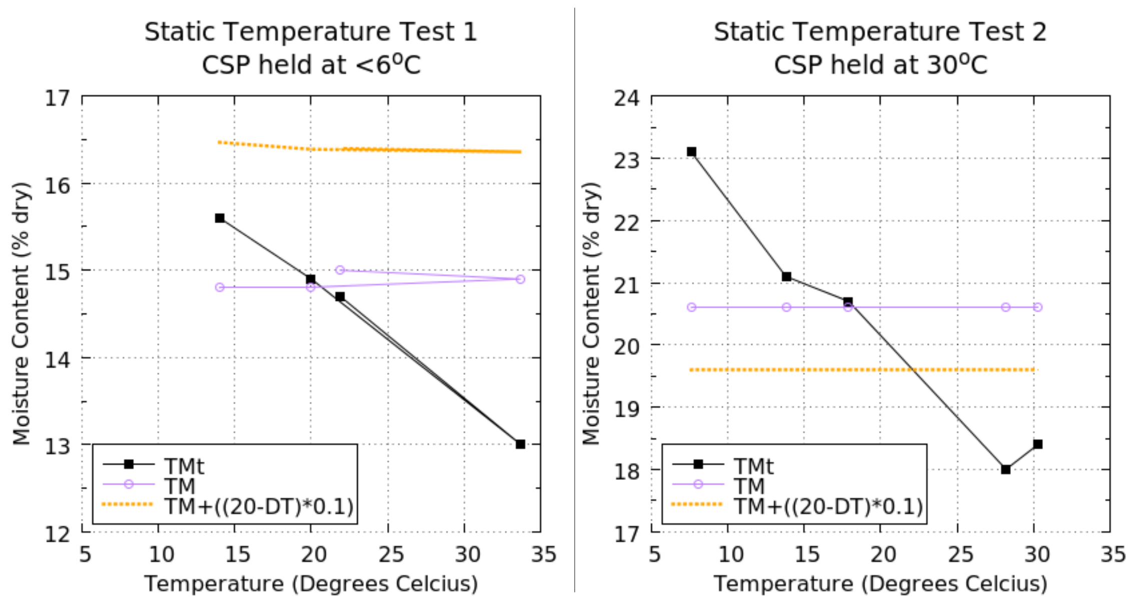


*Figure VI.3: Results of varying the thermocouple temperature*

This experiment was naturally biased, subjecting the Timbermaster to a false temperature reading thereby forcing inaccuracy however, this highlights the need to obtain the temperature at the point of measurement under observable extremes. The GM equation has, in the case of this experiment, been demonstrated to be ineffective as an accurate method of moisture measurement for straw.

## VI.3.2-Dynamic Temperature Test

Following on from the previous static temperature experiments, the affect of temperature on Timbermaster readings as a consequence of adjusting the straw temperature in the compressed straw probe was investigated. The Timbermaster should be capable of returning a moisture content result equilibrated for a certain temperature and within a defined degree of accuracy. The compressed straw probe in the case of this experiment is recognised as a sample of straw bound in a rigid hydrophobic container with a standardised density. Two sets of experiments were conducted analysing the effect of temperature cycling, and observing the hysteresis effect (Figure II.4 p59).

The first experiment used two non-perforated compressed straw probes (CSP1 and CSP2) placed within a layered insulation blanket that could be heated in an oven or cooled in a freezer and was designed to adjust the temperature of the compressed straw probe through conduction. As a result the straw underwent a rapid temperature change as the blanket was placed over the body and the subsequent experiment monitored the adjustment of the temperature, returning to the laboratory temperature in a controllable method by way of removing insulation layers. The mass of the probes was recorded after every experimental run of which at least three were conducted per test. The straw loaded into CSP1 was placed in an sodium chloride environment for one month giving a gravimetric analysis measurement of 14.2%MC, the density was calculated at 110kg/$m^3_d$.

The straw in CSP2 was restricted to the laboratory environment returning a gravimetric analysis of 11.0% and 90kg/$m^3_d$. The straw was restricted to a maximum of 15%MC as this is the limit agreed upon by the majority of literature at which straw will be free from decomposition, a concern at the time not to allow the possibility of mould development which may influence the results (section V.7.2 p174).

The second experiment placed CSP3, a perforated probe, into a blanket that was used to eliminate moisture transfer but provided minimal insulating capability. The compressed straw probe was constructed from straw held at laboratory conditions and attained a density of 120kg/$m^3{}_d$. This experiment controlled the temperature of the probe, eradicating rapid rates of adjustment as experienced in the previous test. Conducted during the winter months the probe would be cooled outdoors in temperatures reaching -5°C and heated gradually to temperatures of around 40°C in the vicinity of a wood-burning stove. Degrees of temperature between the two extremes were attained by placing the probe at incremental distances away from the heat source until stabilised.

In order to provide another comparative between the first experiment the moisture content of CSP3 was adjusted after each set of runs was completed. The initial moisture content was attained from insertion of the probe into the Test Rig, position B5.7, this reached a maximum of 19.9%MC. The probes was then subjected to a high moisture content for a restricted amount of time at temperatures of over 10°C. The probe was placed for 3½ minutes in a kitchen steamer, until the weight reached an equivalent of around 30%MC. The idea of the steamer was to provide a rapid change in moisture through vapour passage similar to, but quicker than the environmental chamber forcing moisture into the internal structure of the straw. The probe was then removed, returned to the blanket and placed at 10°C for 18 hours, this time period and temperature was chosen to allow the moisture time to distribute throughout the probe, at a maximum temperature to provide the vapour with energy to distribute but avoid mould development. The moisture was then dropped to a level deemed by the Risk Assessment System (Figure III.3 p100) to be at 'Low Risk' by leaving the probe exposed, cap and blanket removed, to a low relative humidity environment.

The experiments were designed to confirm the ability of the resistance meter to reflect an accurate assessment of the moisture level of the straw and to check the validity of the GM equation.

#### *VI.3.2.1-Dynamic Temperature Test: Results*

The results for the two dynamic temperature experiments are presented in Figure VI.4 and demonstrate the fan effect (Figure V.38 p176), Compressed straw probe 1 and 2 representing the first experiment restricted to an adsorption cycle at temperatures over 20°C and the desorption cycle at temperatures below. The temperature (x-axis) is plotted against moisture content (y-axis) providing the raw data, and the obtained gravimetric analysis result for each run is shown in the key; each test had at least three runs to check repeatability.

From the results of CSP3 the hysteresis effect is visible as the probe was subjected to cyclic temperatures, runs five and seven demonstrate an error band of around ±1%MC. Figure VI.4 demonstrates the potential inaccuracy of applying the GMSensing Equation (Equation II.5) to the illustrated data, as the equation disregards any increase in gradient over a range of moisture levels; the gradient of the lines increases with increasing moisture content. The evidence suggests that the GM equation is invalid in converting a resistance meter reading to an accurate reflection of the moisture content of the straw and therefore assessing the Risk posed by moisture.

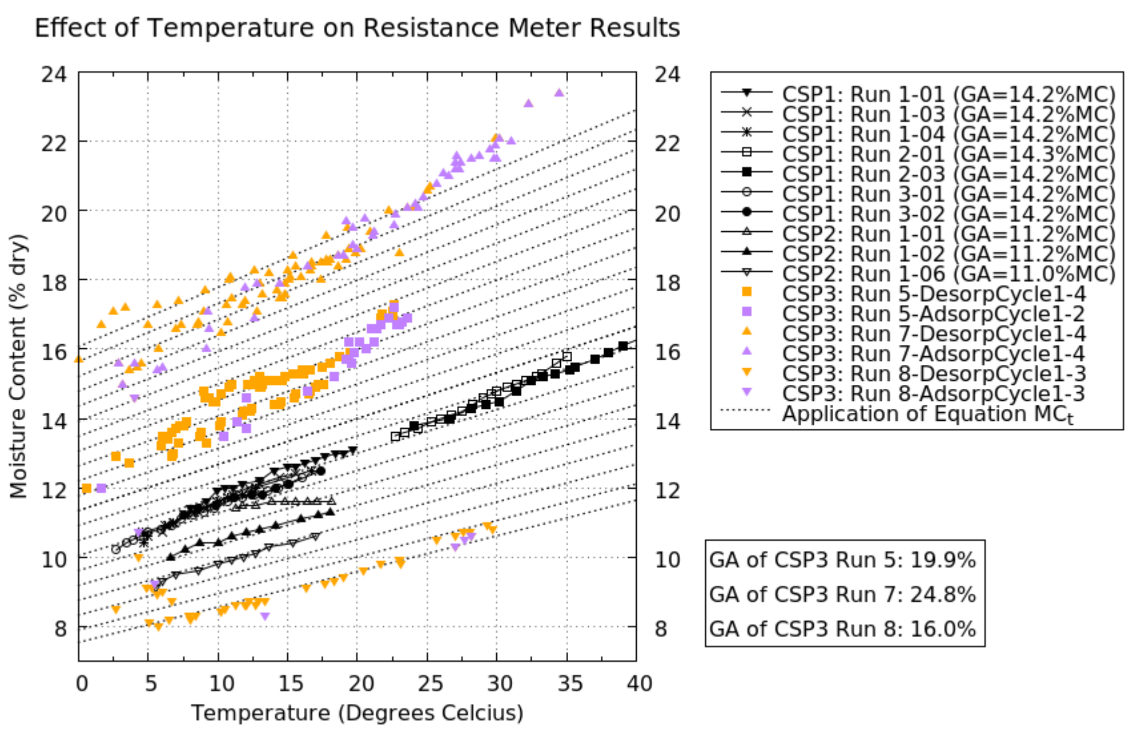


*Figure VI.4: Effect of Temperature on Timbermaster Results and lines of best fit*

Lines of 'best fit' were applied to the data in order to reflect the results for each of the runs (not shown). Utilising the line of 'best fit' and extrapolating the results provided by compressed straw probe 1, 2 and 3, it was possible to obtain a point of intersect, due to the increase in gradient of the lines as the moisture content increases over temperature, to produce a single equation (Equation VI.1). From this equation a quick reference graph for moisture levels between 7-23%MC (Figure VI.4) could be developed. The point of intercept (-125,-5.3) was selected to represent the point that produced the most accurate equation, with minimum of error, adjusting the resistance meter readings to a comparable and standardised 20°C. The intercept point is an approximation but alters the results insignificantly between a temperatures of 0 to 40°C (<0.1%MC).

$$y_t=\left(\left(\frac{(y-a)}{(x-b)}\right)*(t-b)\right)+a$$

$y_t = Timbermaster\ reading\ corrected\ for\ t$
$y = Timbermaster\ reading\ without\ thermocouple$
$x = Temperature\ at\ point\ of\ measurment$
$t = Desired\ calibration\ temperature$
$a = -5.3\ (y\ intercept)$
$b = -125\ (x\ intercept)$

*Equation VI.1: Equ$_t$: Calibration equation MC$_t$ for the Protimeter Timbermaster*

The equation corrects any reading taken with the Timbermaster combined with the temperature at the point of measurement standardised for any desired calibration temperature as read from the meter. However, there remains the disparity between the resistance meter result and the gravimetric analysis results. CSP1:Run 1 (Figure VI.4) should return 14.2%MC gravimetric analysis, yet the equation suggests 13.0%. CSP3:Run7 suggests a gravimetric analysis of 24.8%MC whereas Equ$_{20}$ (Equation VI.1) returns 19.4% on the adsorption cycle. The 20 in Equ$_{20}$ refers to the application of 20°C as the desired calibration temperature and can be changed dependant on the desired output temperature; the equation can  therefore be referred to as Equ$_t$.

There also exists a maximum moisture content range for which the equation will work, beyond the results shown for CSP3:Run7 the equation fails to describe the moisture level accurately. This does not however present a problem when assessing the Risk level proposed by the Risk Assessment Method (III.3); the level of the moisture content falls within the category of '*High Risk*' that the cause of the elevated moisture content needs to be identified and the problem resolved.

One hypotheses made in the early stages of the study suggested that moisture content internal to the surface of the straw could not be detected by the resistance meter which finds the path of least resistance across the surface of the straw, disregarding moisture held within the plants structure or within the spongelike structure of the hollow stems (Section V.6 p167). CSP3 Run 8 provides evidence to support this; results show a low resistance meter moisture reading of around 9.5%$MC_{20}$ , whilst the gravimetric analysis reading suggests 16%MC. This disparity in readings is an effect of the relatively rapid change, over a 24 hour time period, from a high to low moisture content done to avoid prolonged exposure to high levels of moisture. The disparity can be explained by regarding the external surface of the straw as drying more rapidly than the internal surface or internal structure of the straw stem thus the resistance meter reading is less than the gravimetric analysis result.

The consequence of this difference promotes the compressed straw probe as a monitoring device with multiple assessment methods. A results of 16%, gravimetric analysis, may provide the historical context to suggest that moisture was recently at a higher level opposed to the 9.5% reading displayed by the resistance meter that provides an instantaneous result based on current conditions within the atmosphere of the bale. This multiple method of assessing the straw is an important observation that require a model capable of evaluating and assessing the health of a construction using this information.

At this stage the relationship between the resistance meter reading, the gravimetric analysis reading and the density of the straw being measured remained unclear. The emergence of a complex pattern suggests the requirement of a more comprehensive study focussing on refining and combining the density and temperature experiments. Alone Equation VI.1 provides the Timbermaster results with greater credibility and accuracy dependant on interpretation of the data however, a conversion factor for the Balemaster was required, as documented earlier (Figure V.29 p165).

### VI.3.3-Balemaster to Timbermaster conversion

There exists a requirement to develop, as demonstrated by Figure V.29, a conversion factor between the Timbermaster and Balemaster meters. The aim of this investigation was to develop an equation capable of changing the Balemaster results to an equivalent Timbermaster value. Existing results were analysed from the laboratory experiments and the Test Rig investigations; Experiment 1 from the Dynamic Temperature Test (Section VI.3.2.1 p190) together with the averaged results from the Test Rig Module-block B1 (Section V.4.2 p147) and the individual records from B1.4. It is important to note that this study used a Balemaster purchased in the USA that measures moisture content in wet basis, in a conversation with Jim Carfrae it was established that the UK version provides data in dry basis.

### *VI.3.3.1-Balemaster to Timbermaster conversion - Results*

In order to enhance the capability of the Balemaster, and of the compressed straw probe, a further assessment was performed to convert Balemaster (USA version) data to an equivalent Timbermaster value. Using the data from Experiment 1 in the Dynamic Temperature Tests (Section VI.3.2.1 p190), data from Test Rig position B1.4, and the mean data from Test Rig B1, Equation VI.2 was produced to translate the Balemaster reading to a Timbermaster value.

$$y=0.68\mathrm{x}+1.92$$

$$y=Balemaster\,reading\,without\,thermocouple$$
$$x=Equivilent\,Timbermaster\,reading$$

*Equation VI.2: Calibration equation converting Balemaster to Timbermaster readings*

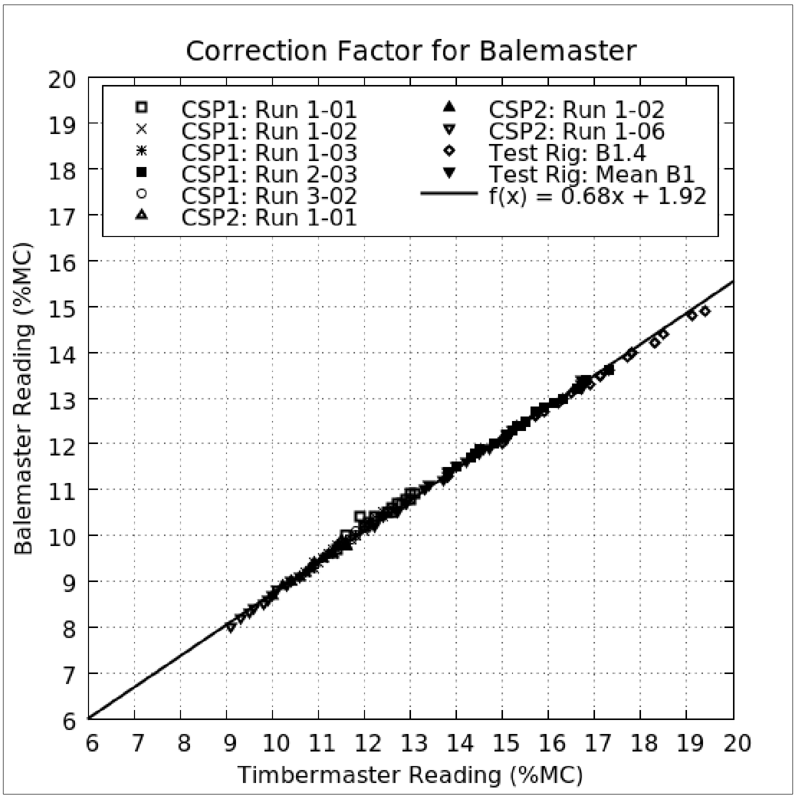


*Figure VI.5: Conversion of Balemaster to Timbermaster results*

Figure VI.5 demonstrates the effect of the equation plotting the Timbermaster results (x-axis) against the Balemaster results (y-axis) and applying the equation to the line f(x) which produces an error of less than ±0.15%MC.

## VI.3.4-Test Rig Resistance Meter Study Revaluation

Utilising the conversion equation for the Balemaster to Timbermaster (Equation VI.2), together with the recommendations from the Dynamic Temperature Test (section VI.3.2.1 p190), the Test Rig resistance meter study results (section V.5.2 p165) were re-evaluated comparing data for a real world study conducted with confounding variables.

### VI.3.4.1-Test Rig resistance meter Study Re-evaluated: Results

The development of an equation to confidently change the Balemaster data to Timbermaster values could consequently be applied to the Test Rig resistance meter Study (section V.5); Figure VI.6 shows the results of the four blocks highlighted in the earlier study compensated using equation's VI.1 (p192) and VI.2 (p194). Balemaster and Timbermaster readings obtained with the thermocouple are back-compensated using the GM Equation (Equation II.5 p73), prior to the application of Equation VI.1 (compensated for 20°C).

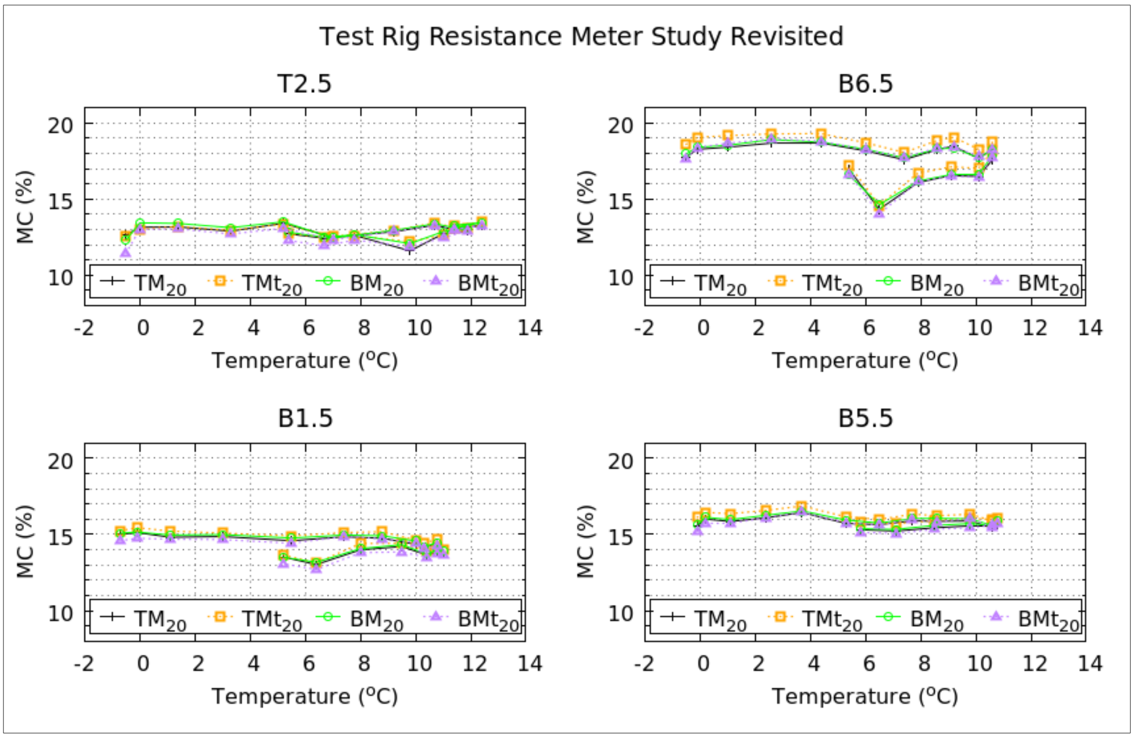


*Figure VI.6: Correction of Test Rig resistance meter Study*

The results show that by utilising equations VI.1 (p192) and VI.2 (p194) the readings can be translated with a ±0.3%MC degree of accuracy, the Timbermaster with thermocouple gaining around 0.5%MC over the range 13 to 18.5%MC above other results, as illustrated by T2.5 and B6.5 in Figure VI.6.

The hysteresis effect is also evident as the temperature reaches the maximum for the experiment, 11°C, illustrating the appearance of a cyclic system posing the question: if the temperature returned to the starting point of -1°C, without loss of humidity in the bale, would the straw in theory return to the original moisture content thus completing the cycle (Section VI.4 p202)?

## VI.3.5-Test Rig Resistance Meter Study 2

With the re-evaluation of the Test Rig data (Section VI.3.4) a second Test Rig study was conducted using the same method as discussed in section V.4.1 (p139) with the exception that only one position, B1.5, was monitored. It was reasoned that the continual removal and insertion of the Balemaster probe may disrupt, or influence the readings. The experiment was designed to assess the effect of a higher range of temperatures on the Test Rig results. A relative humidity sensor was also used and was placed at the point of measurement (Figure V.28 p164) to confirm the atmospheric bale conditions. One error made at the beginning of the experiment was not to stabilise the temperature of the Balemaster probe with the interstitial wall temperature prior to the experiment, this can clearly be seen in the results.

### *VI.3.5.1-Test Rig Resistance Meter Study 2: Results*

In order to obtain a comparative set of data, a second study of the Test Rig was conducted in the following summer based on the original Test Rig resistance meter study (Section V.5 p163). Figure VI.7 (left-hand graph) shows the results of the 10 hour study with the relative humidity converted using the Lawrence equation (Equation II.1 p61). The error in results with Equation VI.1 (p192) applied compared to an uncompensated reading is ±0.5%MC at temperatures above and below 20°C. The right-hand graph shows the results as temperature is substituted for time on the x-axis changing the shape of the curve as the optimum temperature is achieved.

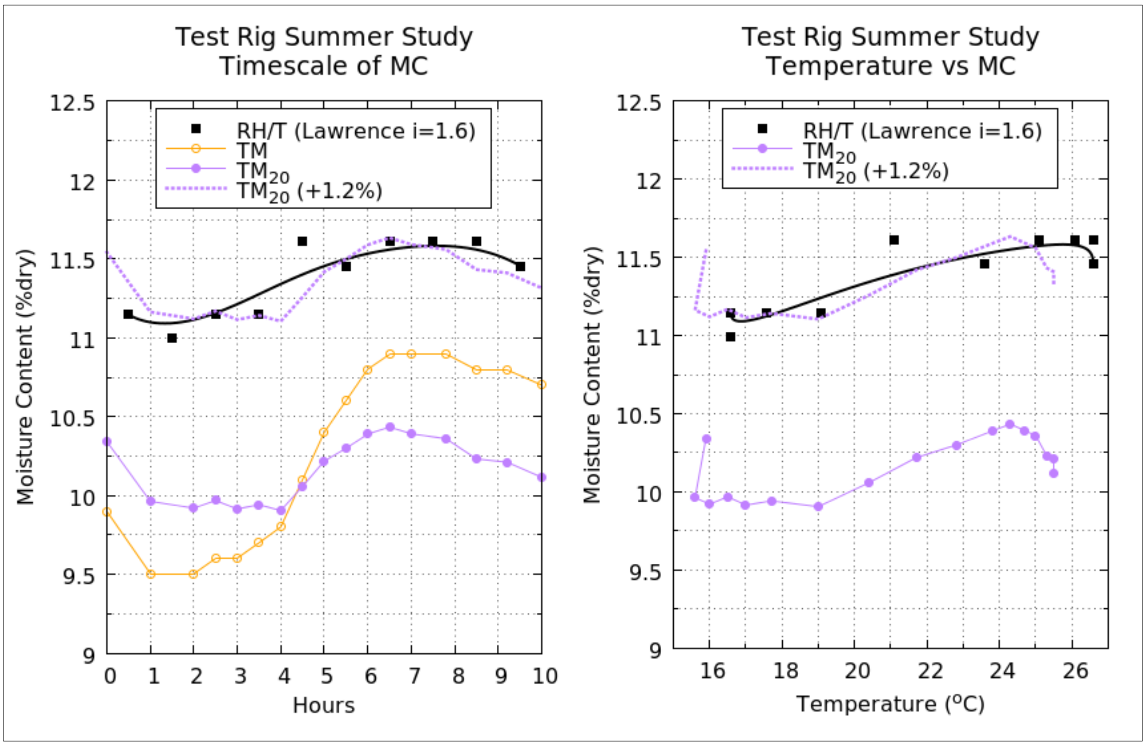


*Figure VI.7: Results of the intensive study*

The displayed relative humidity, obtained from the iButton sensor, gives the graph a jagged-stepping appearance due to the sampling accuracy (graduations of 0.6%RH/reading), the connecting line has therefore been replaced by a bezier curve to provide a smoother graduation of the data. It can be seen that the atmosphere becomes more humid as the temperature increases. The rise in relative humidity is small however, increasing from around 11.1% to 11.6%MC, this would potentially support reasoning to suggest that as the straw warms it releases moisture to the atmosphere thus increasing the atmospheric moisture level, or relative humidity as the temperature increases.

The path however, is not represented by the Timbermaster ($TM_{20}$) readings that track the converted relative humidity bezier curve, at a reduced moisture content of 1.2%. The graph shows that in both cases the moisture content starts to increase after four hours at a temperature of around 20°C, increasing by 0.5% before dropping whilst the temperature continues to increase by around 1-1.5°C. This suggests an alternative mechanism at work within the bale; the movement of warmer moisture laden air travelling through the bale, possibly from the warmer external straw/render wall surface subjected to solar gain. The warmer air makes contact with cooler straw as it progresses through the bale and the dew point is reached, thus depositing moisture onto the surface of the straw until equilibrium is reached however, further evidence was required to further the explanation.

From the study of direct sunlight on the render (Table V.1 p158) it was hypothesised that the sun directly affects module-block B1 from 07:00 to 11:00, between which time temperature increases but relative humidity and moisture content remain similarly static. After 11:00 the temperature of the measuring point (interstitial measurement) continues to rise together with the moisture content for a further 2.5 hours at which point the rate of the temperature increase slows and the moisture content drops. The question brought about by this experiment concerned the interaction of moisture with straw in the environment of a bale. One hypothesis is that transient moisture is passed through the bale from the external straw/render interface as direct sunlight provides energy and a potential for the warmer moisture laden air to move through the bale to the cooler less moist areas. The warm moist air meets the cooler straw and moisture condenses thus raising the moisture content of the straw to equilibrate to the atmosphere. This is then reversed when cooling; the warmer moist air is drawn back towards the cooling straw/render interface bringing with it the moisture that condensed onto the straw, hence 'transient moisture'.

It is worth noting that the monitoring equipment must be at the same temperature as the measurement medium, as demonstrated by the first result

(Figure VI.7); the moisture content of the straw is 0.33% higher in moisture and 0.4°C higher than the next reading, this is not echoed by the relative humidity/temperature sensor which was already equilibrated. The Balemaster probe being at a different temperature to the surrounding straw therefore influenced the result; this highlights an important monitoring technique and potential error in the readings.

The advanced study of the resistance meters gave rise to a number of observations and concerns with the evaluation of data provided by different monitoring techniques. The major interest involves the description of how moisture interacts with the straw in a bale and subsequently how this data can be evaluated.

## VI.4-Moisture Transfer

As the thesis investigation advanced it became clear that the interaction of moisture with the straw together with the description of a transfer rate was required in order to describe the relationship between the monitoring devices and techniques, the related moisture measurement, and for the subsequent development of a model to assess the Risk.

Many laboratory studies have utilised isothermal studies (Lawrence et al. 2009a, Carfrae et al. 2009b, Jolly 2000) to investigate and describe the interaction of moisture with straw. In general this involves the creation of a small sample (bundle) of straw placed in either an environmental chamber, or a Dewal jar. The sample is then subjected to a set relative humidity for a sustained period of time at a constant temperature, then assessed for the resultant moisture content.

Whilst Isothermal studies have their uses in identifying different regimes (King et al. 2006) and absolute levels of moisture content at certain relative humidity's (Lawrence et al. 2009a) the type of investigation is of restricted use when representing an atmosphere within a straw bale  as experienced in the field; an atmosphere in a bale is limited to a certain amount of moisture for a limited amount of time and the effect of temperature must be taken into account. Isothermal studies can therefore be misleading if relied upon as model in their own right. An isothermal study set in a laboratory environment will subject the sample to an atmosphere of a continuous unchanging humidity and temperature for extended periods of time; or a 'stable atmosphere' using static variables. The continued humidity provides an 'unabated' level of moisture 'surrounding' the straw sample, rather than a 'limited' level 'within' the sample as would be experienced in a field study situation.

The Isothermal study demonstrates the potential for straw's moisture content under a stable environment, with many of the other variables removed or controlled. One question raised by the Isothermal studies however, is that of cyclic analysis in an isolated environment. How would the straw in a bale of infinite dimensions, devoid of any external influence, react to it's own internal atmosphere (Figure VI.8)? If a section of that bale were taken, placed in an impermeable container and analysed then it could be quantified for moisture, carbon atoms, void space, lignin, etcetera. Assuming the only variable was temperature, how would the straw react? This would of course depend on the location (source) of the temperature change which would ordinarily come from the extremities of the bale or in this case of the sample.

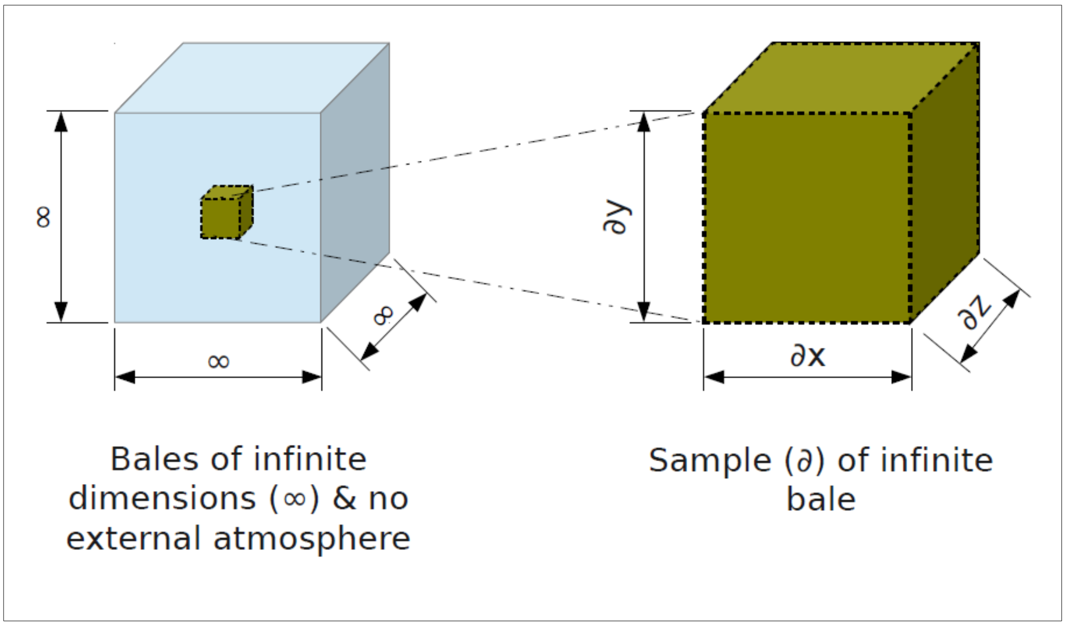


*Figure VI.8: Section of an infinite bale*

The question now would be: what happens to the moisture within the system if the sample was placed into a sealed container and either heated or cooled? The volume of the container will remain the same, the amount of straw will remain the same however, the relative humidity surrounding the straw will change together with the moisture content of the straw, if the moisture of the straw changes then so does the straw's density. Conventional building physics would suggest that during heating the straw should give up moisture into the atmosphere raising the relative humidity and as the straw cools water vapour should condense back onto the straw's surface as the dew point is reached (Figure I.8 p37).

The temperature however, is likely to drop from the extremities of the sample first, the moisture in the straw at the extremities will condense out at this position first leaving the centre of the bale at a warmer level and with less atmospheric water vapour, humidity, to affect the more centrally placed straw's moisture content.

On another heating cycle the moisture will be taken up by the atmosphere and distributed equally into the atmosphere of the bale however, the temperature of the straw within the centre of the bale will be at a lower temperature and therefore may provide a surface for moisture to condense. This will set up an oscillation between moisture levels if performed in a sealed environment however, in a straw bale construction, a dynamic environment, moisture will be added or removed continually from the system.

The measure of humidity relating to the moisture content of straw could therefore be somewhat misleading as it is dependant on where the moisture is most likely to condense or vaporise from. Consequently, it may be more apt to refer to relative humidity as a 'potential' for influencing the level of moisture within a dynamic environment such as a straw bale construction. Developing this thought out of itself provides a question concerning transfer rate of moisture through a bale. Straw bales contain pockets of air and voids plus the stem of the straw is hollow posing the question concerning paths for moisture movement and areas of stagnation; how do the results of a monitoring device at a specified position in a bale differ from the results of another located 50, 100, 200mm's away? This question can then be expanded to encompass other monitoring methods and the ability of these to cope with a dynamic environment.

The questions raised by the experiments to this point of the thesis required further description of moisture's interaction within straw, together with, the transition through a straw bale. Further studies in the Laboratory and Test Rig were therefore required in order to gain an understanding of this interaction.

## VI.4.1-Laboratory Study: Method

A laboratory experiment (Figure VI.9) was devised to test the rate at which moisture would pass through a straw bale, a straw sample (100.56g at 10.6%MC) was packed into a rectangular plastic tubular section of air conduit (Containment Sleeve: 217x108x50mm) to an average density of 78kg/$m^3_d$ . Three relative humidity iButton sensors were placed in the sample, two 40mm from either end of the tube and the third located centrally. Care was taken to replicate the layering of the straw in a bale with the stems laid roughly longitudinally.

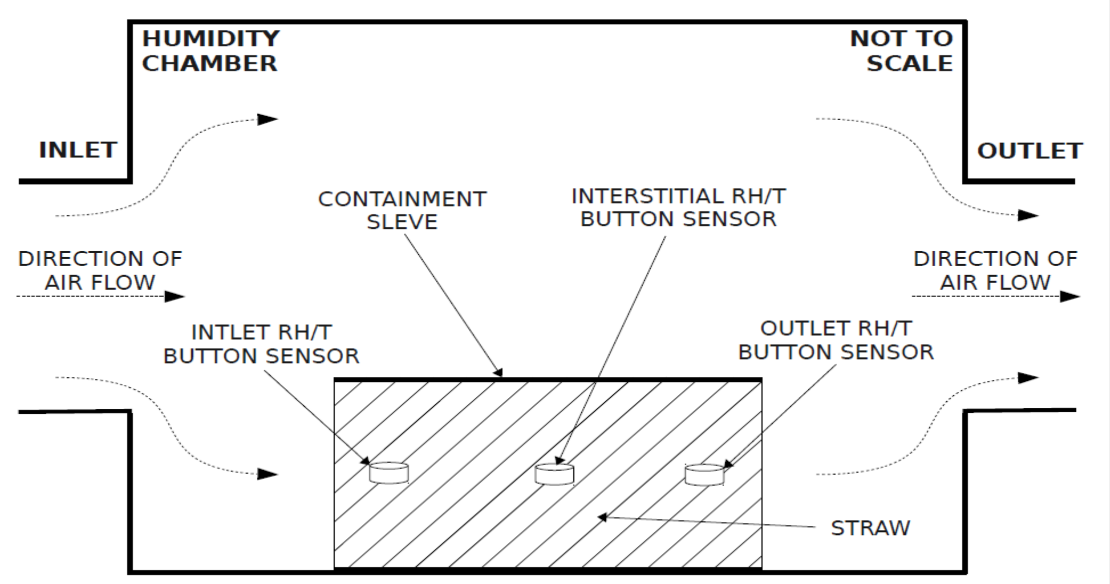


*Figure VI.9: Moisture transfer experiment in humidity chamber*

Due to an unforeseen circumstance that rendered the laboratory environmental chamber unrepairable a replacement chamber was designed using salt solutions to regulate the chamber humidity (Figure VI.10), consisting of a salt chamber a main humidity chamber and fan. The fan circulated the air across the salt solution at around >0.4m/s and into the environment chamber (Figure VI.11). Temperature was maintained by the laboratory at between 23°c and 26°c over the entirety of the experiment; a confounding variable.

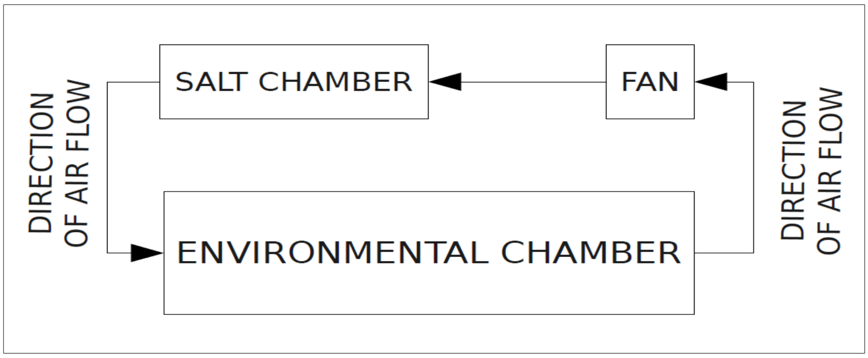


*Figure VI.10: Design of Environmental Chamber*

The straw was not rendered as the application would provide an additional variable and therefore greater complexity as the experiment was interested in humidity passage through a bale irrespective of protection; the experiment was shielded from any light source.

*Figure VI.11: Environmental Chamber with Containment Sleeve Sample*

The objective of the laboratory experiment was to demonstrate the pattern in the time lag as moisture is transmitted through the bale, not to measure moisture content, but to determine the moisture in the atmosphere that is likely to affect the straw. At the time of the experiment there had been no scientific data published concerning this topic.

The experiment was allowed to stabilise for a duration of 10 days in a NaCl regulated environment, generating a humidity of 72%RH, the salt solution was then exchanged for MgCl reducing the humidity of the chamber to below

40%RH. Once the mass of the sample had stabilised the MgCl was replaced with NaCl. The aim of the experiment being to isolate relative humidity as the variable and subject a mock bale to a dramatic and prolonged change, and to investigate the potential influence that relative humidity has on the moisture content of the straw irrespective of temperature and therefore dew point. By extending the cycles of a fluctuating relative humidity the experiment sought to compare the findings to a real wall. It was hypothesised that the experiment would demonstrate the effect of relative humidity on the straw's internal structure and external surfaces.

## VI.4.2-Laboratory Study: Results

Figure VI.12 shows the results of the  relative humidity/temperature sensors used to record the transition of atmospheric moisture within the straw sample enclosed by a containment sleeve (Figure VI.10), plotting time (x-axis) against the overall percentage decrease in relative humidity as the experiment is changed from an environment of 70%RH to 40% (left-hand y-axis). The right hand axis provides the overall gravimetric analysis of the straw sample as a whole.

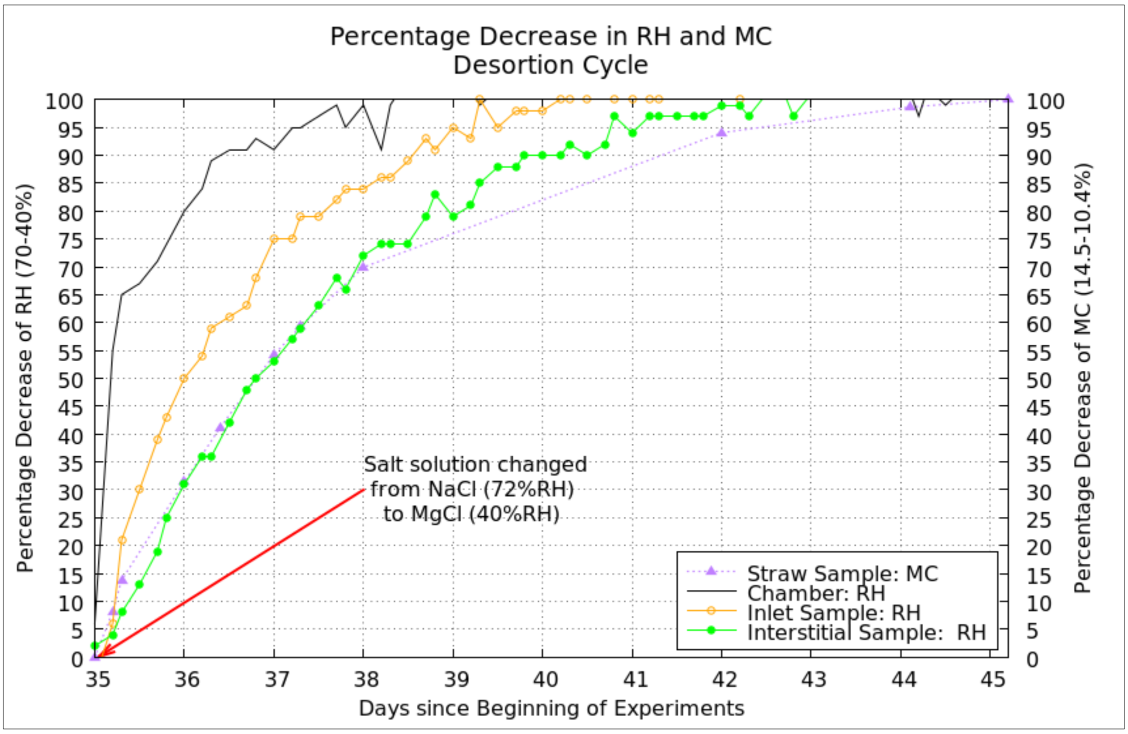


*Figure VI.12: Reduction of humidity within the sample*

Figure VI.12 demonstrates the effect of reducing the relative humidity of the chamber atmosphere from 70%RH to below 40%RH on the chamber sensor (Figure VI.10): inlet sensor (referring to the sensor located 40mm from the end of the sleeve closest to the inlet of the chamber), the interstitial sensor and the overall moisture content of the sample, which drops from 14.5%MC to 10.2% over the course of the experiment. After 24 hours the chamber humidity has been reduced by 80% compared to 50% for the inlet sensor, the interstitial relative humidity decreases less rapidly, 69% of the moisture still remaining in the atmosphere surrounding the sensor. The rate of vapour movement slows as the straw approaches equilibrium with the Chamber atmosphere, the interstitial reading taking around seven days to reach 100% vapour loss. The rate at which the straw equilibrates demonstrates the efficiency of the straw bale to retain it's own atmosphere.

It is worth noting that an NaCl generated environment was chosen as it produces a humidity within the bounds of safety for the straw, it was considered important not to allow any degradation to affect the straw and thereby introduce another variable. The spikes in the chamber sensor results are an effect of the chamber being opened in order that the sample's mass could be determined.

The MgCl salt solution was changed for NaCl on day 50 of the experiment as demonstrated by Figure VI.13 however, on two separate occasions the salt ran dry producing interesting results. On the introduction of the NaCl environment to the chamber the Inlet sample humidity rises rapidly gaining a 15% increase in vapour within three hours, the rate then slows, peaking at 21% before receding to an relative humidity of 15% as the salt solution runs dry. The interstitial relative humidity continues unabated however, suggesting that it is attempting to stabilise with the environment external to it thereby reducing the Inlet relative humidity which in turn reduces the Chamber relative humidity. The moisture content of the sample also stabilises at a 15% increase in overall moisture.

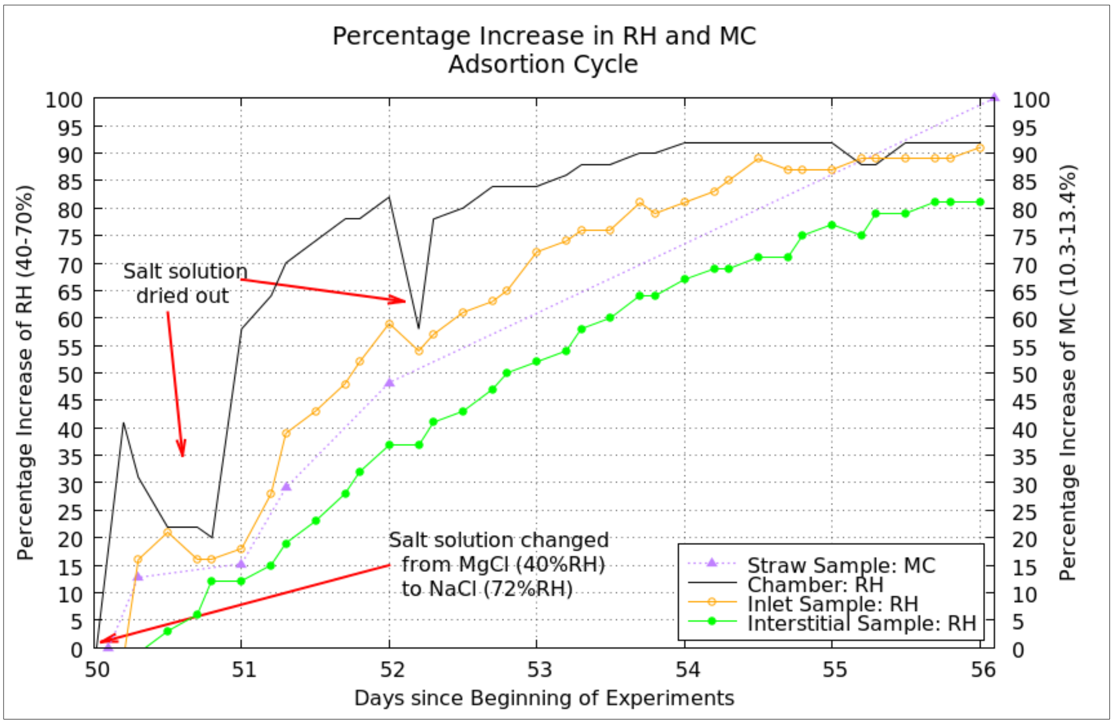


*Figure VI.13: Increase of humidity within the sample*

The experiment was ended on day 56 with the intention of analysing the information obtained in order to influence the method adopted for the test rig (section VI.4.4 p214). There are several points to note however, the results in the appendix (Figure X.16 p321) demonstrate a difference in the humidity rates between the Inlet and Outlet sample monitoring points. Although the sensors are both located 40mm from either end of the containment sleeve the Inlet sensor is affected more readily by the changing humidity. One explanation of this could be due to an air flow of 0.5m/s through the chamber; air is blown against the inlet side of the sample but extracted from the outlet side. Alternatively it could be caused by differences in straw density, greater leakage paths between the straw stems, or both in combination.

In summary a pattern has been established providing evidence of a time lag; vapour transfer is restricted by the internal structure of the bale, the chaotic union of straw retarding the permeability. The experiment indicates also a model of vapour passage within the bale, and the attempt of the straw to equilibrate with its surroundings distributing vapour evenly throughout the bale atmosphere. This would in theory disagree with Summers et al.'s (2003) assumption that moisture tends to migrate and condensate randomly however, the experiment does not take into account temperature as a variable. Figures VI.14 and VI.15 also provided evidence to suggest a difference in effects of moisture on the internal structure and external surface, the generation of a time lag and the change in moisture content of the sample obtained by gravimetric analysis.

The relevance of this experiment depends on the transfer of the knowledge gained in combination with a study of a real world environment with dynamic and oscillating environments and multiple confounding variables. The laboratory experiment exposed one sample to one run at one temperature, over an extended period of time, although the design of the experiment was intentionally designed to observe moisture transfer a comparison was also required with a real world environment.

## VI.4.3-Test Rig study: Method

The results from the laboratory study (Section VI.4.2) entailed a study researching the effects of moisture transition within a straw sample however, the straw was subject to long periods of static humidities and temperatures which will not be present in a real world environment; a comparable study on the Test Rig was therefore initiated. Three iButton sensors were utilised, one placed within 10mm's of the external wall (access gained from the interior wall), the second was placed centrally and the third 10mm into the internal side of the wall (Figure VI.14).

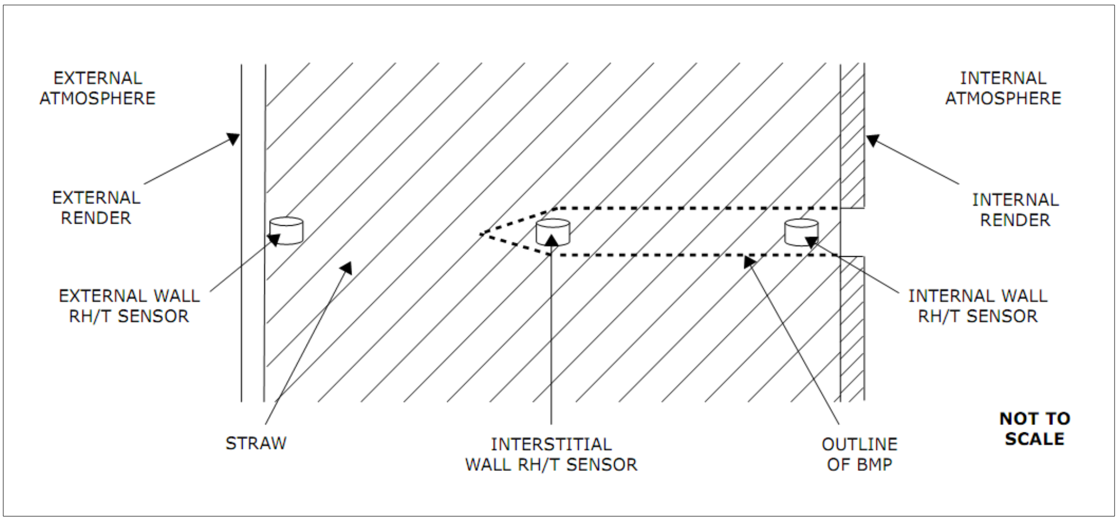


*Figure VI.14: B3.4 of Test Rig- Location of relative humidity/temperature Sensors*

The aim of this particular study was to assess moisture in a dynamic system focusing on positions B3.4 and T2.5 singled out due to the influence of the topography surrounding the section of wall and the difference in moisture content measurements taken between the two points.

B3.4 exhibited consistently higher values of moisture content than T2.5 with respect to the Timbermaster measurements. The study of moisture interaction based on evidence obtained from the laboratory results (Section VI.4.2) for the relative humidity of the atmosphere in a dynamic system was required therefore to verify transfer rates through the bale, between the straw and the atmosphere, and to assess the interaction of moisture with the external atmosphere through the medium of the protective render. The study was also designed to evaluate the relationship between the measuring devices and the straw or bale atmosphere, and to provide information to influence the development of a model.

## VI.4.4-Test Rig Study: B3.4: Results

To contribute to the understanding of moisture transfer within a bale, position B3.4 and T2.5 of the Test Rig were studied with the insertion of three iButton sensors located towards the exterior of the wall, interstitially, and at the interior side of the wall (Figure VI.14). The relative humidity of the internal and external atmospheres were also recorded. Note that the adoption of Equation VI.1 (p192) is shown as the type of Resistance Meter used followed by the subscript for the desired calibration temperature: $TM_{20}$ therefore refers to results measured using the Timbermaster meter standardised for 20°C.

Figure VI.15 shows the results of the study for B3.4, the rainfall appears as short-lived events on the back of light winds (lower graph) and is assumed therefore as inconsequential with respect to wind driven rain; the effect of the render, the overhanging roof and immediate topography providing protection. The sunlight at this point of the year is cast on the module for around 4-5 hours per day between 10:00 and 14:00 (Table V.1 p158), the temperature lag is demonstrated in Figure VI.15 (central graph) and the $MC_{20}$ drops by 0.6% over the 15 day course (upper graph).

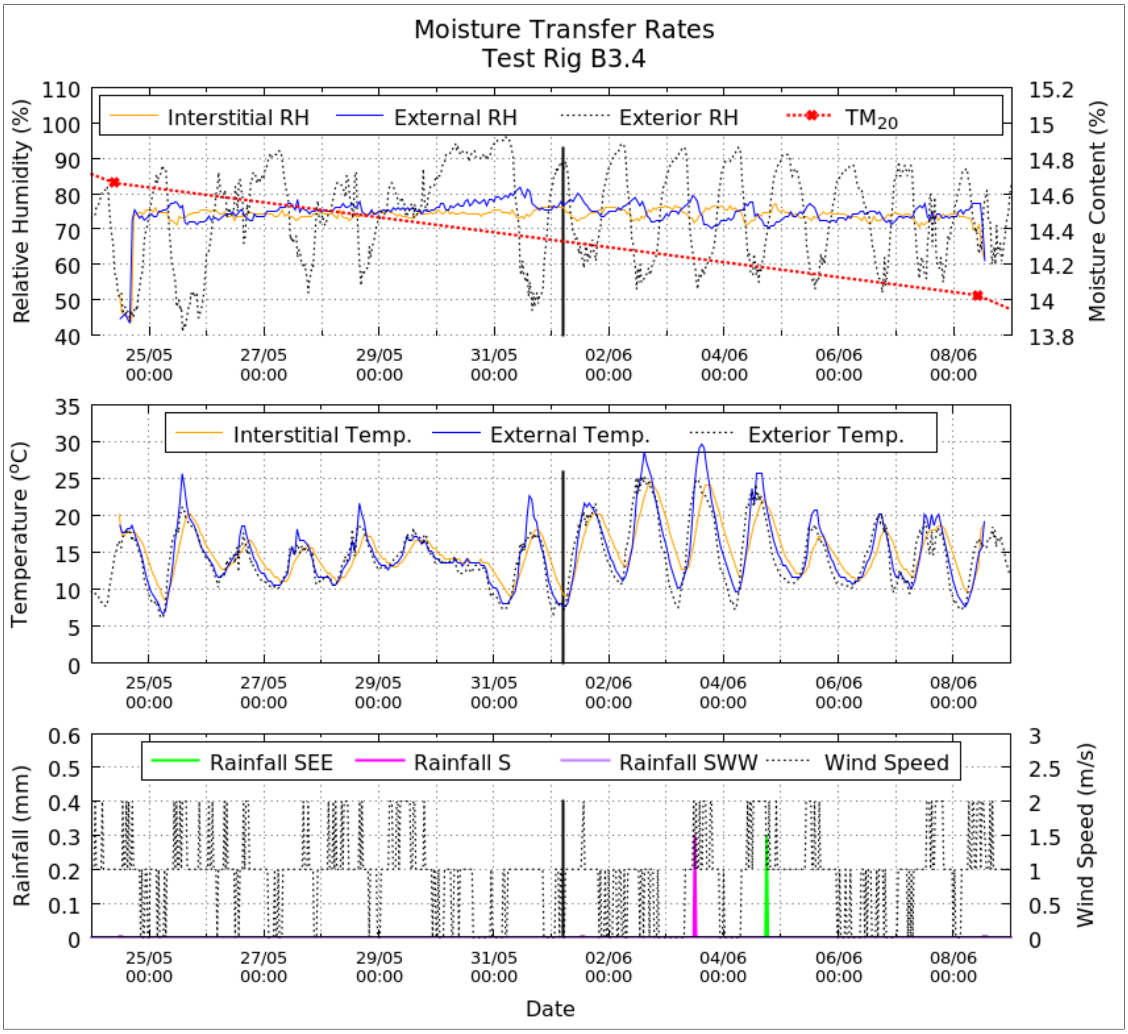


*Figure VI.15: Overall Moisture Transfer Rates of B3.4*

An unexpected outcome was provided by the External Wall relative humidity, fluctuating in opposition to the atmospheric relative humidity. The vertical black line has been placed on the graph (Figure VI.15) to illustrate the peak, or trough, in the readings highlighting the data recorded by the External Wall relative humidity/temperature sensor. It shows that, as the temperature of the External atmosphere and wall temperature increases the Interstitial Wall and External atmospheric relative humidity drops (see Figure VI.14 for sensor location details).

The external wall relative humidity increases however, in one case by up to a relative humidity of 9% over a 20°C range suggesting that the render is acting partially as a storage medium for the warming moisture laden atmospheric air. Figure VI.16 focuses on the data depicted by the black vertical line in Figure VI.15 detailing a period of 24 hours. During the time period between 06:00 and 11:00 the relative humidity of the External Wall atmosphere rises along with the temperature suggesting that there is an influx of moisture. At 11:00 the relative humidity begins to decrease, yet the temperature continues to increase peaking at 17:30; this pattern is repeated throughout the study.

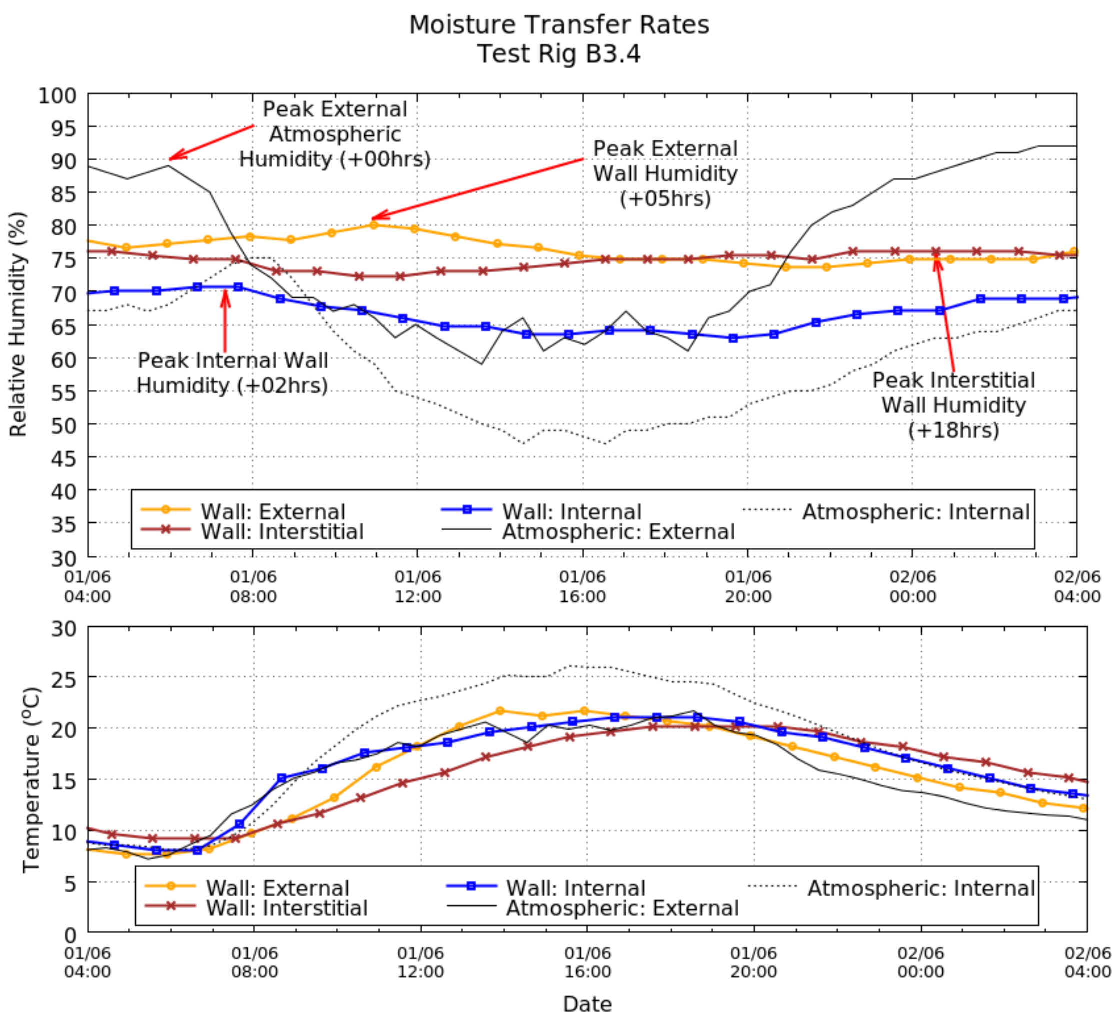


Figure VI.16: Focussed Comparison

It is perhaps more informative to remove the variable of temperature and view the wall in terms of absolute humidity, the measure of the absolute mass of moisture per meter cubed of air. Figure VI.17 demonstrated a distinct difference between the External Wall humidity and the Interstitial, External Atmosphere and the Internal Wall atmosphere, supporting the hypothesis that the render acts as a storage medium for moisture. The straw immediate to the external straw/render interface (Figure VI.16) is subject, by midday, to a higher proportion of moist air than the other measurements portray, indicating that moisture may be driven into the bale from the effectively wetted render as the sun comes into contact with the surface of the wall at around 10:00. The humidity subsides at 16:00 confirming that solar gain maybe influencing the moisture pattern when compared to the relationship between the internal atmosphere and the straw behind the internal straw/render interface.

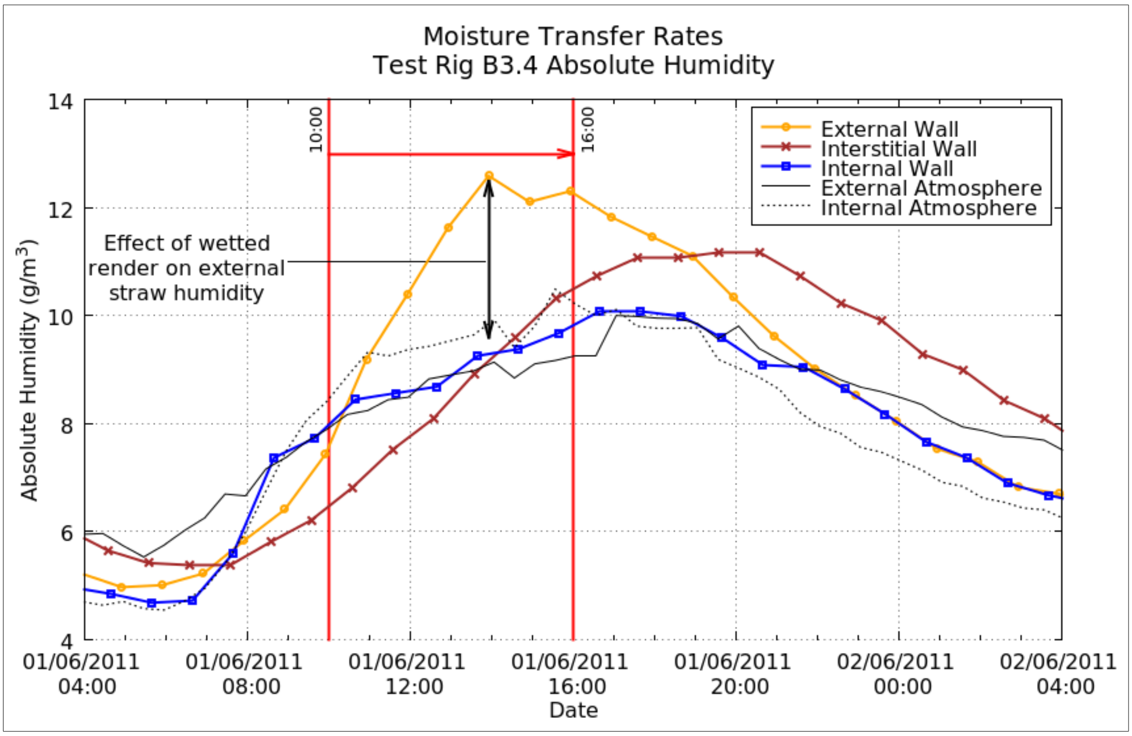


*Figure VI.17: Absolute Humidities of B3.4*

If the interaction was purely between the straw and the bale atmosphere without render then there would be little distinguishable difference in the External Atmosphere humidity and the External Wall humidity as demonstrated by the comparison of the Internal results and by the experimental results in section VI.4.2 (p208). However, it may be argued that the internal render is not subjected to an intense wetting drying regime as experienced by the external render from dew and rain, and therefore does not hold moisture to the same degree. The external straw/render interface is however subject to a greater availability of moisture and thus suggests that moisture has moved into the area from a greater source. This greater source may be the straw itself, as the straw warms it releases moisture into the atmosphere effectively raising the humidity and drying the straw, but it is impossible to discount the render effectively acting as a storage medium for moisture as the straw is likely to release moisture at a far slower rate, especially moisture that is contained by the internal cellular structure of the plant.

The absolute humidity for the External Wall straw/render interface (Figure VI.17) suggests that there is a source of moisture greater than the external atmosphere, a comparable may be drawn between the External and Internal atmosphere and, Internal and External wall results. Although the Internal render is only one layer thick and punctured by a hole to allow for insertion of the Balemaster probe, potentially affecting the results, the frequency of oscillation is similar in the Internal Wall as the Internal Atmosphere thus suggesting that there is no further source of moisture other than that provided by the atmosphere.

From these results it is possible to suggest that the external render is acting as a reservoir for moisture; moisture condenses from the high relative humidity of the warming morning atmosphere, at around 90%, onto the surface of the render as the atmospheric temperature rises exceeding the dew point of the cooler render; this continues until sunlight begins to heat the render surface at around 11:00. Figure VI.16 shows that by 12:00 the temperature of the Exterior Wall has increased beyond the temperature of the External Atmosphere. Beyond 11:00 there must now exist a driving process generated by the solar gain that lowers the wall's relative humidity but increases the absolute humidity until 15:00 by which time the sun is no longer heating the render surface, and the temperature of the module therefore decreases (Figures VI.16 and VI.17). The moisture is now passed back into the render from the warmer straw immediate to the cooling external render surface to vaporise or condense back into the cooling atmosphere.

*Figure VI.18: South facing elevation of Test Rig*

The effect of dew is one cause of External Wall moisture content, a secondary cause is from the protection offered to Module-Block B3 by the topography from wind driven rain. There is a comparative lack of air movement towards the base of the Test Rig at Module-Blocks B2 and B3 in contrast to T2 and T3. The area is sheltered (Figure VI.18) by a high hedge and log store (see also Figure V.13 p144), T2 and T3 exhibit less overall moisture content than the lower blocks and although the upper blocks receive less direct sunlight due to the overhanging roof section the movement of air is increased. The log store acts as a wind break for the lower blocks allowing the development of Sphagnum moss on the bricks piled to the corner, Sphagnum grows best in shaded high humid environments (Fletcher, 1991).

## VI.4.5-Test Rig Study: T2.5: Results

To provide a comparable to the study of Position B3.4 (Section VI.4.4), T2.5 was analysed (Figure VI.19); this module-block is less 'protected' by the topography and the results show a far closer relationship between the External wall, Internal wall and Interstitial relative humidities. The External wall relative humidity fluctuates by around ±2.2%RH whereas, B3.4 observed ±5%RH flux. T2.5's straw lost moisture at around 0.23%/day, B3.4 at around 0.04%/day over the periods analysed reflecting a gradual drop in relative humidity.

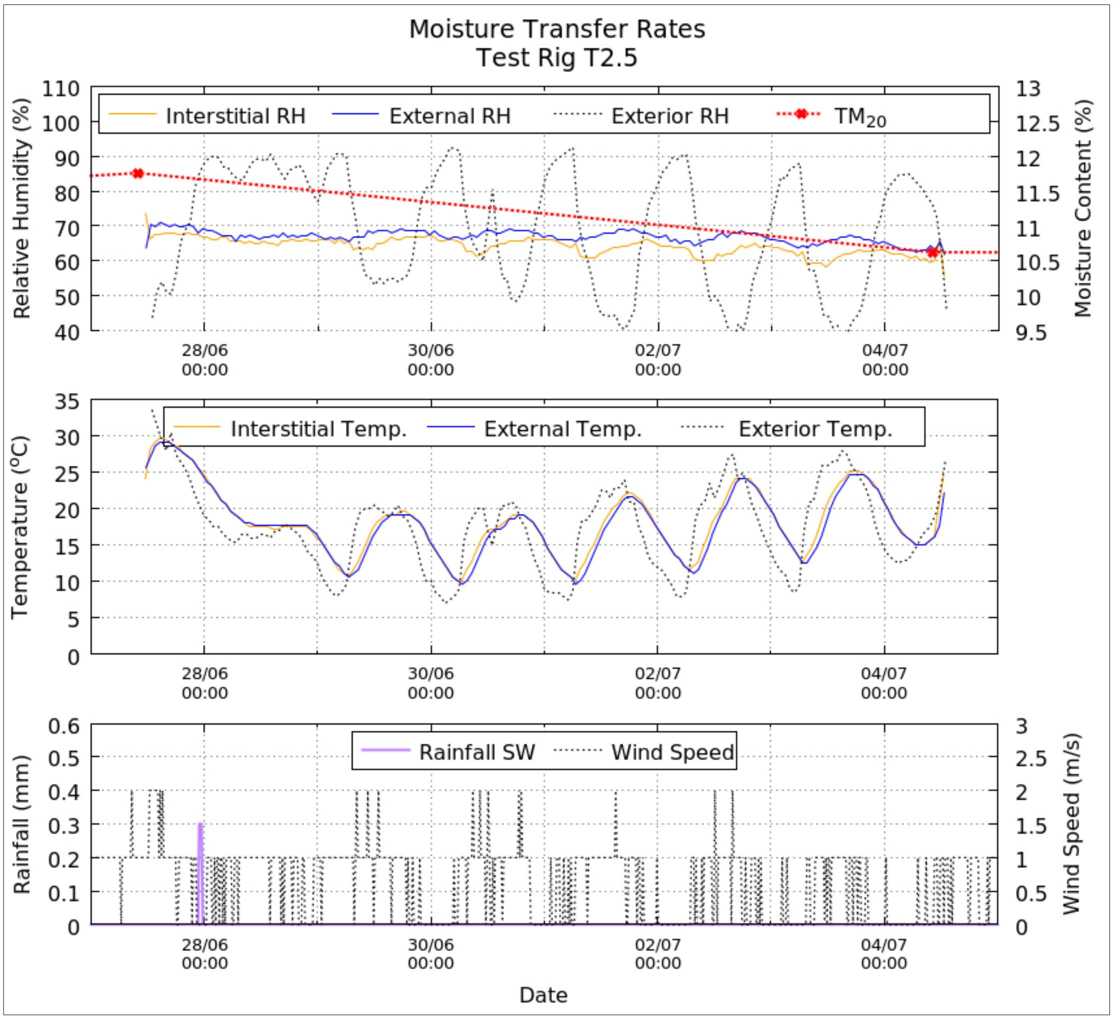


*Figure VI.19: Test Rig T2.5*

The analysis of the External straw/render interface relative humidity and Interstitial wall relative humidity shows a similar outcome to each other. The results are as expected with reference to basic description of this method of construction and of the analysis of relative humidity transition as detailed in the containment sleeve (section VI.4.2 p208) where the Interstitial relative humidity follows the External Wall relative humidity with a time lag. The analysis would suggest that the render is not acting a storage medium for moisture and must therefore be subjecting the straw immediate to it to less wetting, a greater drying regime, or combination of the two.

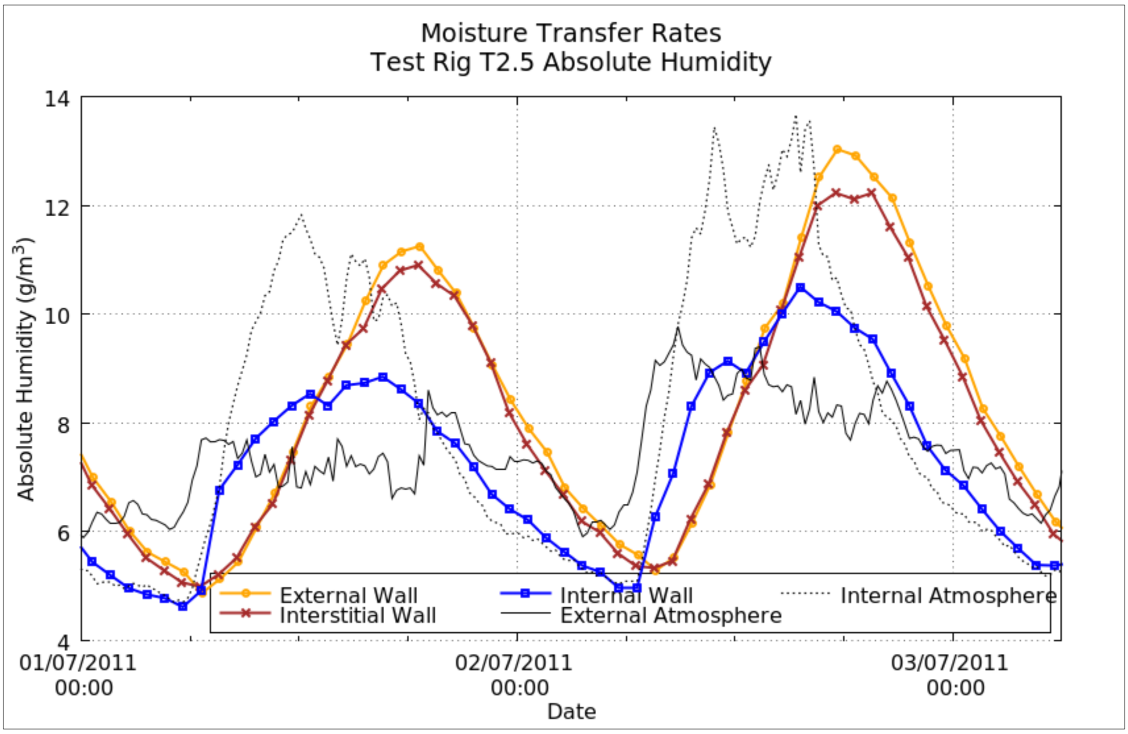


*Figure VI.20: T2.5 Absolute Humidity*

The analysis of the Absolute humidity (Figure VI.20) shows that the External Wall is not subject to any greater moisture source, supporting the case for the render as the cause of the increase in moisture content for the External Wall straw. One point to note is that the External Atmosphere is suppressed compared the Internal Atmosphere, this suggests that the Internal Atmosphere is not directly related to the External despite the unsealed nature of the construction and may be a reflection of the Internal Render moisture content.

#### *VI.4.5.1-Summary*

Lawrence's Equation (Equation II.1 p61), equating relative humidity to moisture content of straw, returns a similar analysis to the $TM_{20}$ results (Figures VI.21 and VI.22). The equation must however be used with care, in a laboratory environment relative humidity remains constant for a set temperature, yet applying the equation to a rapidly oscillating condition, as experienced by the Internal Wall in Figures VI.21 and VI.22, could provide an error in recordings. How should a scenario where the internal bale atmosphere relative humidity is affected by a rapidly changing environment be described in relationship to straw moisture content, if the internal cellular structure of the straw is not affected by the vapour?

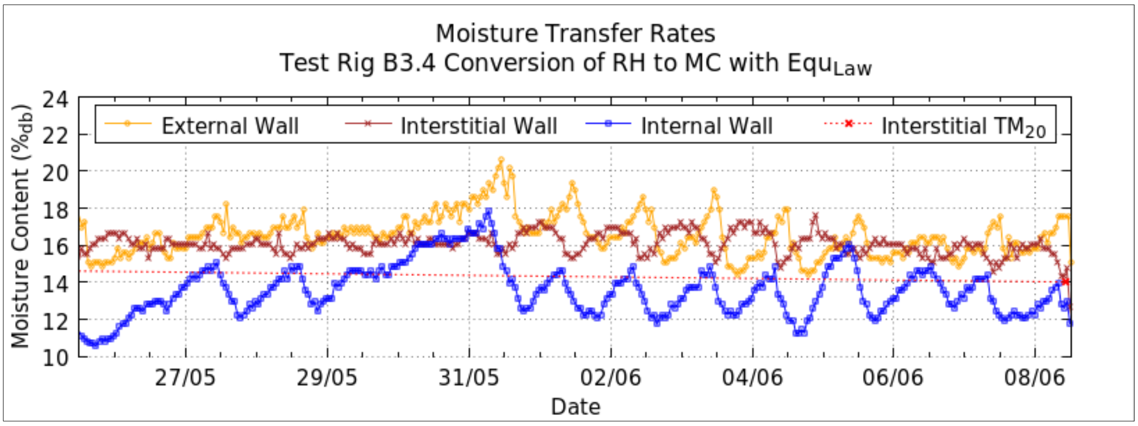


*Figure VI.21: B3.4 conversion of relative humidity to moisture content using EquLaw*

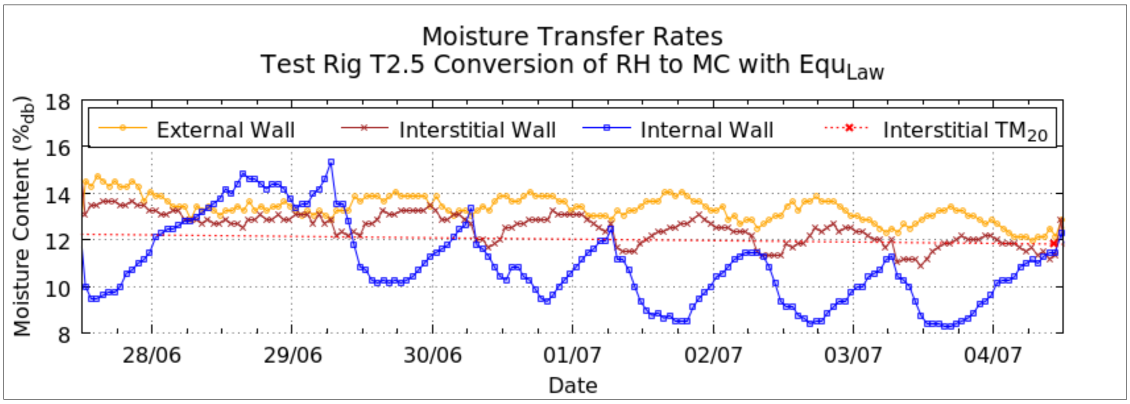


*Figure VI.22: T2.5 conversion of relative humidity to moisture content using EquLaw*

The rate at which moisture will adsorb, absorb and desorb into, onto or from straw will affect the Lawrence Equation and any other calculation if variables are inconsistent. Figure VI.23 details the entirety of the laboratory experiment from the Preliminary Experiments (Section IV.3 p114), showing the moisture content by mass to the above graph and the log of the moisture transfer rate (percentage moisture content per day) to the underneath. The moisture transfer data was initially multiplied by 1000 in order to fit it to the graphical log display.

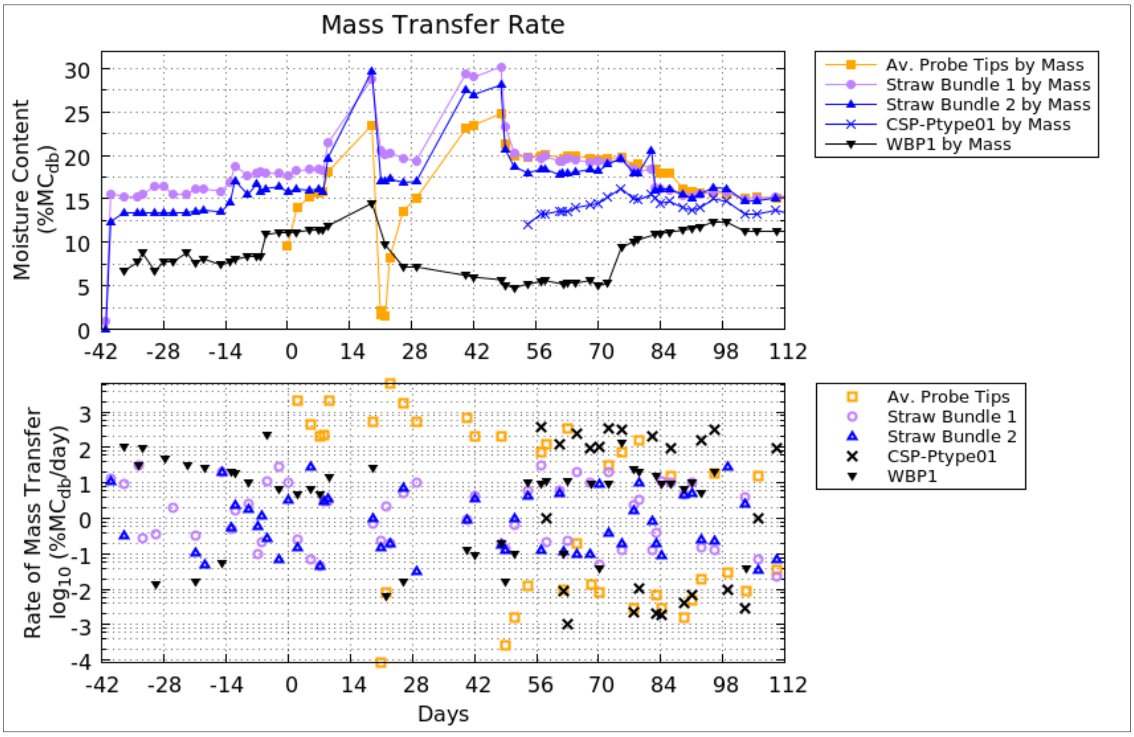


*Figure VI.23: Moisture Transfer of Preliminary Experiments*

The most apparent observations, ignoring the use of negative log, are on days -41 and +21, the Straw Bundles and Probe Tips are removed from the oven and placed directly into the environmental chamber, attaining high initial absorption and adsorption results, compared to a less dramatic increase in relative humidity from 80% to 85% (day 8). The straw samples on day -41 attain a reading of 4.15 equating to a 14.1%MC/day increase; utilising Equation VII.2 below.

The experiment officially started on day 0 however, checks and conditioning was carried out prior to this, hence the -42 days. A less incremental increase in relative humidity demonstrates a reaction, as shown on day -14, the straw samples attain 3.5 equivalent to 3.5%MC/day. The comparison between the wood-block probes and the compressed straw probe on day 72 suggest that the closer the moisture content of the material to the humidity affecting it, the less potential it has to be modified.

$$C_T = \frac{10^y}{1000}$$

$$\begin{aligned} C_T &= \ Moisture\,Transfered\left(Percentage\ MC/day\right) \\ y &= \ y - axis\,Reading \end{aligned}$$

*Equation VI.3: Moisture rate conversion factor*

In summary the transfer rates of moisture through a straw bale is a complex process involving not only the passage of moisture through the internal bale atmosphere but in the interaction between the straw and the atmosphere. The straw is affected by temperature and the location of the moisture is a significant part also, if the moisture is mainly affecting the surface of the straw then the rate at which it can be released into the atmosphere is rapid in comparison to the moisture held by the cellular structure. The rate at which moisture can be passed from the atmosphere to the straw is also apparent from the results, the potential of the atmosphere is important, a small disparity may not be enough to change the moisture content of the straw. This appears not to be the case in reverse, the desorption cycle.

The effect of render in an area of poor air circulation can have a potentially negative effect on the straw acting to retain moisture whilst monitoring devices must be able to interpret any effect. The device must be able to monitor the whole width of the bale in order to provide data to allow interested parties to make an informed assessment, or to inform a model capable of generating advice based on historic data and prediction.

## ***VI.4.6-Monitoring Site***

Due to the change in research direction from the study of multiple case studies defined in Section IV.1 (p105) the identity of the Preliminary Case Study at Loch Tay changed to become a monitoring site. A weather station (Watson W-8681: Appendix Figure XI.1 p323) was installed in early 2011 located 15 meters to the south-east of the house; the data logger was placed in the living room but did not record any data during the first summer and was replaced in the September. It should be stated that this is not a precision instrument and results shall be viewed as general data localised to the immediate area. The introduction of the weather station provided more data from which to make an informed decision regarding reasons for moisture content within the walls. The recorded data could then be plotted against the wood-block probe data in order to form a comparative study identifying areas that are influenced by certain weather patterns.

Prior to the analysis of results, as Carfrae et al. (2009b) and Wihan (2007) suggest, it was assumed that the south-western wall would exhibit a lower moisture reading than the north-western as it had been afforded extra protection in the form of timber cladding, although one drawback may have been that any moisture finding a path behind the cladding may remain trapped generating an area of high humidity. The sun may also affect the moisture content of the southern walls whilst the northern has far less solar gain; solar gain was not measured during this study however.

The establishment of the Monitoring Site offered the ability to assess a real world scenario comparing it against other data obtained by this thesis. Figure VI.24 shows the house outline and orientation with an overlay detailing the direction and strength of the prevailing wind (m/s) together with the amount of rain (mm/hr) set on a logarithmic scale. The time scale for data collection must be analysed with caution however, as it does not encompass the whole three year study as some data was lost and other weather situations may have occurred when monitoring was not undertaken.

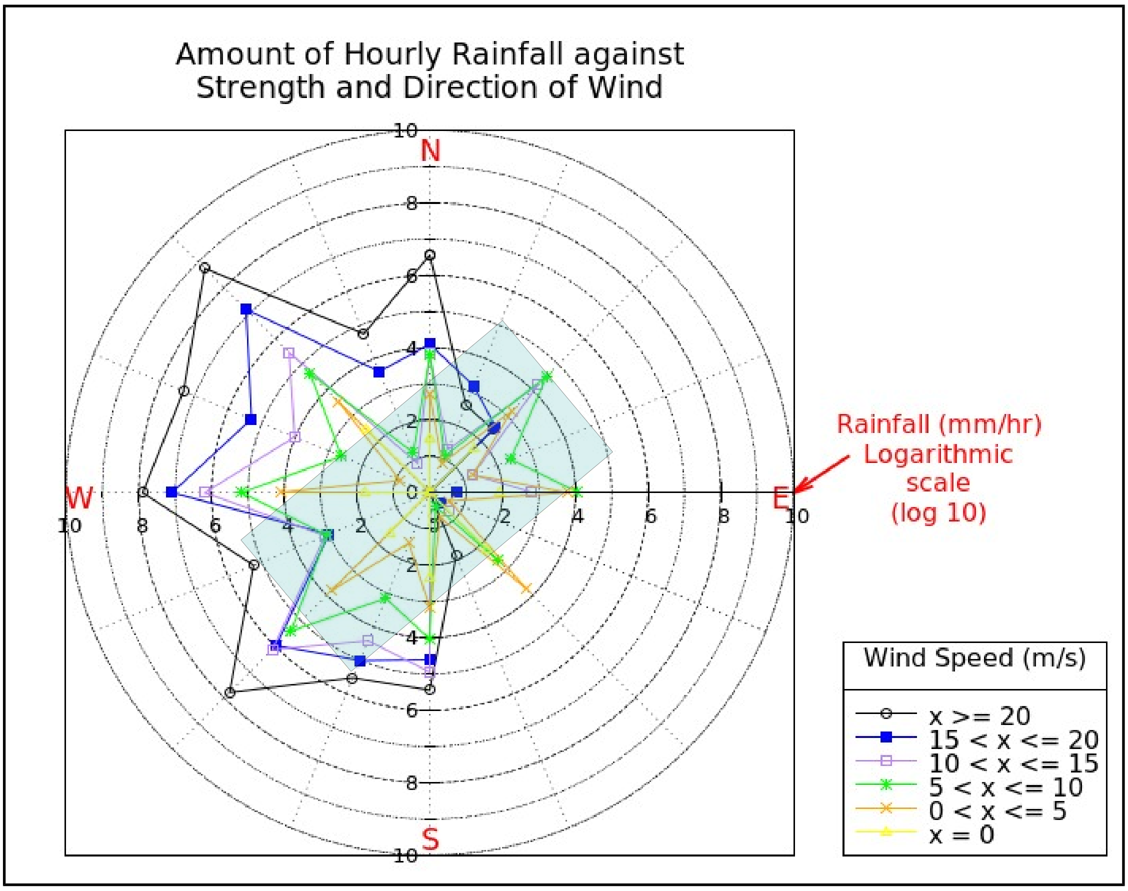


*Figure VI.24 Rain and wind in relation to the house*

The results that are available suggest that the majority of the rain comes from a westerly direction combined with strong winds, a total of 6277mm of rain was recorded falling at wind speeds of over 20m/s from the north-west opposed to a maximum wind speed of 5m/s depositing only 43mm of rain from the south-east, hence a conclusion may be drawn that the north-westerly and south-westerly façades would be the most susceptible to external moisture penetration from wind driven rain.

Figures VI.25 to VI.28 show the uncompensated results obtained by the Timbermaster; the data has been grouped together in relation to floor level and wall direction (Figure IV.4 p109), plotting date (x-axis) against moisture content (y-axis) with the addition of the 15%MC safety factor margin and a Bezier algorithm highlighting the trend of the data. Analysing the results it is of interest to note the fluctuation in results, peaking during the summer months and descending into a trough in January/February, this may be as a product of temperature on the analysis of the results as discussed in Section VI.3.2.1 (p190) as the moisture content was expected to peak during the winter months due to the wetter weather patterns. It is possible that the comparative warmth of the house offset against the temperature of the wood-block at the point of measurement within the wall has generated an error however, no temperature data exists as evidence to support this hypothesis.

In June 2011 (Figure VI.25) wood-block probes 01 and 02 were replaced as it was thought there may be a problem with the contact between the timber and the metal rods (Figure IV.1 p106), the replacement probes never regained the previous moisture content level, continuing however, to exhibit a similar wave pattern at a reduction of 4%MC. This may also be a reflection of the results discovered during Experiment 2 (Section IV.3.2.1 p121), the effect of a hysteresis as the new probes approaching the bale moisture content from a lower starting level, whereas the initial probes had dropped in moisture content with the bale level. This phenomenon may cast doubt as to the data obtained in the first peak in 2009, the bales may have reached a higher level of moisture than suggested by the wood-block probes results.

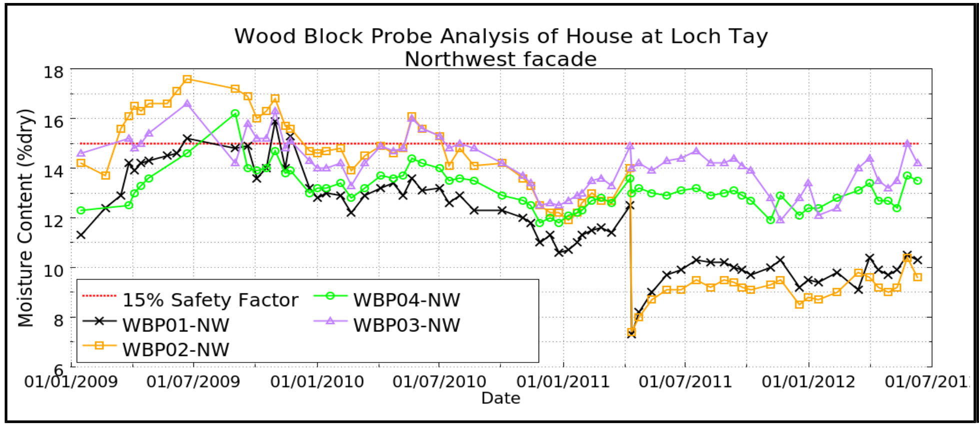


*Figure VI.25: North-west Façade Focussed Results*

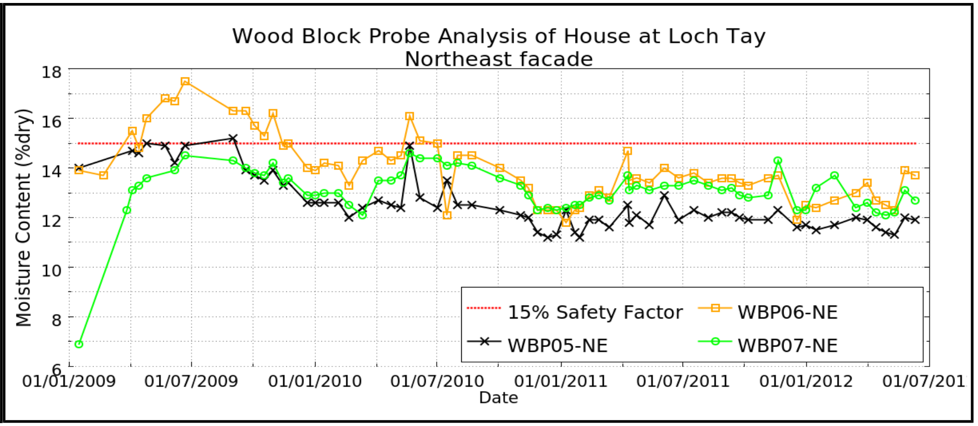


*Figure VI.26: North-east Façade Focussed Results*

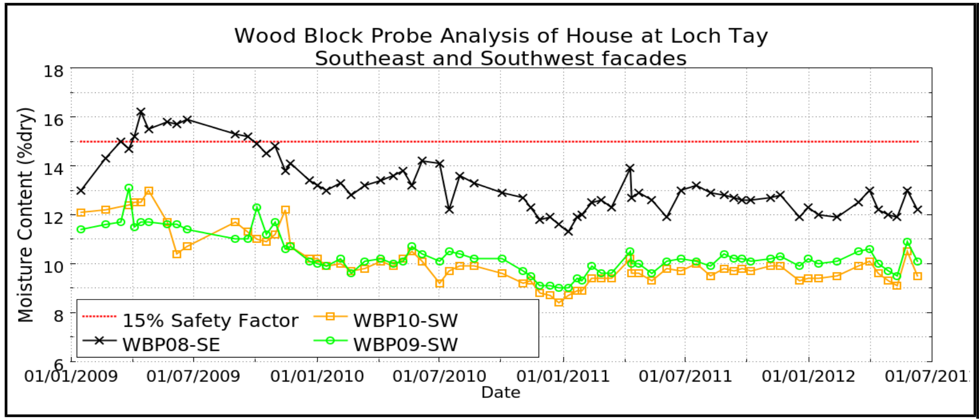


*Figure VI.27: South-east and South-west Façade Focussed Results*

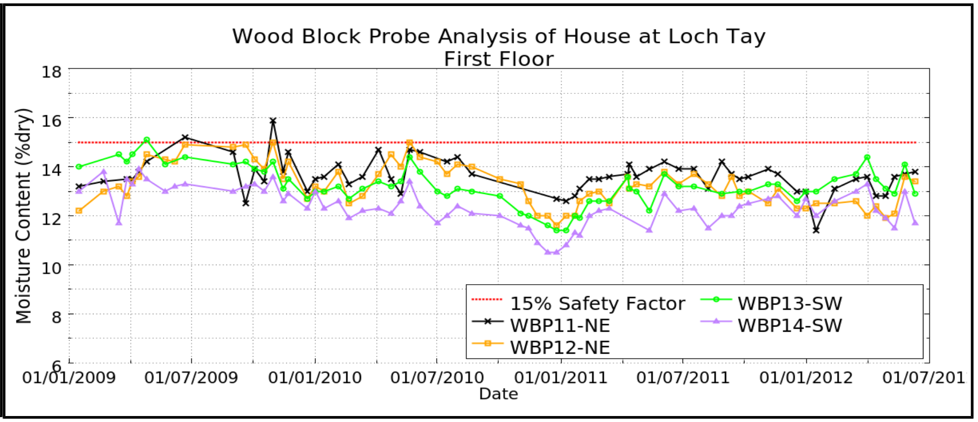


*Figure VI.28: First Floor Focussed Results*

The overall trend of data (Figures VI.25 to VI.28) suggests a rise in moisture content in early 2009 immediately post construction followed by a drop in the moisture level of all the probes to a permanent record of under 15% moisture content post 2010. It was hypothesised that the north-west wall would exhibit an elevated moisture content in comparison to the other façades, especially the clad walls, as it is unprotected from ensuing wind driven rain (Figure VI.25). However, there appears to be a difference in moisture content values post 2010 throughout the data stream with the exception of Probes 09 and 10.

An encouraging result can be seen from the analysis of Probes 09 and 10, located in the clad wall on the ground level. The two probes show a reduced level of moisture together with a depressed flux despite facing the majority of the wind driven rain. It could therefore be proposed that the lean-too is providing this additional protection, by removing the affect of rain impacting the surface of the cladding.

Since February 2010 no readings have surpassed a moisture content of 15% when assessing the bezier curve, yet the individual readings can oscillate by 1-2% in the course of a couple of weeks posing the following questions:

- Are these fluctuations a product of the resistance meter, environmental conditions, or a true representation of the straw?
- Are the wood-block probes able to react quickly enough to the changes in the straw moisture content?
- Is a schedule of monthly readings enough; would the Monitoring Site have benefited from a more intensive study?

Overall the findings suggest that there is no moisture related problem with the building at the particular monitoring points, all readings falling below the Risk factor threshold set at 15%MC and appear to show no future concerns. The hypothesis concerning the added protection of cladding of the south-west wall compared to the unclad north-west wall, both subjected to driving rain, returns a null response as the evidence does not suggest a difference between the first floor results, probes 13 and 14, and probes 1, 2 and 4. However, the south-west ground level does have the benefit of an additional lean-too acting as a second overhanging roof section, the results do not conclusively suggest that the reduction in moisture levels is caused by the additional protection, but could suggest that the addition of a breaker or screen between the oncoming driving rain and the affected wall could be of benefit. There must however be adequate provision for air circulation as described by Jolly (2000) concerning a critical assessment of a West Coast construction (Section II.6 p81) and supported by the research conducted in Section VI.4.4 (p214) upon analysis of the Test Rig.

The main weakness of this study included the inability to perform destructive testing and to conduct a highly concentrated monitoring assessment. Questions raised and concerns highlighted by this investigation given the inherent weakness of the study suggested that further investigations were required.

## VI.5-Summary

The Focussed Results chapter aimed to investigate in detail the gaps in knowledge as identified in Section II.8 (p87) and to refine previous experiments presented in the Preliminary Results chapter part II (Chapter IV-) based on the collated evidence. Continuing the previous chapter a refinement of the density experiments was conducted utilising repeated load cycling to obtain a 'stabilised' record of results. The results show that direct use of a resistance meter cannot confidently describe the risk associated with straw bales from moisture unless the density can be measured and a compensation factor applied; the compressed straw probe offers this ability.

If the compressed straw probe was to be an effective monitoring solution the resistance meter reading accuracy had to be compensated for temperature also, Section VI.3 demonstrated that the GM equation (Equation II.5 p73) was ineffective for straw. In Section VI.3.2.1 a new compensation factor (Equation VI.1 p192) was developed for the Timbermaster based on the temperature of the measuring point of the straw, Section VI.3.3.1 presents Equation VI.2 (p194) a conversion equation for the Timbermaster and Balemaster (USA version).

The equations (VI.1 and VI.2) were checked against the previous Test Rig resistance meter study data producing a conversion error of ±0.3. A second Test Rig study (Section VI.3.5.1 p198) showed evidence of transient moisture relating to the temperature variance of the bale, the impact of direct sunlight providing energy which lead to the moisture transfer experiments (Section VI.4 p202).

The moisture transfer laboratory experiment (Section VI.4.2 p208) demonstrated, over a prolonged study, an effective time lag when a straw bale is subject to a dramatic sustained change in humidity. Evidence also suggested that moisture does not migrate and condense randomly in a bale, and that the internal cellular structure of the straw reacts to humidity at a different rate to the external surface. In order to elaborate on the laboratory study a similar experiment was conducted in the Test Rig comparing two sections of the South facing wall (Sections VI.4.4 p214 and VI.4.5 p221). The evidence suggested that the render acts as a reservoir for moisture in areas that have little or no air circulation which affects the straw as direct sunlight heats the render, driving the moisture into the external straw/render interface. The moisture that is driven into the bale is mainly transient and upon cooling of the render is drawn back towards the external atmosphere.

In evaluating the Focussed Results chapter, the monitoring devices require interpretation for a number of complex factors. The interaction of moisture with straw involves not only the passage of moisture into the bale atmosphere from an external source but a requirement by the straw to equilibrate with the surrounding atmosphere. The difference in the moisture content of the internal cellular structure of a stem when compared to the external surface in a dynamic system of oscillating temperatures and humidities was evident throughout the results. Each monitoring device records a different aspect of the moisture content of straw and although individually the devices can prove accurate in a steady state environment a combination of readings is necessary to evaluate the risk to the straw fully, hence the compressed straw probe provides a solution.

The compressed straw probe does however provide only part of a solution, combined with an understanding of the complex interactions of moisture and straw together with other variable such as temperature, and a model, the ability to quantify and evaluate the risk posed to a straw bale construction can be achieved.

# Chapter VII-Model

## VII.1-Introduction

It is proposed that, for a model that evaluates the risk posed to straw from moisture to be produced, the complexity of the moisture mechanics must be understood with relation to the monitoring method being used to quantify it. The Focussed Results chapter utilised the benefits of the compressed straw probe in addressing density and temperature issues, producing equations to increase the accuracy of data acquisition. The Focussed Results chapter, combined with the results and observation made in the Preliminary Investigative chapters, established a model and description for moisture transfer within a straw bale.

The Model chapter combines the knowledge gained in the previous chapters and assembles it to produce a meaningful equation combining the density and temperature calculations, before evaluating each type of monitoring device for usefulness and effectiveness. The risk assessment system proposed in Figure III.3 (p100) is then revisited and undergoes modification with respect to the knowledge gained, feeding into the overall model which is in turn evaluated against the Test Rig data.

## ***VII.2-Density Analysis***

From the density results presented in the Focused Results chapter (Section VI.2.2 p182) it was demonstrated that moisture content readings stabilised under repeated load cycles. With the ability to compensate resistance meter results for temperature (Section VI.3 p185), the density experiments were re-evaluated aiming to combine the method of compensating for temperature with density thereby increasing the accuracy of the resistance meter and the ability to interpret the results. The adoption of an equation to compensate for this gap in knowledge would provide greater confidence in readings and evaluations of straw's moisture content.

### VII.2.1-Density Calculations

When adjusted for a standard of 20°C (Equation II.5 p73) the density experiment results for the NaCl environment (Section VI.2.2.2 p183) suggest that readings of below 145kg/m$^3$ would fit a constant gradient between density and moisture content, above which the data suggests that the line takes a second order polynomial trend tending beyond the results indicated by the gravimetric analysis. Figure VII.1 utilises the straight line results of the density experiment data generated by the MgCl and NaCl environments to produce a graph demonstrating the fan effect hypothesis (Figure V.38 p176). Due to the lack of experimental data confirming the polynomial trend and the likelihood that straw used in construction will not conform to densities beyond 145kg/m$^3$ the straight line data was extrapolated to gain an intercept point with the gravimetric analysis. The intercept density for 15.3%MC (NaCl) is 152.7kg/m$^3$ and for 10.3% (MgCl) is 160.7kg/m$^3$.

The underlying aim of the fan effect hypothesis is to provide an assessment tool to compensate for the density of the straw by using the data from the

Focused Experiments (Section VI.2.2 p182). Applying a line of best fit (Figure VII.1) to the data for the MgCl experiment Run03 (29-05), used as the most stable data set, Equation VII.1 was produced, the NaCl experiment Run03 (01-06) results produced Equation VII.2.

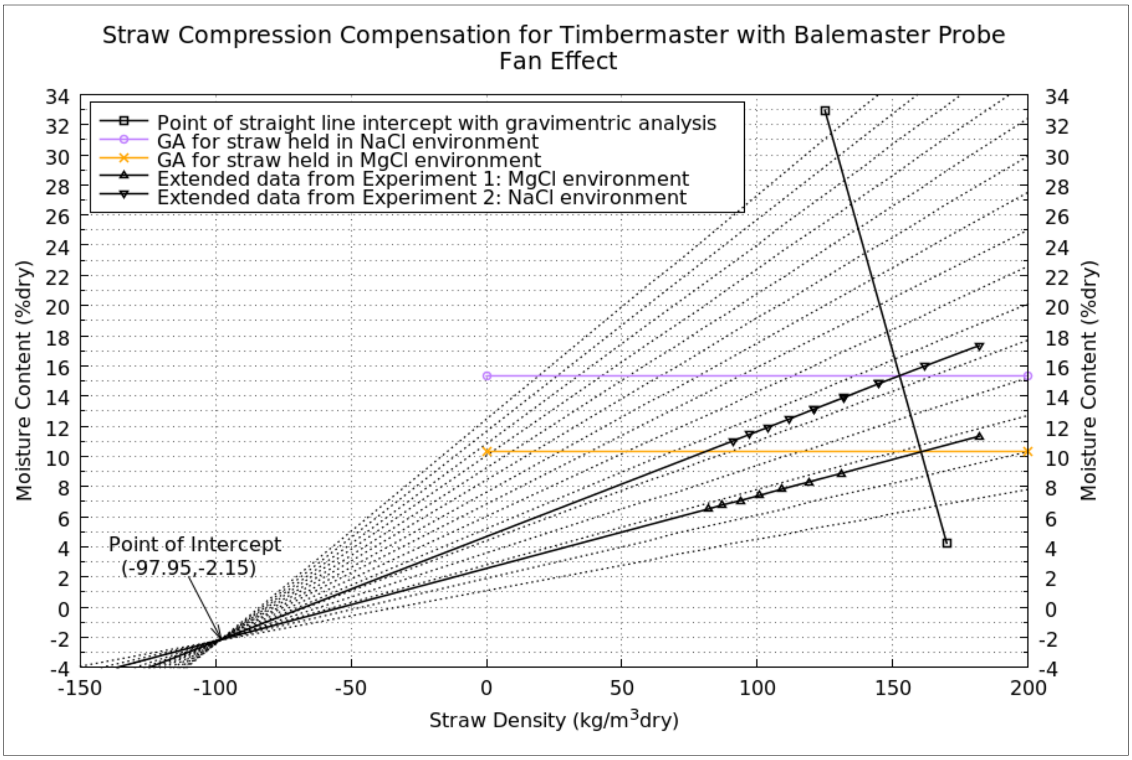


*Figure VII.1: Density Fan Effect*

$$y = 0.048x + 2.567 \quad \left(R^2 = 0.9956\right)$$

*Equation VII.1: Straight line equation for MgCl Run03 (29-05)*

$$y = 0.0697x + 4.680 \quad \left(R^2 = 0.9982\right)$$

*Equation VII.2: Straight line equation for NaCl Run03 (01-06)*

The intercept of the two equations (-97.95,-2.15) was then used to develop a formula capable of producing a series of gradient lines and therefore the fan effect (Equation VII.3).

$$y_d = mx + c$$

$$m = \frac{y + y_i}{d + x_i}$$

$$c = y - (m * d)$$

$y_d = MC \text{ compensated for density}$
$m = \text{Gradient of line}$
$c = \text{Constant}$
$y = \text{Measured MC compensated for temperature}$
$d = \text{Dry density of measured straw}$
$x_i = \text{Intercept of experiments } x-\text{axis} \ (-97.95)$
$y_i = \text{Intercept of experiments } y-\text{axis} \ (-2.15)$

*Equation VII.3: Establishing an equation from the results obtained*

In extracting the points at which the gravimetric analysis and experiment results intercept, Equation VII.4 was generated taking a straight line between the two gravimetric points and extrapolating it over the course of the graph, thus providing a line in which to determine the equivalent gravimetric analysis reading for any given density and resistance meter reading.

$$y = -0.638\text{x} + 112.7$$

*Equation VII.4: gravimetric analysis intercept equation*

In essence it is possible to gauge the potential steady state gravimetric analysis result from the knowledge of the resistance meter and density results by reading from the graph. Equation VII.5 represent a mathematical description to calculate the equivalent gravimetric analysis based on a single reading taken by a resistance meter reading for an established density of straw.

$$C_{GA} = \left(d_{GA} * k\right) + \left(y - \left(k * d\right)\right)$$

$$d_{GA} = \frac{112.7 - \left(y - d * k\right)}{k + 0.638}$$

$$k = \left(\frac{y + y_i}{d + x_i}\right)$$

$C_{GA} = MC\ of\ the\ straw\ at\ GA\ intercept$
$d_{GA} = Density\ of\ the\ straw\ at\ GA\ intercept$
$k = Gradient\ of\ line$
$y = Measured\ MC\ compensated\ for\ temperature$
$d = Dry\ density\ of\ measured\ straw$
$x_i = Intercept\ of\ experiments\ x-axis\ \ \left(-97.95\right)$
$y_i = Intercept\ of\ experiments\ y-axis\ \ \left(-2.15\right)$

*Equation VII.5: Equ$_{GA}$: Gravimetric analysis intercept equation*

## VII.2.2-Application of Density Calculations

Re-application of the data from previous experiments produced Figure VII.2 however, the fan effect remains unconfirmed whilst based on only two data sets, and therefore results must be interpreted with this assumption applied. It is therefore suggested that this area requires a greater independent study evaluating in detail the reactions of straw under alternative conditions of temperature, sample size and with a greater diversity of moisture contents.

*Table VII.1: Results from FRC section 2.2*

| **Probe** | **$TM_{20}$ (%MC)** | **Density ($Kg/m^3{}_d$)** | **GA (%MC)** | **$Equ_{GA}$ (%MC)** |
|---|---|---|---|---|
| CSP1 | 12.9 | 100 | 14.2 | 16.0 |
| CSP2 | 11.0 | 90 | 11.2 | 15.3 |
| CSP3:Run5 | 16.0 | 120 | 19.9 | 18.3 |
| CSP3:Run7 | 19.5 | 120 | 24.8 | 21.7 |

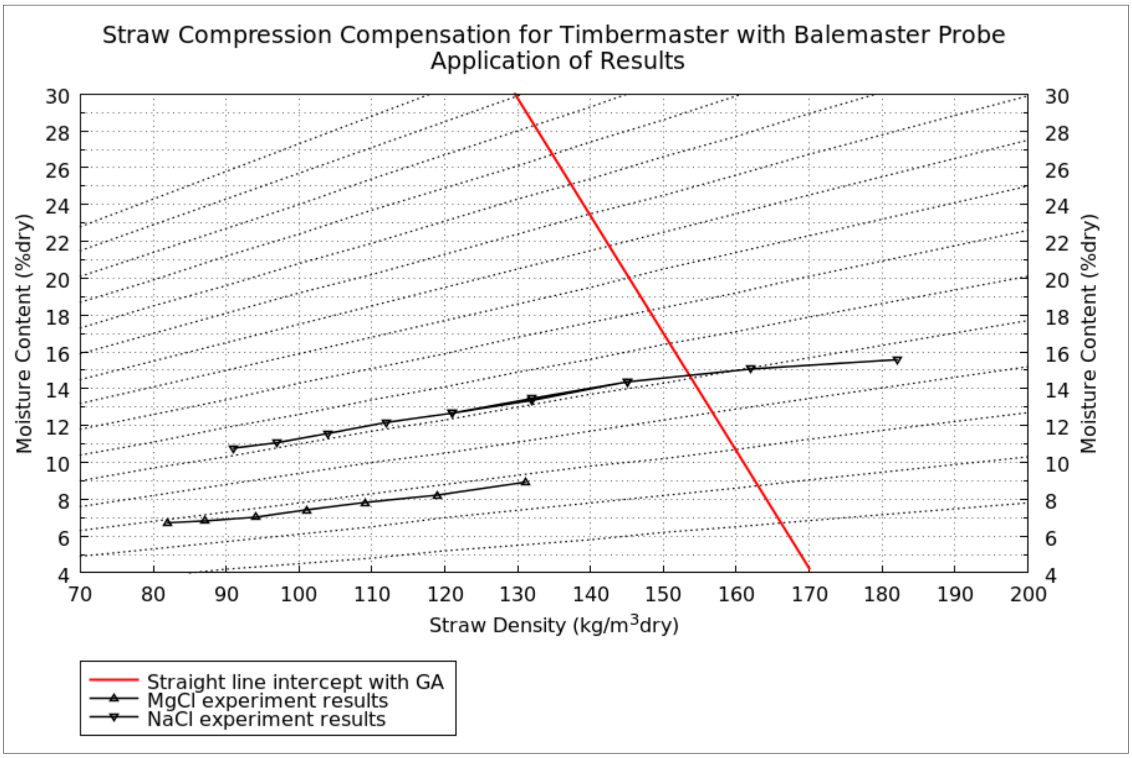


*Figure VII.2: Application of Experimental Data*

Equation VII.5 was applied to the compressed straw probe temperature experiment results described in Section VI.3.2.1 (p190). Table VII.1 details the results, combining the Timbermaster records corrected for 20°C ($TM_{20}$) with the established dry density values, the original gravimetric analysis is compared to the results predicted by Equation VII.5 (p239).

The $TM_{20}$ results underestimate the gravimetric analysis value as discussed in Section VI.3.2.1 however, upon conversion of the data using Equation VII.5 compressed straw probe 1 and 2 overestimate the gravimetric analysis whereas CSP3 stipulates a undervaluation of the relationship. The lack of repeated load cycling of the straw prior to loading of the probe body creates a potential for this error as the straw is not under 'stabilised' conditions as demonstrated in Section V.7 (p171). Compressed straw probes 1 and 2 maintained previously in a stable environment are subjected to a dynamic situation and the difference can also be explained by the time lag created by the cellular structure in equilibrating to the external atmospheric relative humidity.

The development of Equation VII.5 has little relevance to a direct assessment of a straw bale construction unless a method of obtaining the density of the straw at each monitoring point can be made. In the development of the compressed straw probe however Equation VII.5 is of value; as the density of each compressed straw probe can be established, and a correction factor applied to the resistance meter results, a more accurate assessment of the construction could be made depending on further studies undertaken to confirm this hypothesis.

## *VII.3-Monitoring Device Evaluation*

The evaluation of the monitoring devices forms the backbone of the thesis including the knowledge concerning: how the devices work, how the data should be interpreted, and perhaps most importantly the shortfalls of each. This section therefore discusses the individual monitoring devices or techniques applicable to straw bale construction with the aim of informing the model and addressing the precautions required to avoid possible misdiagnosis.

### VII.3.1-Temperature

Alone the monitoring of temperature with a digital thermometer placed at intervals throughout the bale will provide an assessor with the knowledge to describe thermal efficiency and will also act as a warning signal signifying the onset of degradation. Unusually high temperatures are associated with micro-organism activity (Summers 2003) as the straw is decomposed however, in the case of high temperature associated with degradation it will be too late to save the straw and therefore this monitoring method is not recommended as a sole indicator of risk, although in combination with other methods temperature can be used to increase accuracy and thereby confidence. The use of room temperature and temperatures external to the construction are also instructive.

### VII.3.2-Weather Stations

A Weather Station is a valuable addition to the analysis of a structure when providing a data input into a model as Wihan (2007), Grmela (2010) and Bronsema (2010) conclude. Obtaining weather patterns within the immediate area of a monitoring site offers an insight into the potential causes of problems, Figure VI.24 (p227), and highlights significant weather events that could potentially be correlated with these problems. Determination of air movement in protected sections of a construction can also provide benefit as discussed in

Section VI.4.4 (p214) together with an account for the exposure to wind-driven rain.

### VII.3.3-Gravimetric Analysis

Gravimetric analysis is the measure of the mass of the straw where the variable is moisture; it can be a destructive method of analysis confined mainly to laboratory assessment, or in extreme circumstances analysis of a construction (Goodhew 2004, Holzhueter 2009). The method of analysis depends upon the amount of moisture present at the time of analysis however, this may not be an accurate reflection of the immediate moisture content in a dynamic environment, as demonstrated in Section VI.3.2.1 (p190). The external surface moisture content of the straw is subject to rapid change by adsorption and desorption, the internal cellular structure and internal stem surface of the straw on the other hand is comparatively delayed by the rate at which absorption occurs.

The external surface of a straw stem is highly dynamic in relation to moisture exchange adapting quickly to the surrounding atmosphere, yet in the case of high atmospheric flux the internal cellular structure is less able to equilibrate. With reference to the experiments conducted in this thesis it is concluded that the potential for the air to affect the cellular structure depends on whether the straw is undergoing absorption and desorption or, adsorption and desorption, the later being the fastest of the processes (Section VI.5 p232).

The rate at which the internal cellular structure equilibrates affects the gravimetric analysis reading. The rate is in comparison to a resistance meter reading, or relative humidity equivalent moisture content calculation, which takes account of either surface moisture content or atmospheric vapour (Section VI.3.2.1 p190). The rate at which the straw's gravimetric analysis changes in a dynamic system can be viewed in the context of a historical record depicting conditions prior to a reading when compared to a resistance meter reading and should not be valued as an immediate indicator of moisture content (Section VI.5 p232).

In conclusion the gravimetric analysis in a steady state environment is a valuable tool, yet it can also be used to provide evidence as to the environment recently imposed on the straw in a dynamic system. The evidence is due to the comparatively slow rate of absorption and desorption from the internal cellular structure compared to a surface moisture content reading; as obtained by a resistance meter. The draw back as Table VII.1 (p240) indicates is in the ability to provide an immediate and accurate moisture content reading. A gravimetric analysis reading from either a wood-block probe or compressed straw probe should only be used to assess the risk posed to a construction with the correct interpretation based on recent history.

### VII.3.4-Wood-Block Probes

The accuracy of the wood-block probes was researched in Section IV.3.1.1 (p116) showing the probe tips under a desorption phase returning an error of ±1%MC within five days of a raised moisture content however, when subjected to an absorption phase errors of -2% to -4% were recorded after one month (Figure IV.11 p122). This time lag illustrates a weakness in utilising oak as the timber of choice together with the time lag of a wood-block probe under rapidly rising moisture condition within a bale, reducing the confidence in the ability to highlight a severe problem within an adequate time period (Figure II.7 p70). The restriction to the monitoring of only one immediate point within a wall is a concern also as the probe is effectively monitoring the straw in the immediate surrounding area and is incapable of providing a detailed assessment of a section of bale or, the overall wall.

The research conducted on temperature effects for the resistance meters highlighted the requirement for the temperature at the point of measurement to be acquired before adjusting the readings (Section VI.3 p185). Caution is advised when wood-block probes are intended to be used in a construction and it is suggested that further studies are conducted on the temperature equation for timber (Equation VI.1 p192); the results in this thesis are bound to straw only.

The study of the straw and an equivalent resistance meter reading demonstrated that the density of the straw affects the results, although not directly associated, it was noted that the timber expanded and contracted with moisture content suggesting that contact may be lost with the probe under low moisture content conditions. Maintaining contact with the probe tip is naturally essential, yet it was observed also that different degrees of pressure placed on the contact rods produced differing results.

Wood-block probes offer a cheap and reasonably accurate method of monitoring a construction and with correct interpretation can be used with a high degree of confidence, therefore in conclusion the history of the moisture content should be tracked and as a safety guideline an additional 4%MC should be added to readings taken under adsorption conditions, whilst regarding the potential for delay in observing a rapid change in straw moisture content.

### VII.3.5-Resistance Meters

Resistance meters have a certain ability that differs from other monitoring devices, the Balemaster Probe with either the Timbermaster or Balemaster meters attached will provide a measure of the path of least resistance across the straw medium, most likely to represent the level of moisture to the external surface rather than the integral cellular structure of the straw. The readings are however not without potential inaccuracies, temperature at the point of measurement (Section VI.3 p185) and density (Sections VI.2.2 p182 and VII.2 p236) are significant influencing factors.

It must be noted that Equation VI.1 (p192) corrects the moisture content reading obtained for straw only and no further work was conducted to evaluate any other material. A potentially important difference in the measurement of timber and straw includes the underlying structure of the material, obtaining a resistance reading through the cellular structure of timber can produce a different reading compared to one obtained across the surface of a material such as straw.

It is concluded that a resistance meter should not be used directly to make an assessment of a straw bale construction without the calibration equations discussed in earlier chapters (Section VI.3 p185). It must also be considered that the resistance meter reading provides an instantaneous reading of the material at that particular point in time. In the case of direct measurement of straw, with the incorporation of the density and temperature equations, the overall risk to straw from moisture can not be obtained from a one off measurement, in order to perform an adequate survey the history of the straw must be known. The history will then inform the interested parties of changes over a course in time, the combination of a gravimetric analysis and resistance meter assessment is an effective technique in the evaluation of Risk.

Another point to note is in the difference between the use of the Balemaster probe and the use of rods as used in the wood-block probes and compressed straw probe. The Balemaster probe will measure the path of least resistance down the length of a straw stem due to the way it is inserted into a bale (Figure VII.3). The rods create in straw a partial separation between several individual stems thus relying on continuous contact between the electrodes. It remains an unresearched preliminary observation and this thesis has assumed that it has negligible influence on results.

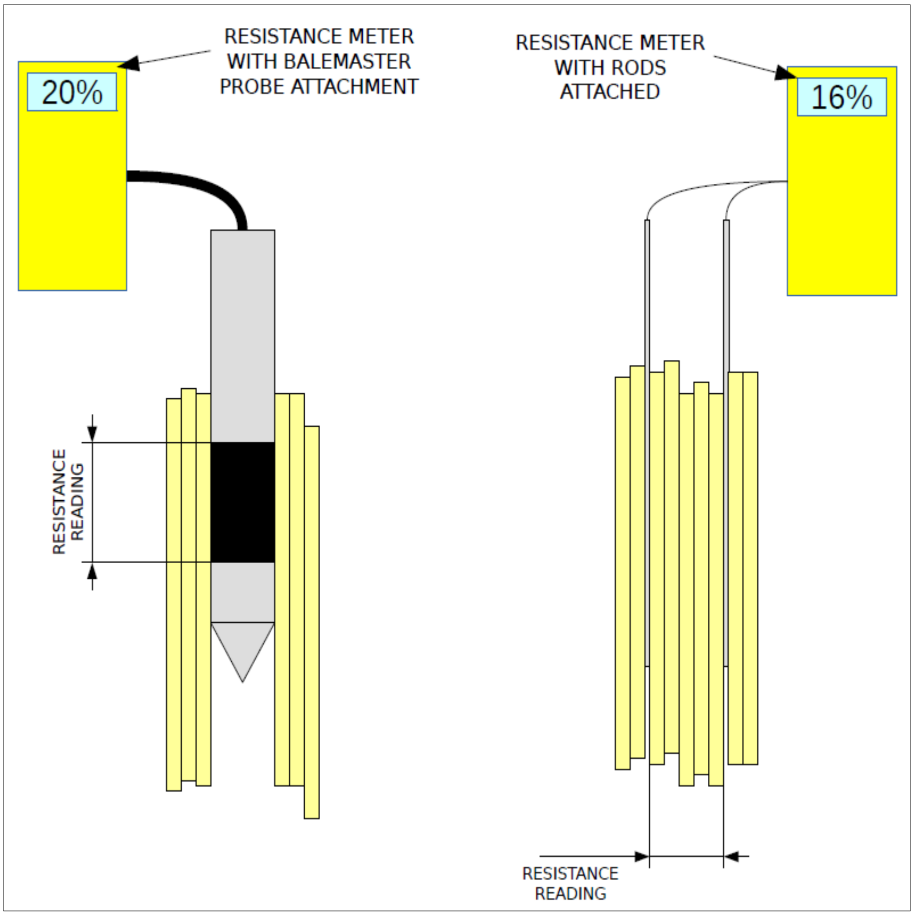


*Figure VII.3: Difference in measurement methods between Balemaster probe and Rods*

## VII.3.6-Relative Humidity

The assessment of humidity as an accurate reflection of the moisture content is subject to a similar evaluative conclusion as the gravimetric analysis (Section VII.3.3). In a laboratory environment under sustained humidity and temperature a straw sample will provide a reading of steady state; the humidity will be comparable to the moisture content: as in Lawrence et al's equation (Equation II.1 p61). If the humidity is altered the time taken for the straw to react to the change is two fold, the external surface responds rapidly however, the internal structure has a pattern of lag, the time influenced by the phase it is subjected to, desorption or absorption, and the potential of the atmosphere to force the change.

Although relative humidity can be used without a conversion to moisture content as a guide to the Risk posed to a straw bale construction it remains that the moisture content is easier to read and understand due to relative humidity fluctuating dependant upon the influence of temperature. Assessing the application of isothermal studies within this thesis highlighted several disparities between the results portrayed in the literature and the conversion of relative humidity to moisture content at high levels and in dynamic situations (Table VII.2). These are addressed under the Discussion chapter rather than in the Literature Review in order to make an informed evaluation based on the studies conducted within this thesis.

The literature in Table VII.2 does not comment upon mould development at the higher relative humidities with respect to the Isotherm studies, in evaluating the methods adopted the straw took around 10 days in most experiments for the mass to stabilise however, using isopleth studies it can be demonstrated the there is a high potential for mould to develop within this time. For highly xerophilic moulds it could be expected, at relative humidities above 80% and temperatures of 20°C, for spores to begin germination within eight days (Figure II.8 p70) and for mycelium to grow at a rate of over 0.1mm/day (Figure II.7 p70). Increase the level to 90%RH and spores may germinate within two days, mycelium growing at a rate of 1.2mm/day.

*Table VII.2: Comparison of Isotherm studies*

| **Researcher** | **Page ref.** | **Basis** | **Pre-set RH%** | **MC% Results** | **Temperature conducted (°C)** | **Medium** | **Sample Preparation** | **Results, wet/dry basis** |
|---|---|---|---|---|---|---|---|---|
| Duggal and Muir (1981) | 3 | - | 70<br>80<br>90 | 14 (Emp.)~16.3<br>20 (Emp.)~25.0<br>28 (Emp.)~38.9 | 15<br>(5-35) | Wheat straw | Individual GA after | Wet ~Dry |
| Straube (2002) | 10 | Lamond and Graham (1993) | 70<br>80<br>90 | 15 (Emp.)<br>20 (Emp.)<br>31 (Emp.) | 21 | Grasses | Individual GA after | Dry |
| Wihan (2007) | 49 | Bigland-Pritchard (2005) | 70<br>80<br>90 | 14 (Emp.)<br>19 (Emp.)<br>29 (Emp.) | 20 | Straw | Individual GA before | Dry |
| Lawrence et al. (2009a) | 2766 | $Equ_{LAW}$ i=1.6 | 70<br>80<br>90 | 14.6 (Emp.)<br>20 (Emp.)<br>33 (Emp.) | 5-26 | Wheat Straw | Individual GA before | Dry |
| Lawrence et al. (2009b) | 2766 | $Equ_{LAW}$ i=1.0 | 70<br>80<br>90 | 12 (Equ.)<br>14.7 (Equ.)<br>20 (Equ.) | - | Wheat Straw | Individual GA before | Dry |
| Carfrae et al (2011) | 159 | - | 70<br>80<br>90 | 12 (Emp.)<br>15.5 (Emp.)<br>20 (Emp.) | 23 | Wheat straw | Hysteresis GA before | Dry |

Individual/Hysteresis: samples were subjected either an Individual set environment and experienced no other or were cycled through a range of humidities.
GA after/before: Sample's gravimetric analysis was obtained after or before the experiment by drying sample out completely in oven.
Emp: information based on empirical data
Equ: Information obtained from equation

It could therefore be suggested that the experiments be repeated and measures taken to ensure no mould develops thereby clarifying the results obtained at higher relative humidities; possibly in an inert atmosphere with sterilised straw. Further work based on the doubt that this highlights is therefore suggested.

Table VII.2 portrays three differing results, demonstrated by Carfrae, Duggal and Muir, and Bigland-Pritchard. There are two different experimental procedures, Carfrae cycling one sample through a range of humidities demonstrating the hysteresis effect and Bigland-Pritchard subjecting one sample to a static relative humidity, both drying the samples in an oven prior to the experiments; the procedures are discussed in Section II.2 (p58). One experiment that does not dry the straw initially was performed by Duggal and Muir, presented in wet basis, and has been converted to dry using Equation I.4 (p39) for the purpose of this section of the investigation.

Duggal and Muir's experiments suggest that the equivalent moisture content for wheat straw is significantly higher than the other authors discovered. Previously concerns were raised by drying straw prior to conducting experiments (Phanopoulos et al. 2000), the effect may be that the straw's internal cellular structure is disrupted by the process of extensive drying, thus it will not return to the mass equivalent compared to straw that has not undergone extensive exposure to heat. Phanopoulos et al. note debris to the surface of the straw post drying and although there is no publication of the results the thesis noted changes to the smell, texture at a macroscopic scale and colour changing to deep yellow-brown from bright straw-yellow. It is therefore suggested that any experiment reliant on obtaining the mass of a sample performs the gravimetric analysis at the end of the experiment; an area of study recommended for future investigation.

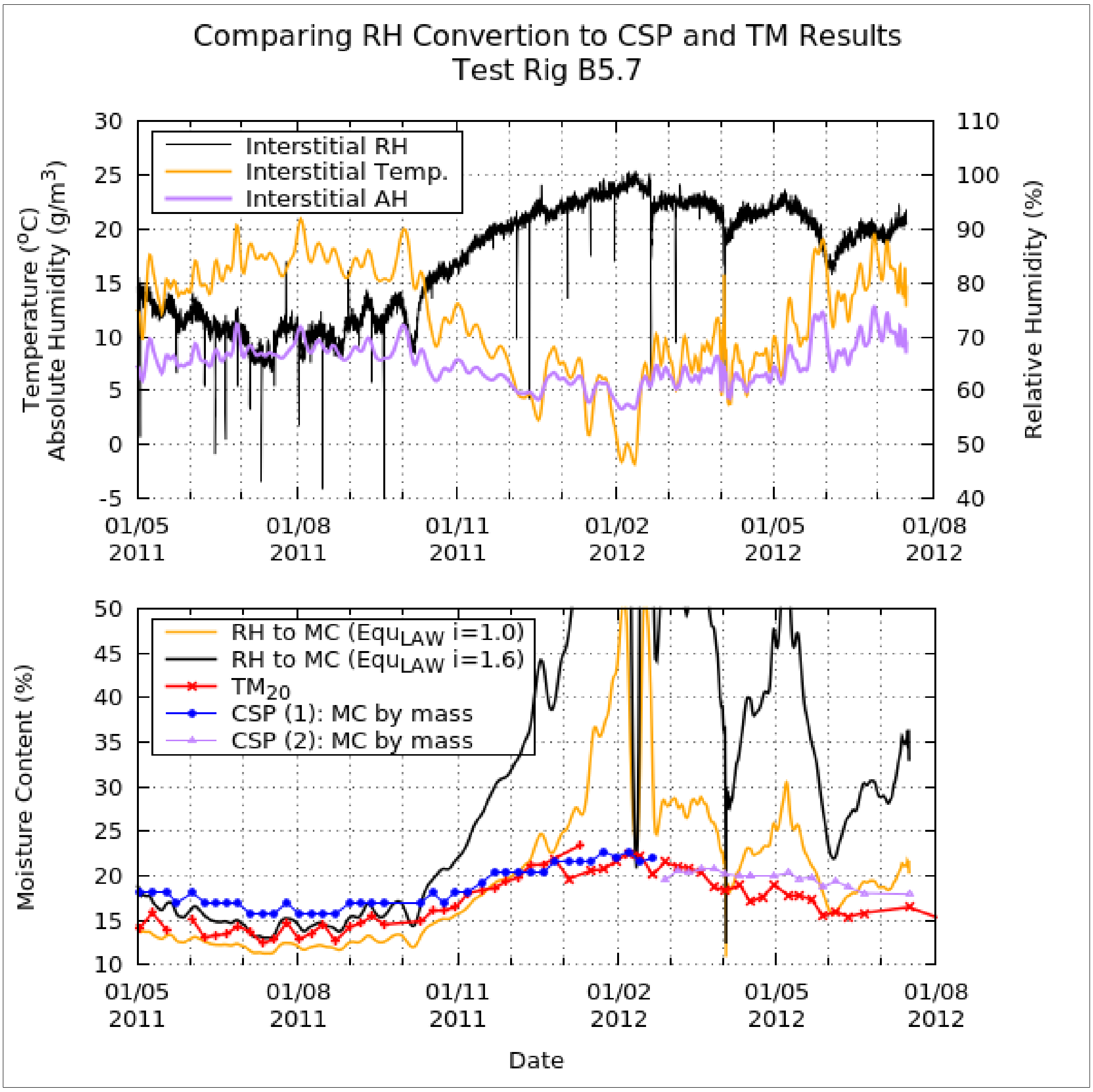


*Figure VII.4: Conversion of relative humidity compared to moisture content reading of compressed straw probe and Timbermaster*

Figure VII.4 shows the results of the study for B5.7 which included a relative humidity/temperature iButton sensor (located at the interstitial position within the Test Rig), a compressed straw probe and the Timbermaster data ($TM_{20}$) adjusted for 20°C; the results using relative humidity have had a bezier curve applied for presentation purposes thus cutting down the noise and producing a clearer illustration. The lower graph illustrates the conversion of relative humidity with the Lawrence equation (Equation II.1 p61), demonstrating under and overestimation of the moisture content when compared to the $TM_{20}$ (no density calibration) and compressed straw probe mass readings. It is hypothesised that this disparity is generated by the inherent differences between the moisture regimes that occur in laboratory experiments opposed to field investigations.

Readings taken from June 2011 to October 2011 show the bale atmospheric temperature oscillating between 15-20°C with relative humidities ranging between 65-75%, the compressed straw probe remaining between 16-17%MC and the $TM_{20}$ obtaining measurements between 12.5-16%MC. The Lawrence equation (i=1.6) based on empirical laboratory data suggests the moisture content varies between 13-17%. In December 2011 to June 2012 the relative humidity within the bale gave readings in excess of 90%RH equating to readings of 25-60%MC (Eqution II.1 p61), when compared with figures from Table VII.2 90%RH should return a reading of 20%MC (Carfrae et al. 2011, Lawrence et al. 2009b) or 29%MC (Lawrence et al. 2009a, Wihan 2007).

$$\phi = 100 * \left( \frac{K_m}{1 + \left( \frac{\left( \left( \frac{C_s}{C} \right) - 1 \right)}{n} \right)^{\left( \frac{3}{i} \right)}} \right)$$

$$\begin{aligned} C &= Moisture\,Content\,(\%) \\ \phi &= Relative\,Humidity\,(\%) \\ K_m &= 0.9773 \\ C_s &= 400 \\ n &= 44 \\ i &= 1.6 \end{aligned}$$

*Equation VII.6: Lawrence et al. equation rearranged*

In order however to take advantage of isopleth studies the relative humidity is required; back-calculating $Equ_{Law}$ (i=1.6) provides Equation VII.6, but as Lawrence et al. (2009b) note there is more work required in the development of the equation to confidently correlate the two figures. Figure VII.5 illustrates the use of $Equ_{Law}$ together with the application of the Risk Assessment System (Figure III.3).

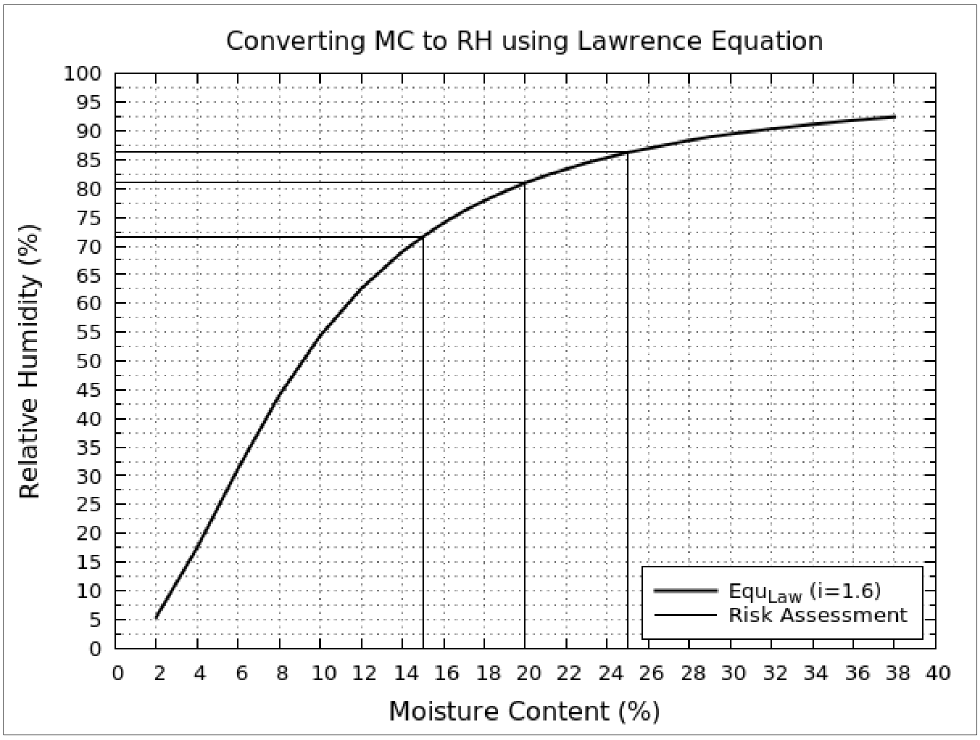


*Figure VII.5: Conversion of moisture content to relative humidity using EquLAW*

The issue affecting the relative humidity conversion equations is of moisture transfer between the straw surface, straw cellular structure, and the atmosphere. From April 2012 (Figure VII.4) the relative humidity remains between 82-96% however, the $TM_{20}$ and compressed straw probe readings drop suggesting that the bale atmosphere is not influencing the moisture content of the straw as the temperature increases. There are four processes affecting these results:

- Firstly the temperature is rising providing energy to the bale.
- Secondly the internal structure of the straw stems decreases in moisture content as demonstrated by the compressed straw probe mass conversion.
- Thirdly the straw stem surface drops in moisture content shown by the $TM_{20}$ results.

- Finally the relative humidity of the bale is subject to two separate effects. Initially the bale relative humidity decreases in mid May 2012 triggering a drop in the compressed straw probe and $TM_{20}$ measurements. However, in June 2012 the relative humidity increases, yet the compressed straw probe results continue to decrease suggesting that the bale is loosing moisture to the external atmosphere, but this is replaced by the addition of moisture desorbing from the internal cellular structure of the straw, due in part to the temperature increase raising the potential of the bale atmosphere to hold a greater amount of moisture. The $TM_{20}$ results from June 2012 suggest that despite the rising relative humidity the straw surface is at a stable or slightly increasing moisture content.

Greater clarification is therefore required concerning the potential for moisture absorption and desorption of the internal structure of straw with respect to oscillating humidity and temperature together with a detailed analysis of moisture transfer through a bale. The use of relative humidity sensors in a construction should be viewed with caution in high relative humidity scenarios if the temperature is also raised. The study of B5.7 shows that relative humidities in excess of 90% corresponded with temperatures below 10°C and moisture content's of between 20-23% signifying a 'Medium Risk' outcome when viewed against the Risk Assessment System (Figure III.3 p100). The straw at temperatures below 10°C is at little risk from micro-organism attack, yet if temperatures increase and relative humidity remains high then the risk is increased (Jolly 2000, Summers 2003).

A weakness that relative humidity sensors share with wood-block probes is the restriction to a one point analytic surrounding, the inability to analyse multiple positions or sections of a bale with one monitoring device. The cost therefore of monitoring a wall system utilising relative humidity sensors must be justified against the benefit of having a system installed. Further disadvantages include the sensor's limited life expectancy and the possible need to extract a failed sensor, a destructive process, together with the requirement for data-logging equipment to analyse results.

The adoption of a relative humidity study to a construction or model however is viewed as beneficial, it provides data concerning changes in moisture that may not be identified by analysis of the straw surface or by mass measurement. In the case of Test Rig position B3.4 (Section VI.4.4 p214) evidence was provided to suggest that the render is potentially acting as a storage medium for transient moisture in areas of poor external air circulation. Further study is therefore suggested analysing the way in which relative humidity interacts with straw and also in confirming results presented in Table VII.2 corresponding with dynamic situations.

### VII.3.7-Compressed Straw Probes

Remaining under development the compressed straw probe has provided a method of analysing a straw bale wall through a linear section of bale, a resistance meter meter reading identifying the maximum moisture content in the width of a bale utilising the path of least resistance, a specific point within the bale, and an ability to describe the average moisture content of the straw throughout the depth of the wall by gravimetric analysis. This provides an advantage allowing the monitoring of the highest moisture content record through a bale, from interior to exterior, most likely to be generated towards the exterior straw/render surface, but providing peace of mind if this is not the case, together with an overall assessment of the moisture content level within the distribution, via mass measurement.

The disadvantages of this method is in the identification of the exact position of the resistance meter reading, and in using an average moisture content throughout the width of a wall, which may conceal high value moisture content readings. However, in utilising straw as the measurement medium there is less uncertainty concerning foreign material influence and the probe can be calibrated prior to installation with a known density and moisture content of straw, combined with an ability to record the straw's temperature. A further advantage of the compressed straw probe was discovered during experimental analysis of the probe, an optical (macro and microscopic) and olfactory evaluation which may be performed confirming the risk posed to the straw. Summers (2003), and Dick and Krahn (2009) also comment on elevated temperature and smell acting as an indicator to microbial degradation.

With further work this method of monitoring could be advanced, allowing the exact location of the maximum moisture level to be identified and with the potential for data-logging capacities to be linked to a piece of evaluative software to describe the risk posed to the construction. The development will depend somewhat on verification of the density calculations (Figure VI.1 p183) and the (Figure II.2 p52) ability to stabilise the straw in the probe body mimicking the repetitive load cycling (Figures VI.1 p183 and VI.2 p184).

# VII.4-Additional Evaluation

The model should have the capability to determine the difference between a high relative humidity caused by transitional moisture opposed to the actual straw moisture content, and a predictive ability to assess the outcome of a worst case scenario by recommending actions to be taken based on Isopleth studies.

## VII.4.1-Render

The transfer of moisture analysed in Section VI.4 (p202) assessed the interaction of moisture with straw through the protective render. The study was also designed to evaluate the relationship between the measuring devices and the straw or bale atmosphere, and to provide information to influence the development of a model.

As demonstrated by the laboratory results (Section VI.4.2 p208) the transfer of moisture through a bale is not a rapid process. Position B3.4 Figure VI.15 (p215) illustrated this. The external straw render interface shows an increase in relative humidity on the 31st of May during a period of sustained high external atmospheric relative humidity, yet the Interstitial level of relative humidity decreases. In analysing the absolute humidity (Figure VI.17 p217) the external peak is offset from the other results indicating that the increased moisture content has no immediate impact on the interstitial relative humidity; an analysis supported by the Timbermaster results adjusted for 20°C over the course of the study which shows a drop of 0.6%moisture content.

If the rate of transfer is comparatively slow it remains that there must be an interaction between the straw and the surrounding air. Accepting that the transfer of moisture through the bale may have only a slight effect on the interstitial region of the bale over a short space of time, the concept introduced in Section VI.4 (p202) concerning a sample of a bale of infinite proportions, may be implemented. This is illustrated by Figure VI.7 (p199) the reaction to temperature of relative humidity and resistance meter measurements in which the moisture content of the straw and the atmosphere increased; it is therefore suggested that there is a greater source of moisture influencing the internal bale atmosphere than the small amount transferred through the bale from external sources.

The structure and the internal surface of the straw stem provides a source for the subsequent moisture increase, yet these have not been monitored directly. Referring to Section VI.3.2.1 (p190), the Dynamic Temperature Tests demonstrate that drying a sample of straw rapidly will reduce the external surface moisture level however, the moisture locked into the structure cannot be released at the same rate and therefore a disparity between the resistance meter and gravimetric analysis is created. It is hypothesised that as the straw warms, it begins to release moisture from the internal structure of the straw thereby increasing the bale relative humidity, but as the air temperature is greater than the straw the additional moisture condenses back onto the external surface of the straw until an equilibrium is met; this equilibrium is described by the Lawrence Equation (Equation II.1 p61). As the temperature starts to cool from the external surface of the bale and if the external moisture level of the straw has dropped along with the relative humidity then the bale environment will attempt to equilibrate redistributing moisture throughout. This explains moisture transfer through a bale and the reason as to why it is a slow process as noted in the Laboratory Tests Section VI.4.2 (p208) and due to the oscillations in temperature moisture may only condense on the straw cooling in the immediate area to a raised relative humidity.

The direct impact of the render on the results is dependent on the situation, the difference in readings between T2.5 and B3.4 Sections VI.4.4 (p214) and VI.4.5 (p221) illustrate that in certain instances the render may act as a storage medium. In the instance of Blocks 2 and 3 the local topography inflicts a shaded area with little air movement thereby trapping morning dew. As the temperature of the moisture laden early morning external atmosphere increases moisture condenses on the cooler render that has not been warmed by solar gain. Once the sun falls on this section of the wall it will heat the moisture held by the render, vaporising it, an amount of moisture will pass back to the external atmosphere, yet the remaining moisture will be driven into the straw/render interface behind. This does not affect the rest of the bale and is unlikely to influence the moisture content of the straw permanently as the moisture in this region is transient. The transient moisture will be passed back to the render as the sun moves from the render surface and the temperature drops, becoming a point at which the vapour in the high relative humidity straw/render interface can condense back into the render; thus the moisture be drawn away from the straw.

It is therefore important to consider: the impact of solar gain, areas of low air movement and the protective medium when evaluating data. These points must be addressed or recognised in order for the model to be used to a sufficient degree of confidence.

## VII.4.2-Isopleths

The development of a model requires a predictive tool capable of utilising the data presented by the monitoring devices to assess possible future outcomes; based on either historical data or worst case scenarios. Isopleth studies offer a method by which to implement this however, the equations and graphs presented in the Literature Chapter Section II.3.2 (p68) represent a worst case scenario (highly xerophillic moulds). The worst case scenario would therefore present a safety threshold for implementation into a model, the combinations of which together with other studies, models and knowledge, could advance a more accurate and robust modelling technique.

The adoption of a technique to assess the potential for growth of mould under dynamic conditions is discussed by Bronsema (2010, pp.45), pointing out that isopleth experiments are conducted in steady state environments and may therefore “overpredict mould growth”. Therefore, the adoption of isopleth studies into a model could be viewed as an early warning system alerting interested parties of the potential Risk associated with the current internal wall environment.

# *VII.5-Model Development*

In order to provide an accurate and meaningful assessment of a straw bale construction a model is required with the capability of using combinations of monitoring devices to evaluate the risk posed to the straw and provide interested parties with confidence in the construction method.

## VII.5.1-Fuzzy Implementation

As discussed in the Methodology Chapter (Section III.3 p96) using a Risk Assessment System may be of use in defining the level at which moisture becomes a problem (Figure III.3 p100). However, the simplicity of this method of identification, although effective as viewed in the contour plan, is of limited value when a detailed picture is required. Utilising a fuzzy method of analysis maintains the simplicity whilst adding a degree of sophistication capable of describing the data with more accuracy (Figure VII.6).

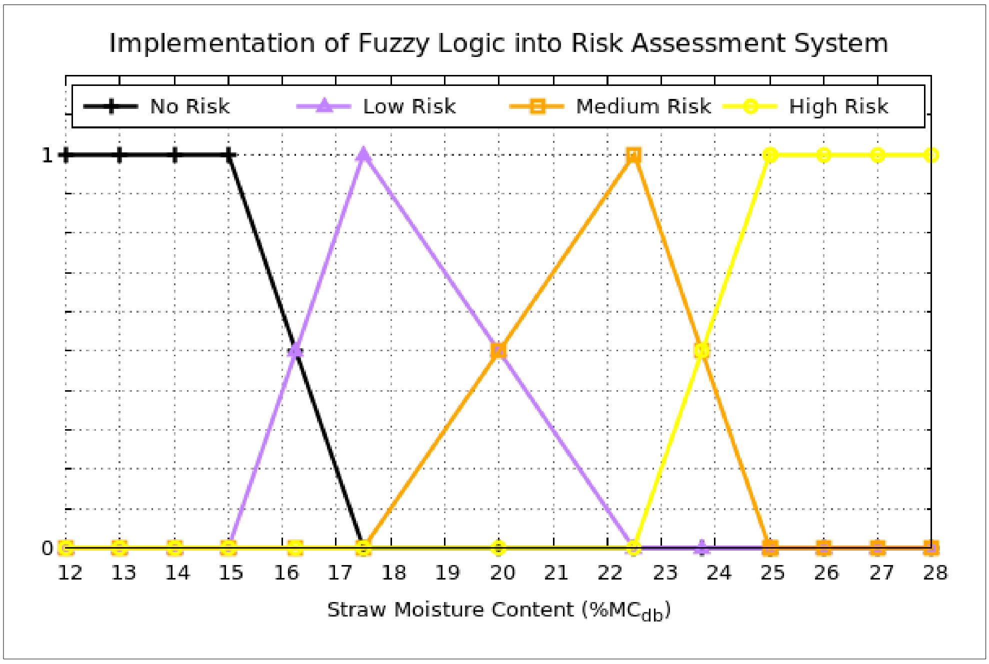


*Figure VII.6: Implementing Fuzzy Risk Assessment System*

The graph (Figure VII.6) demonstrates how the model can be improved to provide information in which to base an informed decision, the x-axis presenting the moisture content of the straw whilst the y-axis represents a probability decision; see Table VII.3.

*Table VII.3: Evaluation of Graph and Fuzzy Risk Assessment System*

| **MC (%)** | **No Risk** | **Low Risk** | **Medium Risk** | **High Risk** |
|---|---|---|---|---|
| 12.00 | 100% | | | |
| 15.00 | 100% | 0% | | |
| 16.25 | 50% | 50% | | |
| 17.50 | 0% | 100% | 0% | |
| 20.00 | | 50% | 50% | |
| 22.50 | | 0% | 100% | 0% |
| 23.75 | | | 50% | 50% |
| 25.00 | | | 0% | 100% |
| 28.00 | | | | 100% |

Table VII.3 demonstrates the outcome for the Fuzzy Risk Assessment System. The system responds to the uncertainty surrounding the absolute values to which straw is susceptible to decay. The idea behind the system is to use commonly used descriptive language to explain the Risk posed to the straw, and to provide an assessor with a tool by which to more easily describe the risk posed; thereby make an informed decision (Table VII.4).

It is generally accepted that readings of below 15%MC are safe from decay, but it is more informative to say that a reading of 19%MC is quite concerning (70% Low Risk) and a little unsafe (30% Medium Risk). This could also be put as: the risk to the straw is Concerning verging on Unsafe, rather than stating it is at Low Risk because it falls within the categorical moisture content range between 15% and 20%.

*Table VII.4: Descriptive language*

| **No Risk** | **Low Risk** | **Medium Risk** | **High Risk** |
|---|---|---|---|
| Safe | Concerning | Unsafe | Dangerous |
| Code-Black | Code-Purple | Code-Orange | Code-Yellow |
| Risk-free | Uncertain | Risky | Hazardous |
| Efficient | Reduced Efficiency | Inefficient | Harmful |
| Effective | Low Effectiveness | Ineffective | Vulnerable |
| Strong | Poor | Weak | Critical |

A moisture content reading of 25% is agreed by most experts as the critical level of moisture, possessing the potential to be highly damaging over extended periods of time. Attaining a reading of this level, or above, will signify a dangerous situation on which to base a detailed evaluative survey and to predict a likely outcome. The major priority in this circumstance will not be further monitoring, but in identifying the problem and solving it. The Fuzzy Risk Assessment System forms only one part of a much more complex model; there is a requirement for the provision of temperature analysis, which, is used to define the Risk posed to a construction based on the level of moisture present in the straw.

## VII.5.2-Main Model

Using the Fuzzy Risk Assessment System (Figure VII.6 p261) and based on the evaluation and decisions made from the experiments conducted for this thesis Figure VII.7 was produced, depicting a control system for assessing a straw bale construction. It relies on the collection and processing of data from multiple calibrated data sources, to perform an evaluation of the data. The correct interpretation of readings from each type of monitoring device is therefore vital in producing an informed output defined by the basic Risk Assessment System presented in general terms of the Contour Plan.

Figure VII.7 assumes, at levels of moisture below 20%, temperature is not a significant factor, but is not to be ignored and must therefore be included in the evaluation on which concluding advice is based. The advice given by the model should include the history of the last month depicting whether the increase of moisture was sudden, and therefore showing the early signs of a potentially major fault, or a slow progression. The inclusion of the Fuzzy Risk Assessment System will provide greater accuracy and confidence in describing the risk, and if supported by weather station data may enhance understanding.

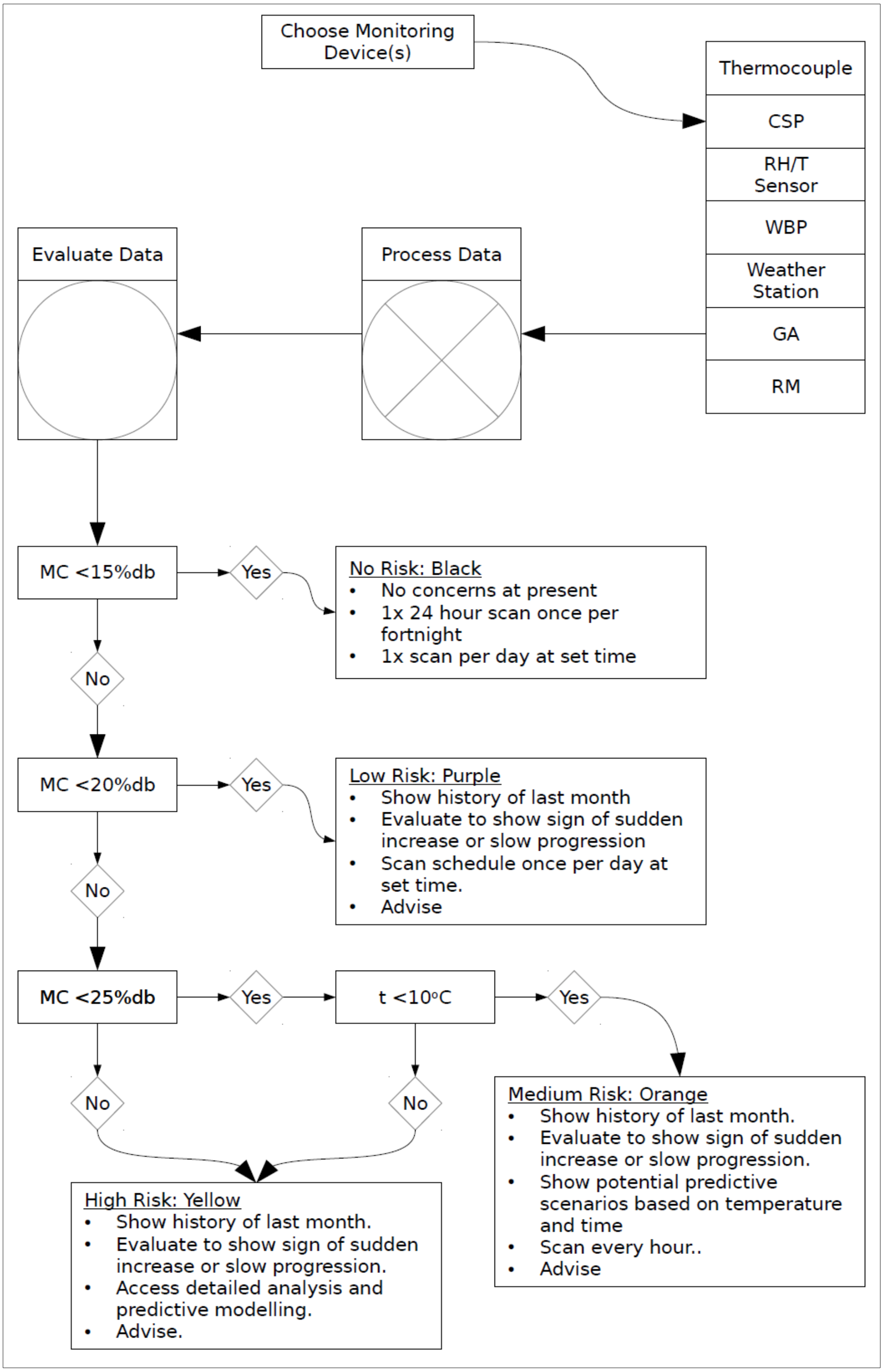


*Figure VII.7: Main Model*

With temperatures over 10°C, based on isopleth studies for highly xerophilic moulds, and moisture contents in excess of 20%, an evaluation of 'High Risk' is given (Code-Yellow). The categorisation of this reading is due in part to the uncertainty concerning the Risk posed to straw with elevated levels of moisture and temperatures that may promote mould development. The history of the monitoring position is required to make a categoric assessment as to how long the straw has been at this moisture level, and at what temperature, together with an evaluation based on isopleth studies.

There are two forms of advice in the scenario of moisture content's in excess of 20% and temperatures above 10°C, either, fix the problem if there is little risk of mould development, or perform remedial work. In the event of a Code-Orange, 'Medium Risk', there is a matter of urgency to locate and fix the problem based on advice; taking into account: isopleth studies, historic weather patterns and predictive climatic seasonal adjustments based on average data for the year. The time basis is less critical than the Code-Yellow, but requires an understanding of the reasons and potential outcomes. Hourly measurements of the monitoring devices are suggested given the level of concern and associated risk.

The model presented here is the culmination of the research presented in this thesis; requiring a detailed knowledge of the monitoring devices chosen to assess the risk to the construction. Under the application of the Fuzzy Risk Assessment System, and a historical assessment method, interested parties are able to use a tool by which confidence is promoted. The Test Rig and Monitoring Site have therefore been used to test the model.

## *VII.6-Model Evaluation*

The following section assesses the application of the model presented in Section VII.5 (p261) utilising the Test Rig and Monitoring Site as test cases in order to establish the model's validity.

### VII.6.1-Evaluating the Test Rig

Module-block B5 was selected for assessment as a continuation of the Preliminary Investigation Chapter, Part II (section V.4.3 p159). The investigation introduced, into the Test Rig, a bale that had suffered previous elevated moisture levels. Equations $MC_{20}$ (Equation VII.4 p238) and Timbermaster to Balemaster calculation (Equation VII.5 p239) were applied to the data producing Figure VII.8. The contour plan has also undergone modification with the removal of 'Day readings taken' and the addition of a time-line placed underneath the plots.

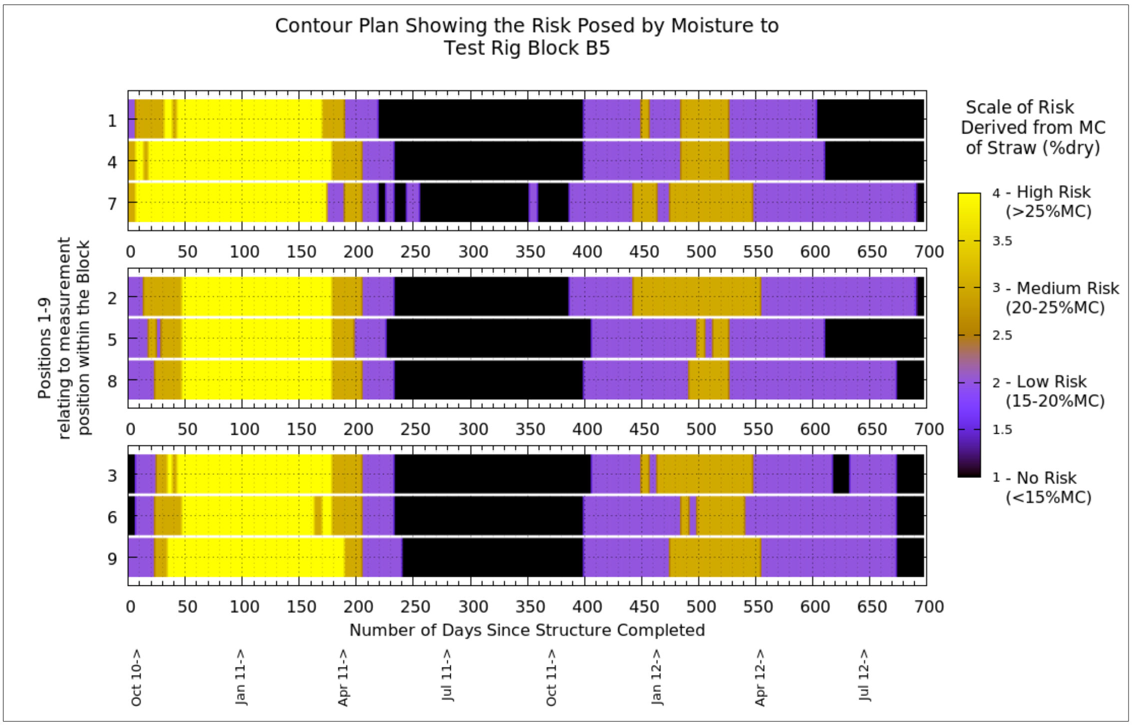


*Figure VII.8: Block B5 Contour Safety Plan*

Figure VII.8 shows the Risk posed to the straw in positions 4 and 7 on Day 0 as at a 'Medium Risk', and rapidly developing to a level of 'High Risk' after render is applied (See Figure V.26 p160 for uncompensated early data). The hypothesis presented in Section V.4.1 (p139)suggested that the use of a bale with a high starting level of moisture in a construction would create an area of sustained moisture, and of weakness in the construction. This would permit pioneering micro-organisms to capitalise on the advantage thereby promoting further breakdown by aggressive secondary and tertiary organisms. By January 2011 however, all positions in Block B5 signified levels of moisture posing 'High Risk', and by April 2011 all dropped to warn of a 'Medium Risk' environment; Block 5 received a 'No Risk' designation by June 2011. After June 2011 positions 1,4 and 7 showed no weakness for sustained moisture retention when compared to elevated moisture levels beyond other positions and no signs of degradation, indicating that the original hypothesis was null in this scenario.

The return of null does not indicate however that installing wetted bales during construction should be recommended, on the contrary Figure VII.8 does not show enough information to make an informed decision. The data does not account for anything other than a level of moisture adapted for a reading of 20°C. For a complete evaluation to be made the temperature of the straw, during this time period, must be taken into account. The external straw/render interface is also important, together with a prediction of mould development and spore germination; in conclusion the application of the model is required to provide further analysis. Another concern can be raised over primary micro-organisms having removed sections of, or all, the lignin and silica; the straw may then be weaker in certain places, and therefore may be more susceptible to decay by more aggressive micro-organisms in the future (Section I.3.2 p29).

The analysis of Position B5.7 is shown in Figure VII.9 detailing the adjusted Timbermaster and compressed straw probe readings. The readings have been compensated for temperature and density, and presented with the relative humidity and weather station measurements. The weather station has some missing data towards the end of 2011 however, the readings demonstrate that 2012 received an increased amount of rainfall from a North/North-Westerly direction which had the potential of affecting Block B5; which faces west. Note that $TM_{20D}$ refers to a Timbermaster measurement adjusted for 20°C (Equation VI.1 p192) and density (Equation VII.5 p239).

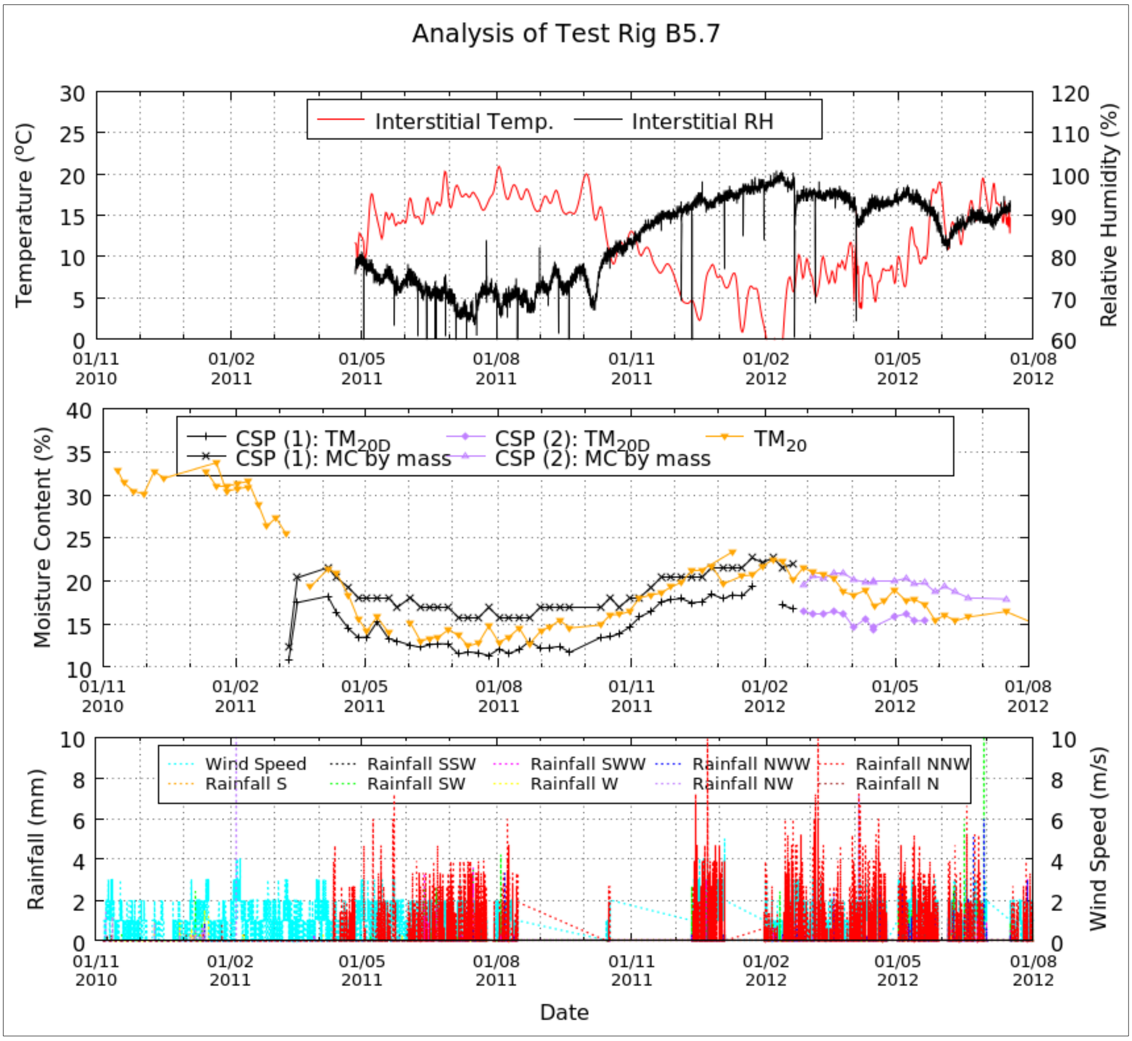


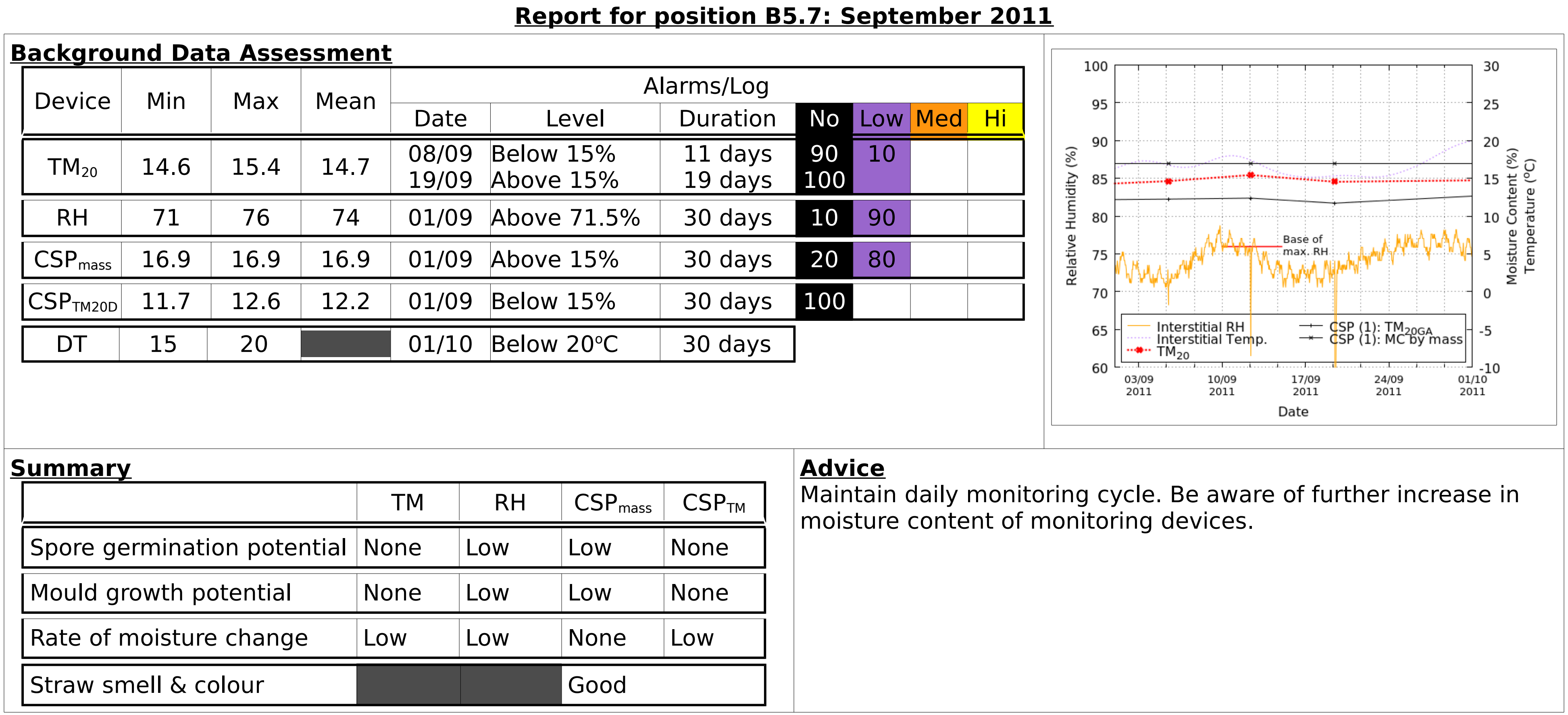
*Figure VII.9: Analysis of B5.7*

Figure VII.9 shows individual data processed for evaluation as per Figure VII.7. Based on the overview presented by Figure VII.8 attention is drawn to day 350 (end of September 2011) and a 'Low Risk' spike in the readings for B5.7. The spike should trigger an alarm if the moisture increase is due to a sudden change however, from further detailed analysis in Figure VII.9 the spike represents an increase in moisture content of less than 1% to 15.4%. This is recognised by the Fuzzy Risk Assessment System evaluation as safe, but of very slight concern (90% 'No Risk'-10% 'Low Risk').

From September (Figure VII.9) it can be noted that the temperature drops and relative humidity increases reflected by an increase in moisture measurements of the compressed straw probe and Timbermaster. The model (Figure VII.7) has therefore been implemented on a monthly review process assessing the findings on which to base further advice. The tables detailing Background Assessment Data (Figure VII.10) represent the review outcomes detailing: the maximum, minimum and mean values for each of the monitoring devices. The outcomes are presented by month, together with a log of events identifying important changes with reference to the Fuzzy Risk Assessment System.

In analysing the data for the tables in Figure VII.10, the Fuzzy Risk Assessment System classification reflects the highest recorded value achieved for the month concerned. However, the relative humidity maximum does not refer to the absolute maximum peak attained during the day, but the base value reading, the least value that could have affected the straw. The report proceeds to make an evaluative summary based on the Holzheuter (2009) equation and isopleth studies (Wieland 2004) predicting spore germination and subsequent mould development (Figures II.7 and II.8 p70). The spore and mould development assesses the rate of moisture progression and shows potential outcomes of predictive scenarios based on temperature and time. The relative humidity value is assessed with respect to Figure VII.5, and the equivalent moisture content is designated by the Fuzzy Risk Assessment System:

1. 71.6%RH ~ 15%MC,
2. 81.0%RH ~ 20%MC,
3. 86.3%RH ~ 25%MC.



**Report for position B5.7: September 2011**

**Background Data Assessment**

| Device | Min | Max | Mean | Alarms/Log | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Date | Level | Duration | No | Low | Med | Hi |
| TM$_{20}$ | 14.6 | 15.4 | 14.7 | 08/09<br>19/09 | Below 15%<br>Above 15% | 11 days<br>19 days | 90<br>100 | 10 | | |
| RH | 71 | 76 | 74 | 01/09 | Above 71.5% | 30 days | 10 | 90 | | |
| CSP$_{mass}$ | 16.9 | 16.9 | 16.9 | 01/09 | Above 15% | 30 days | 20 | 80 | | |
| CSP$_{TM20D}$ | 11.7 | 12.6 | 12.2 | 01/09 | Below 15% | 30 days | 100 | | | |
| DT | 15 | 20 | | 01/10 | Below 20°C | 30 days | | | | |

**Summary**

| | TM | RH | CSP$_{mass}$ | CSP$_{TM}$ |
|---|---|---|---|---|
| Spore germination potential | None | Low | Low | None |
| Mould growth potential | None | Low | Low | None |
| Rate of moisture change | Low | Low | None | Low |
| Straw smell & colour | | | Good | |

**Advice**

Maintain daily monitoring cycle. Be aware of further increase in moisture content of monitoring devices.

*Figure VII.10: Implementation of Model: Report for B5.7 September 2011*

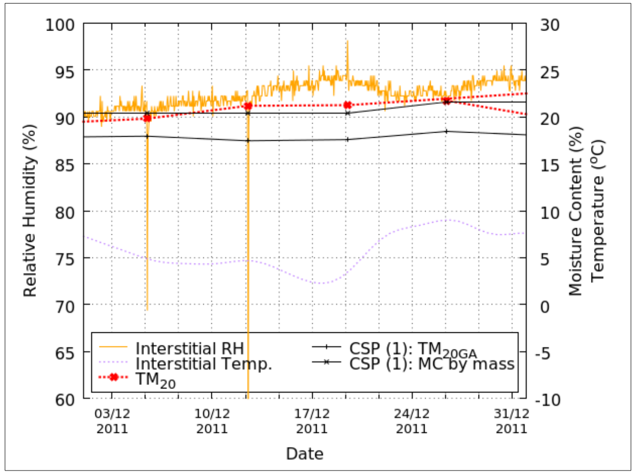
The assessment of September (Figure VII.10) suggests that there is a 'Low Risk' posed to the straw from moisture for the $\text{CSP}_{\text{mass}}$ and relative humidity readings. When analysed by the Holzheuter (2009) equation (Equations II.3 and II.4 p68) and the isopleth studies (Wieland 2004; Figures II.7 and II.8 p70) no risk from degradation is reported. The straw in the compressed straw probe provides more information regarding smell and visual inspection returning a verdict of 'good'. There is little in the way of advice from September to December's reports despite the rise in moisture content of the Timbermaster and compressed straw probe.

From the results in December (Figure VII.11), the Background Assessment Data shows a 'High Risk' alarm for the relative humidity however, the temperature of the bale remains below 10°C minimising the risk to the straw, but the raised moisture content reduces the thermal efficiency of the wall. It is recommended that a solution to the high moisture level be sought based on the potential for micro-organisms to develop in the case of warming of the wall, either from an internal heat source, or a change in weather patterns.

## Report for position B5.7: December 2011

### Background Data Assessment

| Device | Min | Max | Mean | Alarms/Log | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Date | Level | Duration | No | Low | Med | Hi |
| $TM_{20}$ | 19.5 | 21.5 | 21 | 05/12 | Below 20% | 5 days | | 20 | 80 | |
| RH | 90.4 | 94.7 | 93 | 01/12 | Above 86% | All month | | | | 100 |
| $CSP_{mass}$ | 20.4 | 21.5 | 21 | 01/12 | Above 20% | All month | | 20 | 80 | |
| $CSP_{TM20D}$ | 17.5 | 18.2 | 18 | 01/12 | Below 20% | All month | | 90 | 10 | |
| DT | 2.2 | 9.1 | ▨ | 01/12<br>04/12<br>20/12 | Above 5°C<br>Below 5°C<br>Above 5°C | 4days<br>16 days<br>Rest month | | | | |



### Summary

| | TM | RH | $CSP_{mass}$ | $CSP_{TM}$ |
|---|---|---|---|---|
| Spore germination potential | None | None | None | None |
| Mould growth potential | None | None | None | None |
| Rate of moisture change | Low | Low | None | Low |
| Straw smell & colour | ▨ | ▨ | Good | |

### Advice

Although relative humidity suggests a level of High Risk of moisture within the bale. The low temperature will prevent micro-organism development. There will however be a reduction in thermal efficiency.

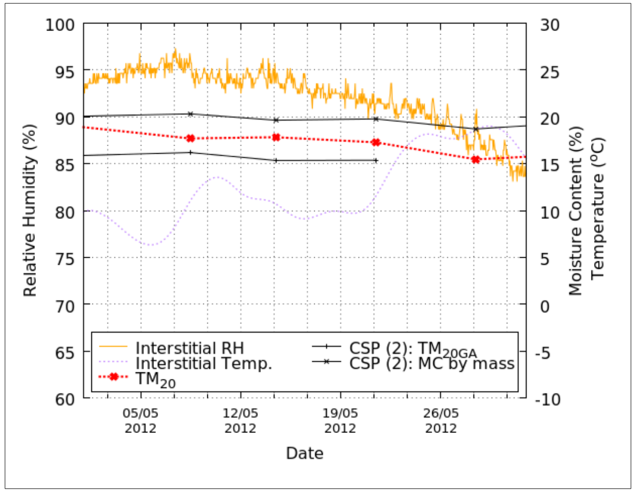
Predictive Scenario: If temperature was to rise suddenly there may be an increased potential for mould development. Suggest four hourly cycle for monitoring of all devices and finding a solution to problem.

*Figure VII.11: Implementation of Model: Report for B5.7 December 2011*

## Report for position B5.7: May 2012

### Background Data Assessment

| Device | Min | Max | Mean | Alarms/Log | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Date | Level | Duration | No | Low | Med | Hi |
| $TM_{20}$ | 15.3 | 18.9 | 17 | 01/05 | Below 20% | All month | 90 | 10 | | |
| RH | 83.5 | 96.5 | 90 | 27/05 | Below 86% | Rest month | | 10 | 90 | |
| $CSP_{mass}$ | 18.6 | 20.2 | 20 | 11/05 | Below 20% | Rest month | | 80 | 20 | |
| $CSP_{TM20D}$ | 15.3 | 16.1 | 15.6 | 01/05 | Below 20% | All month | 90 | 10 | | |
| DT | 6.4 | 19.2 | | 01/05 | Below 10°C | 8 days | | | | |
| | | | | 08/05 | Above 10°C | 6 days | | | | |
| | | | | 14/05 | Below 10°C | 6 days | | | | |
| | | | | 20/05 | Above 10°C | 2 days | | | | |
| | | | | 22/05 | Above 15°C | Rest month | | | | |



### Summary

| | TM | RH | $CSP_{mass}$ | $CSP_{TM}$ |
|---|---|---|---|---|
| Spore germination potential | Low | Med. | Low | Low |
| Mould growth potential | Low | High. | Low | Low |
| Rate of moisture change | Low | Med. | Low | Low |
| Straw smell & colour | | | Good | |

### Advice

Maintain close monitoring of relative humidity and temperature, also smell of straw if possible. Microscopic inspection on a single random straw stem removed from the position surrounding the relative humidity sensor may demonstrate degradation. Predictive scenario: If relative humidity continues to drop at current rate there will be no risk posed to the straw, however if temperatures continue to remain high there is a high potential for mould development and leading to remedial action.

*Figure VII.12: Implementation of Model: Report for B5.7 May 2012*

The temperature of B5.7 remains below 10°C until May 2012 (Figure VII.12). The categorisation of risk at this point is given as: 'Medium Risk' from humidity however, returns a moisture content of over 25% when converted (Figure VII.5). The temperature in May did however rise above 10°C for eight days, and above 15°C for five days, generating a potential for mould development based on the Wieland and Holzheuter calculations. Further analysis of these results would suggest that the straw was not held for a sufficient time period to allow for the onset or development of highly xerophilic moulds.

The evaluation of the compressed straw probe and Timbermaster results (Figure VII.12) show that there is; low to no potential for mould development, and that the moisture content drops steadily over the month. The advice therefore suggests as a precaution that the compressed straw probe be removed and inspected for signs of decay, with a microscopic analysis of the straw being used to confirm the integrity of the straw structure.

In conclusion the evaluation of the Test Rig using the Model (Figure VII.7 p265) agreed with the overall conclusion, based on the physical experience of monitoring the Test Rig,  that no decay was evident within the walls despite high moisture content being recorded.

The Model allows for the detailed evaluation of a straw bale construction to be undertaken, interpreting each individual monitoring device and producing advice to inform interested parties. It is proposed that the reports (Figures VII.10 to VII.12) would only be highlighted, and therefore generated by a graphical user interface, if a potential problem was identified. This would in turn enhance the use of the model as an efficient and effective monitoring tool.

## VII.6.2-Evaluating the Monitoring Site

In evaluating the Monitoring Site and based on Figures VI.25 to VI.28 (p229), the Model (Figure VII.7 p265) produced a result of 'No Risk' to the straw from moisture for any of the probes. A final evaluation was therefore conducted at the end of the study removing four of the wood-block probes in order to verify the findings using the Balemaster, with probe attachment, calibrated for temperature, but not for density.

Wood-block probes 01 ,08 ,10 and 14 were removed from the wall and a Balemaster probe inserted. The moisture contents in the straw behind the internal render were recorded at a depth of: 25mm, 350mm (at the point of measurement of the wood-block probes), and 450mm (the external straw/render).

*Table VII.5: Moisture content readings of Monitoring Site*

| | **Internal Interface** | **100mm from external** | **External interface** | **Wood-block Probe** |
|---|---|---|---|---|
| WBP 01 | 10.5 | 16.6 | 22.3 | 10.8 |
| WBP 08 | 10.5 | 17 | 23.2 | 17.5 |
| WBP 10 | 10.2 | 13.6 | 17.8 | 9.6 |
| WBP 13 | 13.2 | 18.6 | 20.7 | 13.6 |

It is evident from the results that the wood-block probes reflect only the moisture content in the immediate area. As the wood-block probes did not extend through to the external straw/render interface, a potential weakness in the monitoring of the construction had been identified. The high readings for the external straw/render interface however do not relay an entire picture. It was noticed, on extraction of the wood-block probes, a draft emanated from the remaining hole, plus the Balemaster reading fluctuated by ±1.5% during the measurement for both the interstitial and external readings (the internal readings produced a stable result). The initial concern was that an electrical field may be causing the ramping effect, this had been discovered in the early stages of the Test Rig trials when measuring in the vicinity of an electrical flex. In a telephone conversation with Jim Carfrae it was reasoned that the fluctuations may be due to the amount of render applied to the external wall; in excess of 50mm lime. Jim suggested that this may be due to the weight of the render de-laminating from the straw interface and that the amount of render may also be prohibiting efficient drying. The identification of the fluctuation and elevated moisture content, at the time of writing this thesis, is speculative, and will require further testing beyond the scope of this work.

In summary; although the Model could not be employed to the gathered data, it has been concluded that the construction is at 'Low Risk' to 'No Risk' from the effects of moisture. The external straw/render interface, although demonstrating a 'Medium Risk' environment, is subjected to a yearly limewash which could potentially raise the pH of the straw, immediate to the straw/render interface, producing too harsh an environment for the development of most moulds.

## VII.7-Summary

The model chapter began by producing a mathematical equation, Equation VII.5 (p239). The equation obtains an equivalent steady state gravimetric moisture content from a temperature calibrated resistance meter reading; for a known density (Section VII.2 p236). The density of straw at a precise point of measurement in a construction cannot be determined however, the density of the compressed straw probe can. The compressed straw probe allows for the use of Equation VII.5 in generating a reading with a greater degree of accuracy. The chapter proceeds to evaluating monitoring devices aiming to aid in the interpretation of the data provided by each device or method:

1. A temperature probe (Section VII.3.1 p242) can be used in conjunction with other devices to promote accuracy and warn of the process of decay.
2. Weather stations (Section VII.3.2 p242) provide valuable additional data to the assessment of a construction.
3. Gravimetric analysis (Section VII.3.3 p243); due to the way in which moisture interacts with straw, gravimetric analysis can be used to identify recent conditions, but is less informative as an immediate study of straw moisture content in a dynamic system.
4. For oak wood-block probes (Section VII.3.4 p244) there is a concern over time lag in the absorption phase and it is recommended that a moisture content of 4% be added to the readings in this phase; as a function of safety.
5. Resistance meters (Section VII.3.5 p245) must be used with the temperature and density calibration equations in order to make an accurate assessment of risk. The meters obtain an instantaneous

reading of moisture in a straw bale, assessing, the external surface of the straw which is subject to rapid change, in comparison to the internal cellular structure.

6. Relative humidity sensors (Section VII.3.6 p247) offer the results of a bale atmospheric reading and must be used with caution when converting to an equivalent moisture content in a dynamic system. The availability of vapour in the air surrounding the straw may be transient and therefore may not affect the straw moisture content.
7. The compressed straw probe (Section VII.3.7 p255) is capable of measuring the moisture level through a section of a bale utilising both resistance meter readings (compensated for temperature and density) and gravimetric analysis. The distinct benefit of the probe is in the ability to perform an optical and olfactory evaluation of the straw within the probe.

Each monitoring device must be used, with care being taken to evaluate the data, with respect to the device's abilities and restrictions. The use of the relative humidity sensors demonstrated the impact of render when subjected to poor air circulation; illustrating transient moisture that could not have been analysed by other devices. It was concluded that the render (Section VII.4.1 p257), when analysed with attention paid to the direct impact of sunlight, was acting as a storage medium for moisture. The moisture is driven into the external side of the bale by solar gain and then moves back into the render as the external surface of the render cooled.

In developing a model, isopleth studies offer an early warning system for decay however, it is important to note that the conducted studies (II.3.2 p68) are performed under steady state conditions with highly xerophillic moulds. The isopleth studies may therefore not demonstrate the true risk posed to the straw by moisture. To increase the impact of the model Figure VII.6 (p261), the Fuzzy Risk Assessment System aims to provide the model with a descriptive terminology based on the uncertainty of moisture limitations for straw.

Figure VII.7 (p265) represents the main model, illustrating the advice given under different scenarios and based on the correct interpretation of the data. The model together with the Fuzzy Risk Assessment System and contour plot (Figure VII.8 p267) was then applied to the test rig data summed up in a report for each individual monitoring position (Figure VII.10 p272). The report would only be produced for moisture contents in excess of 15% providing advice based on historical records and potential future events; for example a sudden rise in temperature uncommon for the seasonal average.

The chapter finishes by analysing the Monitoring Site (Section VII.6.2 p277) concluding that there was no risk to the construction at the point of measurement however, in a more comprehensive study it was demonstrated that the external straw/render interface  showed significantly higher moisture contents than 100mm's in from the external interface.

In conclusion the model is capable of providing a greater understanding of straw bale construction to interested parties by utilising commonly descriptive terminology to describe the risk posed to the straw.

# Chapter VIII-Conclusions

## VIII.1-Introduction

Straw bale construction, although not an established method of construction in the UK, possesses the potential to have a positive effect on a sustainable future. An increasing world population will consume more resources and require more housing which in turn will place additional pressure on ecosystem services, unless a sustainable method of consumption and a balance between society, economy and the environment can be sort. In the UK, housing contributes to 27% of all the countries $CO_2$ emissions of which 73% is used in the production of heat for space and water; by constructing thermally efficient housing the overall amount of $CO_2$ generation could be cut, straw bale constructions offer a solution.

To some degree a building should address social, economic and environmental needs, and should stand as a reminder as to the constructions historical significance. Straw bale construction uses a material that: can be locally sourced, is renewable (demonstrating a life cycle, due to the organic nature), and contains no inherent toxic elements. Intrinsically linked with human civilisation, wheat straw, a by-product of grain production, has been used as a construction material for thousands of years and with the advent of the baling machine allowed for the construction of the first straw bale constructions.

Straw is effectively a carbon store, and depending on the farming methods adopted, may be used to increase biodiversity. Straw bale construction may also help engage people on a social and personal level, offering a sense of personal achievement and social union together with the power to educate, on a wider scale, as to the effects of a construction on ecosystem services; capitalising on people's curiosity in the construction method.

## VIII.2-Chapter Summary of Investigations

The problem with using an organic material is the propensity for it to be decomposed by micro-organisms in the presence of moisture. The Risk posed to the straw by moisture is therefore one of the major concerns. Moisture can be measured by monitoring devices aimed at generating data by which interested parties may make an informed decision, yet uncertainty surrounding the susceptibility of straw to moisture remains under discussion. It is generally accepted that moisture contents of 15% and under will be safe from decay, and that, dependant on time and temperature, levels above 25% will be at a high risk from decay.

The margins are unclear at moisture contents between 20-25%, some sources stating that there is virtually no risk from decay, others providing no comment on the subject area (Table II.1 p50 and Figure II.2 p52). The study of Isopleths (Figures II.7 and II.8 p70) show that moulds may develop within this range under certain conditions however, these studies are conducted under steady state conditions selecting certain types of spores and are therefore recommended for use in a model as part of an early warning system. The decay of straw requires a community of moulds; pioneer moulds removing the plant's natural defence, lignin, followed by secondary and tertiary moulds with the ability to decompose the remaining cellulosic material, but decay kinetics is a complex subject to investigate. Signs of decay include production of $CO_2$, discolouration of the straw, an increase in local temperature, and an obvious smell of decay.

Decay kinetics are difficult to predict, not only requiring the presence of moisture, but simultaneously the correct temperature range, time period for germination of spores, and nutrients (physical and chemical characteristics of the substrate) in order for the biological metabolic process of decay to be stimulated. This explains part of the reasoning as to why there is an uncertainty surrounding a definitive agreement to the risk posed to straw from moisture, highlighting a gap in knowledge. One of the aims of the thesis was to provide a resolution to the uncertainty whilst researching a definition to the term 'Risk'. The thesis also undertook to: interpret monitoring data and the relationship between monitoring devices and the straw, a description as to how moisture interacts with straw in a bale, and how the moisture is transferred throughout a bale.

The investigation began by assessing a Case Study using oak wood-block probes as the monitoring device of choice (section IV.1 p105); if successful the research was to be expanded to incorporate multiple case studies. The case study results were also to be combined with laboratory experiments (section IV.3 p114) to verify the accuracy and effectiveness of the wood-block probes. It was noted during the laboratory experiments that a time lag exists in the absorption phase of the oak wood-block probes (Figure IV.10 p119), and that the difference in potential between the moisture content and the humidity of the surrounding air can affect the rate at which moisture is absorbed (Figure IV.13 p124); the less the difference the less the potential for moisture transfer. Straw, due to the material structure, has a greater proportional surface area and proportionally less core material than timber, and therefore adjusts to changing moisture conditions at a faster rate (Figure IV.14 p125).

The adsorption/absorption phase is the most significant for the purposes of monitoring, any delay with a reported increase in moisture may be the difference between destructive remedial work being carried out, or just locating and solving the problem. Due to the issue of response rate noted during use of the wood-block probes the research progressed to develop a new monitoring device capable of combating the disadvantages encountered (sections V.2 p129 and V.3 p133). The decision to develop a new monitoring device changed the path of the research from an investigation into multiple case studies to an investigation biased towards laboratory and test rig experimentation, also changing the case study to be viewed as a monitoring site.

Two new monitoring device concepts were devised to establish the moisture content of a straw bale construction. Firstly the relationship between the dimensional change in timber with regards to moisture (section V.2 p129); the experiment subjected timber to a range of humidities whilst measuring the change in diameter, along the grain, under a steady state temperature (Figure V.2 p131). Further research was halted however, due to installation and data recording issues, in favour of the development of the compressed straw probe (section V.3 p133).

The compressed straw probe represents a contribution to knowledge allowing a resistance meter and gravimetric analysis  reading to be established both of which display different results when subject to a dynamic environment. Early investigations highlighted this disparity and hypothesised that the resistance meter reading takes account of the surface moisture of the straw only, whereas, the gravimetric analysis encompasses the change in total mass; including not only the surface, but also the internal cellular structure (Figure V.4 p136). Further investigations were therefore required into both steady state and dynamic environmental conditions.

A field investigation was therefore designed to explore data produced in a dynamic environment. Due to the change in research direction a Test Rig was constructed with the ability to address the limitations of both: the monitoring site (24 hour site access, destructive testing and long term studies on potentially decomposing walls), and the laboratory studies (steady state environments, controllable variables and small scale investigations). The preliminary study of the Test Rig introduced the first section of the model, a visual identification system (Figure III.3 p100) applied to a contour plot (Figures V.17, V.18 and V.19 p148-149). The contour plot has the advantage as a quick assessment method for visualising the risk posed to the straw over a period of time however, the plot does not display detailed data for which further detailed investigations are required if a problem is highlighted (Figure V.27 p161).

During the preliminary investigation of the test rig it was noted that although the bales had been stored in the same environment for several months the starting moisture content of each differed not just from bale to bale, but between each position within a bale. It was hypothesised that the variations in readings were due to confounding variables such as: temperature, density of the bale, and naturally different moisture contents of the straw.

During construction of the test rig the effect of render application was studied (Figures V.22 and V.23 p154) showing that the first layer of render both internally and externally affected the moisture content of the interstitial straw, whereas, the second application showed a reduced effect. A bale containing elevated levels of moisture (advised against by literature and in general practice) was included, surmising; that it would introduce an inherent weakness into the building fabric. At the end of the preliminary investigation for the Test Rig (Figures V.26 p160 and V.27 p161) a hole was drilled into the bale that the elevated starting moisture. The straw was inspected finding no sign of decay despite the bale having experienced conditions of 'High Risk' moisture content at temperatures in excess of 10°C. A compressed straw probe was then inserted into the hole to continue the monitoring process and demonstrate the onset of any decay.

The initial assessment of the Test Rig was conducted with a Balemaster resistance meter, with the Balemaster probe attachment, later to be replaced by the Timbermaster. Both meters have the capability of automatically adjusting the reading for temperature with the addition of a thermocouple attachment. An experiment was conducted to verify the ability of the temperature adjustment equation and to calibrate both meters for use in straw (Section V.5 p163). The experiment produced evidence of a difference in readings between the Timbermaster and Balemaster; a cyclic pattern of temperature and moisture transfer within the bale, and the inaccuracy of the automatic temperature calibration inbuilt into the meters, or applied to the raw data using Equation II.5 (p73).

The relationship between the resistance meter and straw is complex requiring compensation factors for temperature and density together with an understanding that the results provide a moisture content value based on the surface of the straw and not, unless in a steady state environment, an accurate reflection as to the total moisture content of the straw. Equation VI.2 (p194) converts a Balemaster reading to a Timbermaster reading; note that the Balemaster used throughout this research is the USA version. The application of Equation VI.2 is illustrated by Figure VI.6 (p196) also showing the effect of Equation VI.1 (p192) that corrects any reading taken with the Timbermaster combined with the temperature at the point of measurement standardised for any desired calibration temperature.

Figure VI.7 (p199) demonstrated the process by which equilibrium within a bale is achieved. The experiment conducted in a dynamic environment (Test Rig) recorded moisture content from the Timbermaster with probe and relative humidity/temperature sensor together with a temperature measured with a digital thermometer at the point of measurement. The evidence suggests that as the temperature rose in the bale the relative humidity and $TM_{20}$ (Equation VI.1 p192) measurement did likewise, contrary to an earlier hypothesis that the straw moisture content was likely to drop due to the input of energy into the system. The revised hypothesis (Section VI.3.5.1 p198) suggested that transient moisture is driven into the interstitial bale by solar gain, raising the relative humidity and surface moisture content of the straw temporarily until the process is reversed.

Moisture transfer at a set temperature was studied in Section VI.4 (p202), a laboratory study demonstrating a time lag of relative humidity through a replica section of bale. It was concluded that the structure of the bale (Section II.1.3 p55), inhibits the migration of moisture, yet the bale will attempt to settle at equilibrium distributing the moisture throughout the system as observed in Figure VI.13 (p211) when the environmental chamber ran dry. The experiment also provided evidence suggesting that a difference in moisture interaction with the straw exists; the internal structure of the straw differing in moisture content from the external straw surface. The study into moisture transfer was then investigated in the test rig to evaluate a dynamic system.

In Section VI.4.4 (p214) the monitoring of the Test Rig provided evidence to suggest that render acts, in certain circumstances, as a storage medium for moisture, creating a reservoir for transient moisture that during solar gain (Table V.1 p158) is driven into the bale affecting the straw immediate to the external straw/render interface. The transient moisture as demonstrated in Section VI.4.2 (p208), cannot affect the interstitial relative humidity directly within the brief time-scale. The render acting as a storage medium is a product of poor air circulation (Figure VI.18 p219), dew forming externally to the construction on a surface that is cooler than the air temperature thus raising the moisture content.

The rate at which moisture passes through and interacts with the straw in a bale is a complex process dependant on: temperature, bale density, disparity between moisture levels, and location of the moisture. It is important to note that a small disparity between the relative humidity of a bale atmosphere and the moisture content of the internal cellular structure of the straw will not provide enough potential for absorption to affect the straw (Figure IV.13 p124).

The analysis of the Test Rig in comparison to the steady state laboratory experiments casts doubt on the oak wood-block probes and Lawrence's equation (Equation II.1 p61) to confidently and accurately reflect a dynamic environment relating to the moisture content of straw. Monitoring devices require the ability to react quickly to changing environments, such as a relative humidity sensor does, but be able to reflect the absorption-desorption and adsorption-desorption phases. Equation II.1 goes some way to promoting confidence however, the concept requires more development in the form of a model. Wood-block probes, with oak as the timber of choice, prove a useful and potentially accurate method of monitoring, yet the issue of the time-lag must be addressed.

From the study of the monitoring site a conclusion concerning protection was established; cladding suppressed the diurnal variations of the results slightly, yet the addition of a lean-too suppressed and reduced the moisture content of the wall further by increasing protection from wind driven rain whilst maintaining air circulation.

## VIII.3-Model Summary

The Model Chapter sought to combine the knowledge gained by the thesis to provide a platform on which to 'Quantify and Evaluate the Risk Posed to Straw Bale Constructions From Moisture'. The chapter produced Figure VII.2 (p240) and sought to address the limitations of the resistance meter by marrying the temperature compensation calculation (Equation VI.1 p192) with a density correction model (Equation VII.5 p239). The density correction model adjusts a resistance meter reading previously compensated for temperature ($RM_t$) for the dry density of the straw to an equivalent steady state gravimetric analysis however, the development of this method is only of use if the dry density of the straw can be established for instance from a compressed straw probe.

There are a number of devices and methods available for the monitoring of straw bale constructions each with advantages and disadvantages, yet each requires the ability to interpret the results obtained:

### VIII.3.1-Thermometer

A thermometer can be used to assess thermal efficiency and to warn of decomposition, but should be used in combination with another form of assessment.

### VIII.3.2-Weather Station

A weather station offers the ability to observe localised weather patterns and to correlate problems observed within the fabric of the construction with a weather event (Figure VI.24 p227). It can help instruct a model and be used to assess air movement surrounding a structure.

### VIII.3.3-Gravimetric Analysis

Gravimetric analysis is a valuable tool for describing the risk posed to straw in a steady state environment. It is however not a reliable or accurate way of obtaining an instantaneous reading of moisture in a dynamic system, due to the time-lag created by moisture movement through the internal cellular structure of the plant (Figure VI.4 p191). From a recent historical context however, it can illustrate previous conditions experienced by the bale.

### VIII.3.4-Wood-block Probes

The study of wood-block probes within this research project highlighted the care required in interpreting data. It is recommended that a potential 4 points be added to the percentage result acquired in the absorption/adsorption phase and any dramatic change should be verified with a resistance meter to accommodate for a lag in the readings. It is important to note that the wood-blocks analysed in this thesis were constructed of Oak; Ramin is identified by Carfrae as a competent replacement reducing the time-lag.

### VIII.3.5-Resistance Meters

A resistance meter whilst providing an instantaneous reading of straw moisture content requires compensation for density and temperature, and displays the result for the surface moisture level of the straw only. The surface moisture is subject to change at a rate determined by the energy within the system and the potential of the bale atmosphere.

### VIII.3.6-Relative Humidity

The analysis of humidity within a bale presents an issue when an attempt is made to convert the readings to an equivalent moisture content, Table VII.2 (p249) demonstrates the different results obtained from isothermal studies on which different methodological approaches were taken. Duggal and Muir's (1981) experiment stands out due to the adopted method, obtaining the gravimetric analysis at the end of the experiment and thus does not subject test specimens to extreme dry environments for sustained periods of time potentially disrupting the cellular structure of the straw; the drying of straw prior to experimentation requires further research to clarify the effect.

The evidence collected suggests that at relative humidities below 80% Lawrence et al's (2009b) equation (i=1.6) (Equation II.1 p61) is capable of converting relative humidity to an equivalent moisture content within a dynamic environment (Figure VII.4 p251). However, this thesis concludes that Isothermal studies should be re-evaluated taking into account the potential for mould development at high relative humidities. The study should also obtain the gravimetric analysis reading at the end of the study so long as the straw is in a steady state condition and the intracellular structure is in equilibrium with the surrounding environment.

In a dynamic environment the relative humidity of the bale atmosphere does not necessarily relate directly to the moisture content of the straw (Figure VII.12 p275) as the interaction depends on several variables including: position in the bale (the external render may be subject to moisture storage as illustrated in Section VI.4.4 p214), temperature, time, and potential difference in moisture content.

### VIII.3.7-Compressed Straw Probe

An advantage the compressed straw probe has over other mentioned monitoring devices is in the ability to monitor a section of a straw bale, from the construction’s interior to the exterior straw/render interfaces; opposed to a single measurement position. The compressed straw probe also has the benefit as a removable device, allowing for the straw within the probe to be inspected visually and sensed through olfactory perception, noting changes in colour and smell. The probe may also be disassembled and the straw inspected through microscopic evaluation.

The compressed straw probe provides two sets of data, one an instantaneous moisture content reading acquired by a resistance meter, the second a measurement of recent conditions within the bale as obtained from the change in mass (Section VII.3.7 p255). The two data sets take advantage of the adsorption and absorption phases in a dynamic situation providing a monitoring device that is accurate and informative.

## VIII.3.8-Isothermal Studies

Isopleth studies like isothermal studies are conducted in steady state environments and generally use preselected micro-organisms, therefore adopting this type of study into a model will demonstrate an over-prediction of mould development thus presenting an early warning system, but should be used with caution when basing a decision for destructive remedial action.

## VIII.3.9-Model

The implementation of the Fuzzy Risk Assessment System (Figure VII.6 p261) provides one of the contributions to knowledge utilising a descriptive language to explain the risk associated with the moisture level and addresses the uncertainty surrounding absolute values to which straw is susceptible to decay (Section II.1.2 p49). The Main Model (Figure VII.7 p265) is based on the Fuzzy Risk Assessment System, adding the caveat that moisture contents between 20 and 25$^{o}$C must be below temperatures of 10$^{o}$C to be classified at 'Medium Risk'. The model seeks to categorise information and provide advice based on historic trends, future scenarios based on previous seasonal weather data, a warning system to show the rate of moisture increase, and advice to suggest the urgency of locating the cause of a problem, or the need for destructive remedial action.

## ***VIII.4-Further work/Outstanding Questions***

A number of research questions were raised during this research:

1. The identification of a cyclic system in Figures V.29 p165 and VI.7 p199 questioned the affect of increasing and then decreasing the temperature of a bale (section VI.4 p202); if the temperature of the straw in a bale was increased, and was then allowed to returned to the starting temperature, without loss of overall moisture, would the straw return to the original moisture content?
2. Further research is required to quantify the effect of the internal surface of a straw stem on moisture transfer (Figure V.6 p167).
3. Does the act of compression (Section VI.2.2.2 p183) affect the results of the density experiments?
4. Further development is required on the compressed straw probe and relating factors (confirmation of density and temperature calibration equations for the resistance meters, adaptation to remote monitoring and data logging capabilities) to allow for the correct interpretation of the data.
5. The model requires further testing in dynamic environments addressing desorption, adsorption and absorption effects.
6. A question remains as to the number of monitoring devices required in a construction and to verify the best locations to confirm adequate monitoring and provide confidence in the construction.
7. In identifying the way in which moisture interacts with straw, within a walling system, types of render should be analysed under the application of the model.

## VIII.5-Contributions to Knowledge

A lack of definitive agreement concerning the risk posed to straw from moisture was highlighted in the summary of the literature chapter (Sections II.7 p84 and II.8 p87) and discussed throughout the thesis, starting with a definition of the term Risk (Section III.3.1 p96). It is impossible to define an absolute point at which moisture will affect straw in a negative capacity due to the complexity of the variables. In order to define Risk a fuzzy method of analysis has been adopted (Figure VII.6 p261) providing the assessor with an ability to describe the risk through language and percentage risk providing a degree of sophistication.

The knowledge of how to interpret data provided by different monitoring devices involves an understanding of: the way in which moisture interacts with straw and is transferred through a bale environment, together with a knowledge of what the device is capable of recording; resistance meters measure surface moisture of straw, whilst relative humidity sensors reflect the atmosphere.

### VIII.5.1-Major Contributions

1. Main Model: Figure VII.7 p265

   A model capable of evaluating the risk posed to straw bale constructions signalling the conditions acceptable prior to the crossing of a performance threshold.

2. Fuzzy Risk Assessment System: Figure VII.6 p261

   A system to quantify the risk posed to straw from moisture.

3. Contour plots: Figure V.17 and V.18 p148

   Contour plots offer a quick reference visual display system to warn interested parties of previous and current moisture trends.

4. Compressed Straw Probe: Figure V.3 p134

   Provides the ability to describe both instantaneous moisture content of the straw and a historical assessment of recent conditions together with visual and olfactory data through a section of a bale avoiding the issues of single point analysis.

5. Evaluation of monitoring devices: Section VIII.3 p291

   The evaluation of monitoring devices relates to the overall risk posed to a straw bale wall and encompasses an understanding of how the data obtained should be interpreted and perhaps most importantly the shortfalls of each device.

6. Moisture transfer within a bale: Section VI.4 p202

   Determining the rate at which moisture will transfer through a bale is a complex process involving interactions with the surface and internal structure of the straw, and is affected by temperature and density of the bale. The straw in a bale will attempt to equilibrate with the surrounding atmosphere however, the straw in the centre of a bale will react at a slower rate to the external (Figure VI.13 p211).

## VIII.5.2-Further Contributions

1. Moisture storage in render: Section VI.4.4 p214

   In regions of poor air circulation, the render may act as a storage medium for moisture allowing for the generation of transient moisture.

2. Transient moisture: Section VII.4.1 p257

   Transient moisture does not affect the straw in the bale significantly, but will be driven into areas of lower humidity in the external straw/render interface areas of the bale and will therefore be detected by relative humidity sensors. Transient moisture is a product of moisture retention by the render and the impact of direct sunlight.

3. Heliodome: Table V.1 p158

   The construction of a scale model, to evaluate direct sunlight obtained by measuring the path of the sun projected onto the model, provides an evaluative tool for assessment of moisture.

4. Resistance meter calibration: Equation VII.5 p239

   Equations were produced to switch between the Protimeter Balemaster (USA version) and Timbermaster readings (Equation VI.2 p194) and to compensate for the errors produced by straw temperature and density.

5. Hydrophobic, hygroscopic and hydrophilic; Section V.6 p167

   Water will bead on the external surface of straw however, the internal surface of the stem will absorb liquid immediately; the internal surface (Figure V.35 p169) is not commented on in literature.

## *VIII.6-Summary*

In summary the model combines the understanding of moisture transfer and interaction with data interpretation of the employed monitoring devices. The model offers interested parties a method by which to assess the risk posed to a construction and therefore make an informed decision using current, historic and predictive values. The assessment of moisture levels and environmental conditions may promote the construction lifetime by identifying potential issues prior to the onset of decay thereby increasing performance efficiency and reducing the need for repair leading to resource wastage and further $CO_2$ production.

In returning to the objectives of the research (Section I.1 p11); although there is no clear definition as to the point at which moisture becomes an issue to straw (Section II.1 p47), the Fuzzy Risk Assessment System (Figure VII.6 p261 and Table VII.3 p262) provide a tool by which a description of risk may be made. In analysing the different strengths and weaknesses of monitoring devices (Section VII.3 p242) the innovation of the compressed straw probe provides a detailed monitoring device that can be used in a 'stand alone' capacity or linked to a data logger. The compressed straw probe was designed to remove certain disadvantages experienced by other probes, but does not wholly replace the benefit of using a combination of monitoring methods to feed the model.

The interaction of moisture was highlighted as a major gap in knowledge with respect to straw (Section VI.4 p202), the resulting investigations revealed a complex system involving varying rates of adsorption, absorption and desorption dependant on the potential of the surrounding atmosphere. The investigations into moisture interaction lead to the identification of instances of transient moisture in renders exposed to poor air circulation (Section VI.4.4 p214).

The final objective was to develop a visual identification system and model to promote confidence in straw bale construction and in different monitoring techniques; figures VII.7-VII.10 (p267-272) demonstrate the outcomes.

*Table VIII.1: Addressing the Gaps in Knowledge*

| | **Gap in knowledge** | **Summary** | **Reference** |
|---|---|---|---|
| 1 | Agreement over Risk posed to straw. | Fuzzy Risk Assessment System. | Figure VII.6 p261 |
| 2 | Unclear definition of the term 'risk'. | Understanding of uncertainties and analysis of known probabilities. | Section III.3.1 p96 |
| 3 | Interpretation of monitoring device data. | Each device has individual abilities and restrictions. | Section VII.3 p242 |
| 4 | Relationship of straw to the monitoring device. | Correct interpretation of data required | Section VIII.3 p291 |
| 5 | How moisture interacts with straw. | Straw has an external hydrophobic surface and a hygroscopic internal surface. | Section V.6 p167 |
| 6 | How moisture transfers through a bale. | The rate of transfer depends on the potential of the surrounding atmosphere. | Section VI.4 p202 |

From the aims and objectives, and the literature review, six gaps in knowledge were identified (section II.7 p84); Table VIII.1 provides a brief description of how the gap was addressed together with a signpost reference.

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# Chapter X-Appendix A : Additional Data

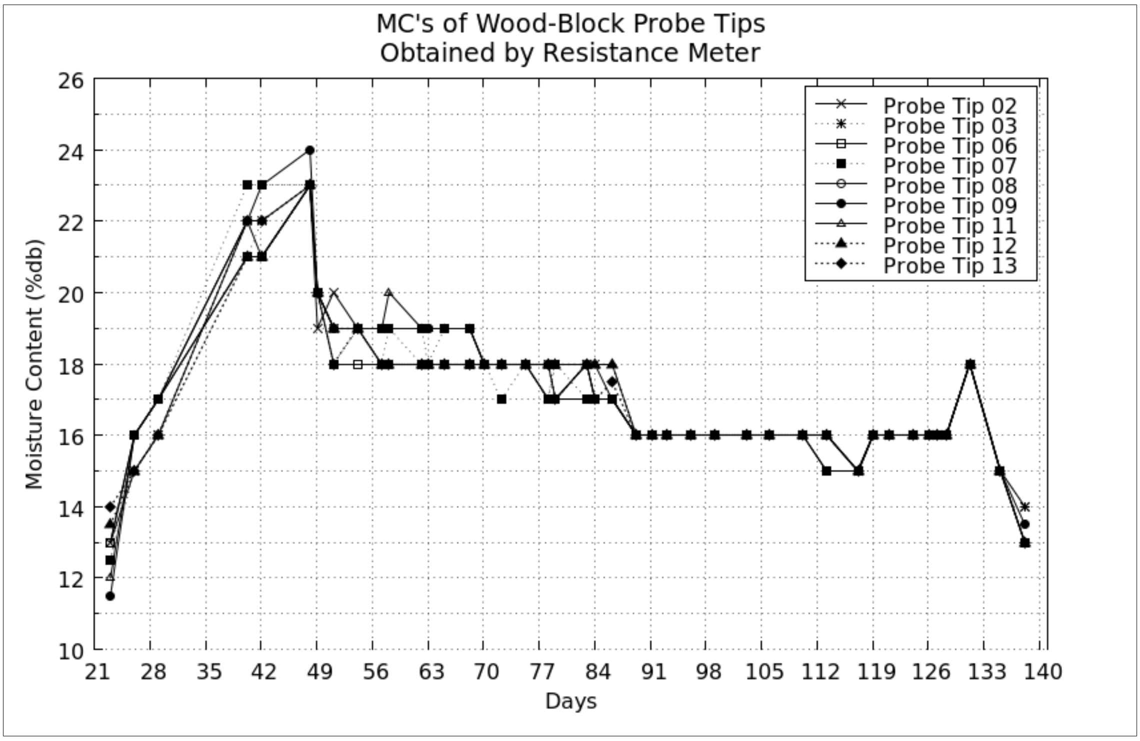


*Figure X.1: Individual wood-block probes tip results (Resistance Meter)*

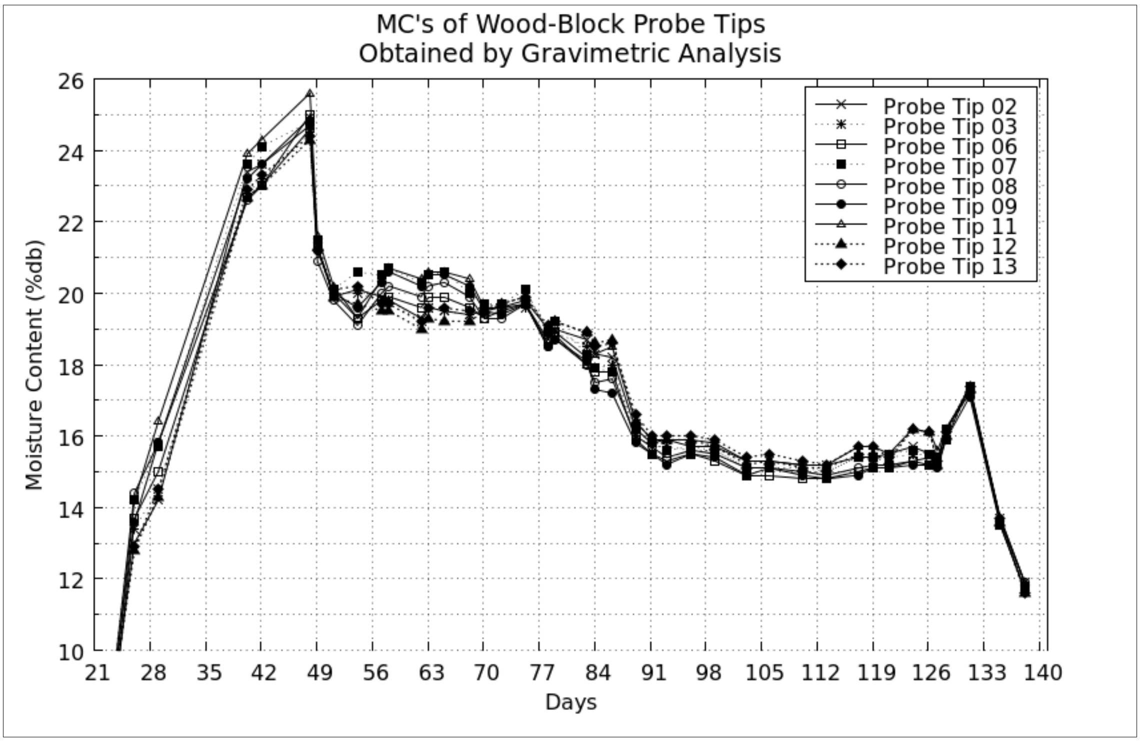


*Figure X.2: Individual wood-block probes tip results (gravimetric analysis)*

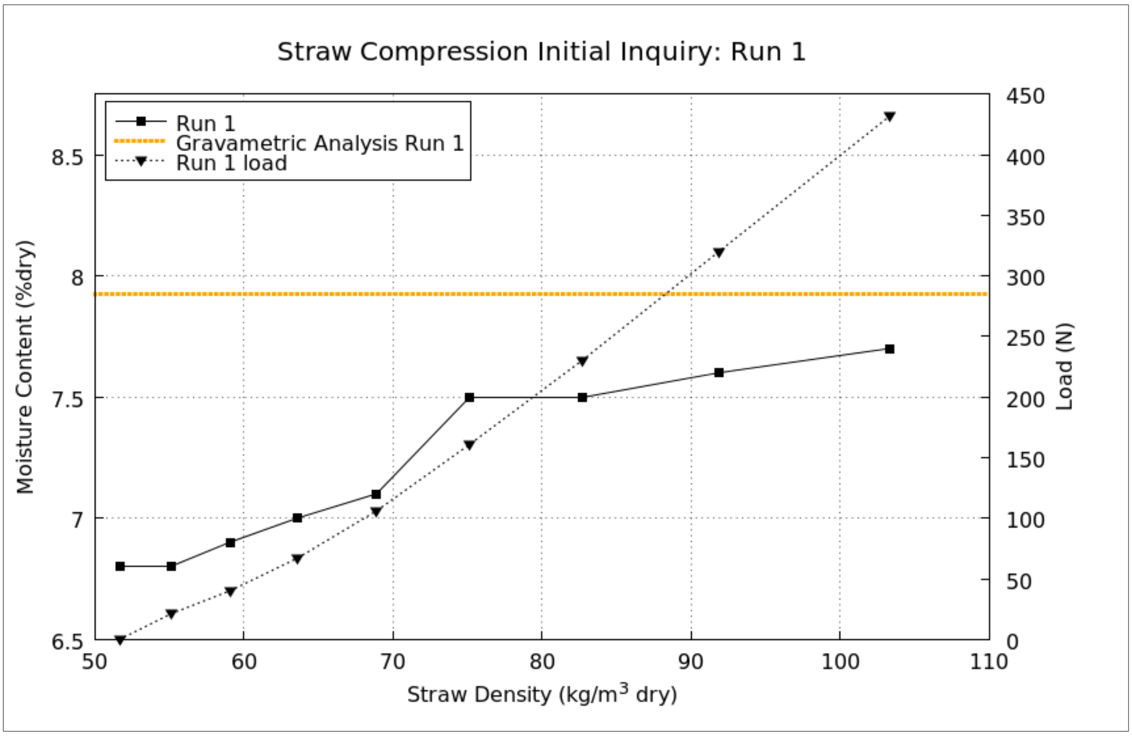


*Figure X.3: Results of Density Investigation Inquiry 1*

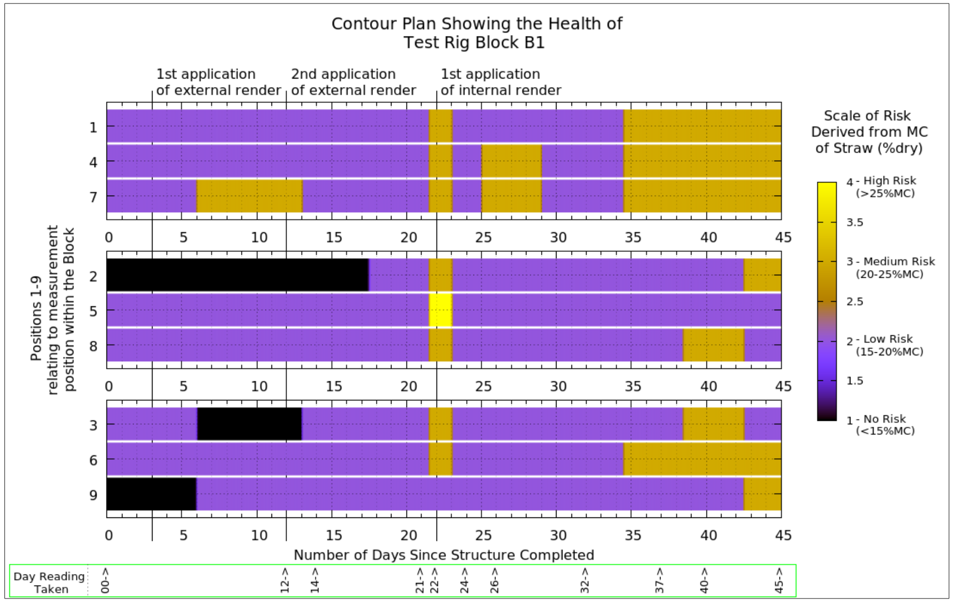


*Figure X.4: Preliminary Test Rig Data - B1*

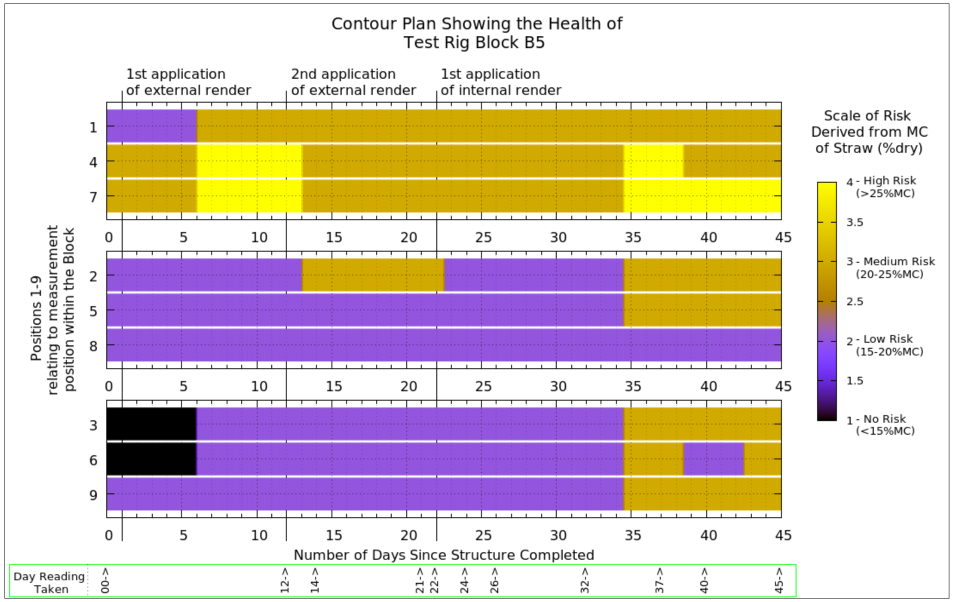


*Figure X.5: Preliminary Test Rig Data - B5*

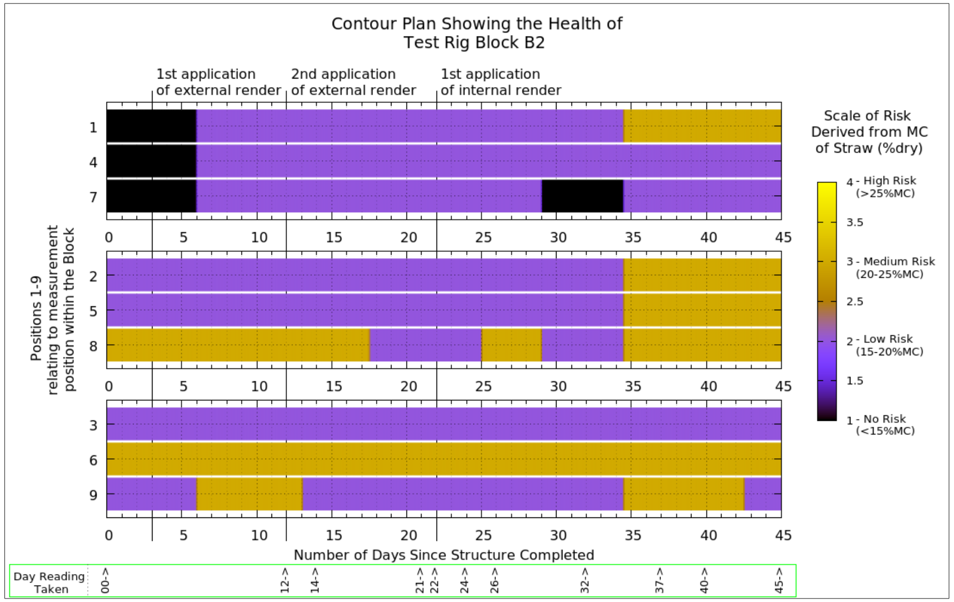


*Figure X.6: Preliminary Test Rig Data - B2*

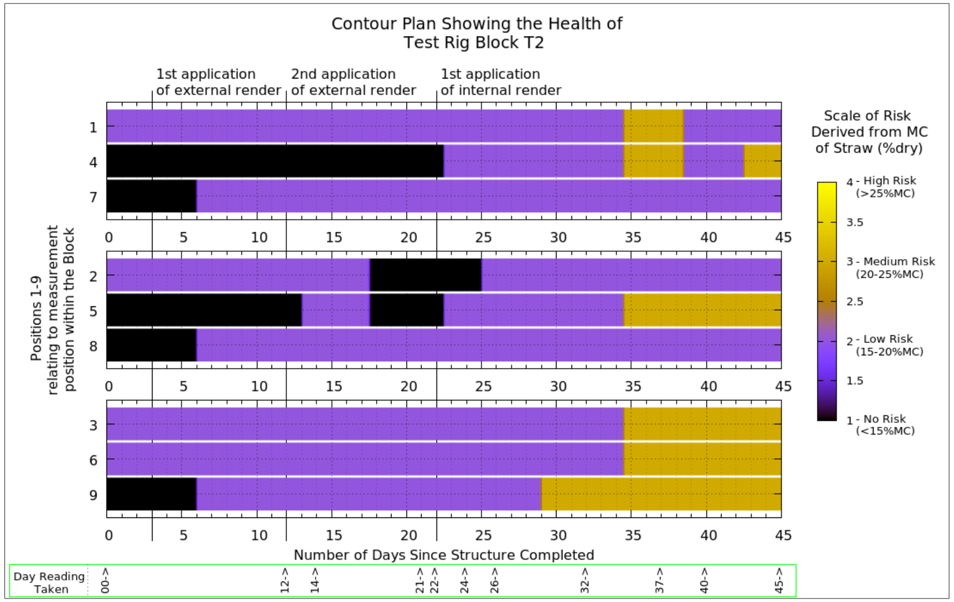


*Figure X.7: Preliminary Test Rig Data - T2*

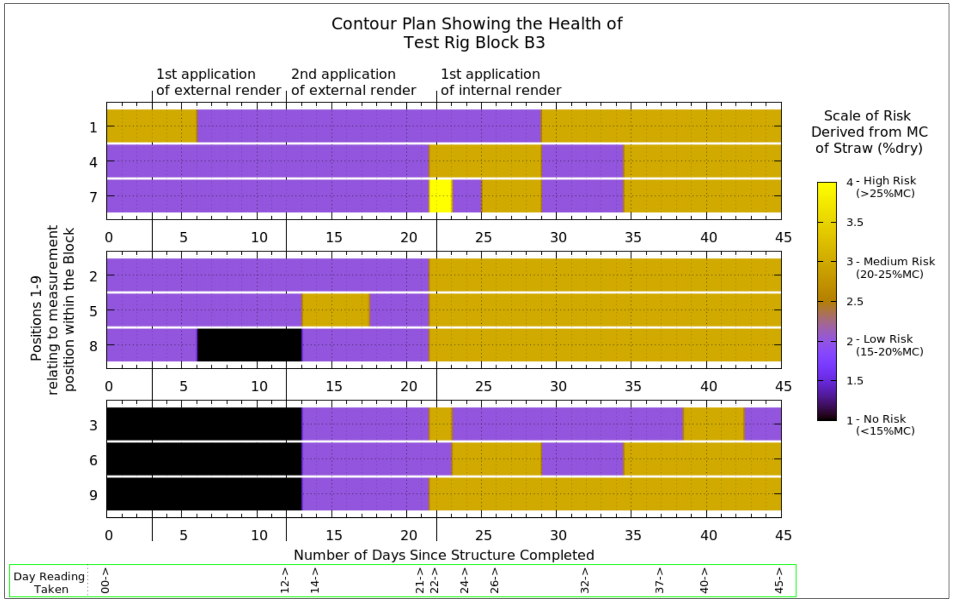
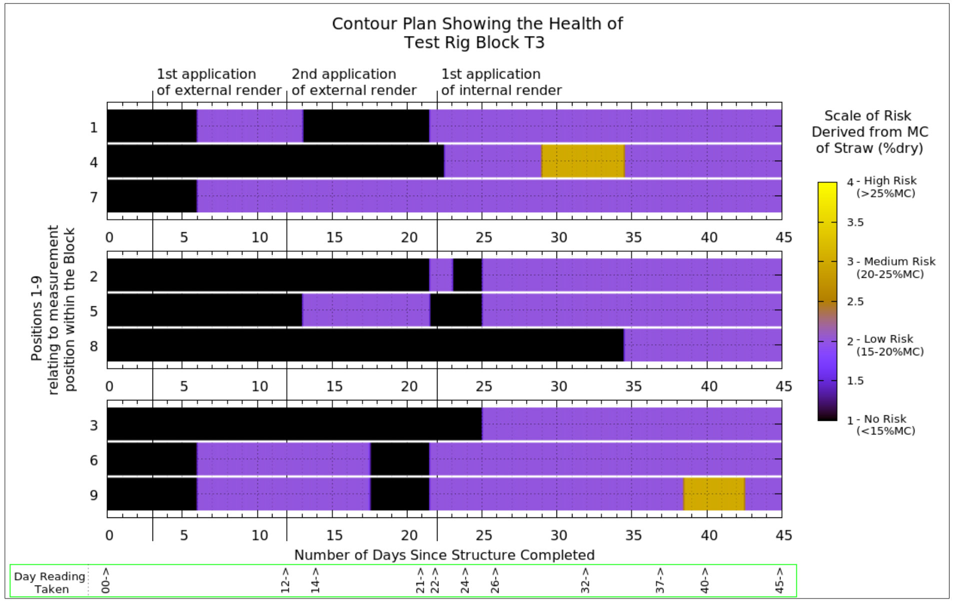


*Figure X.8: Preliminary Test Rig Data - B3*



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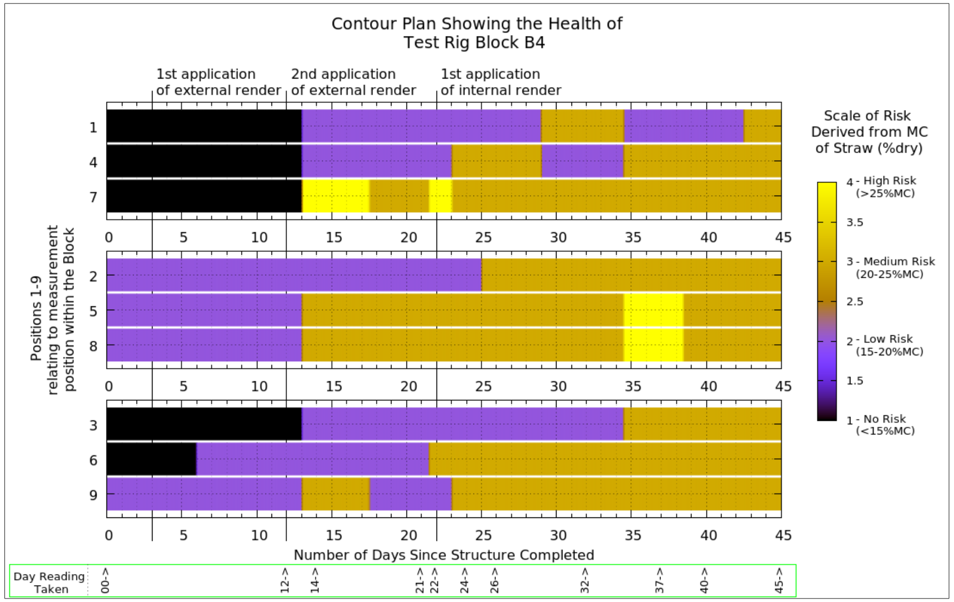

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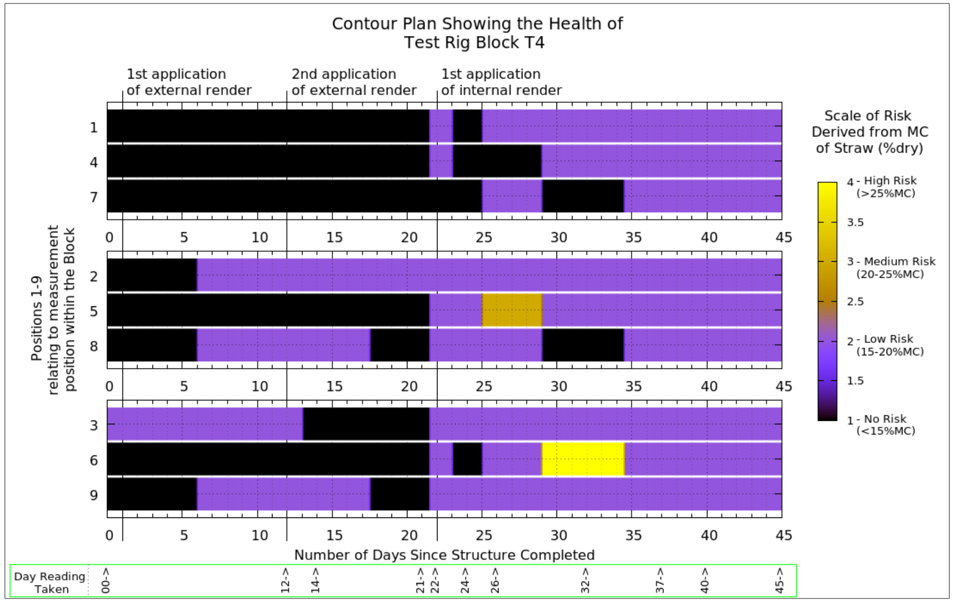

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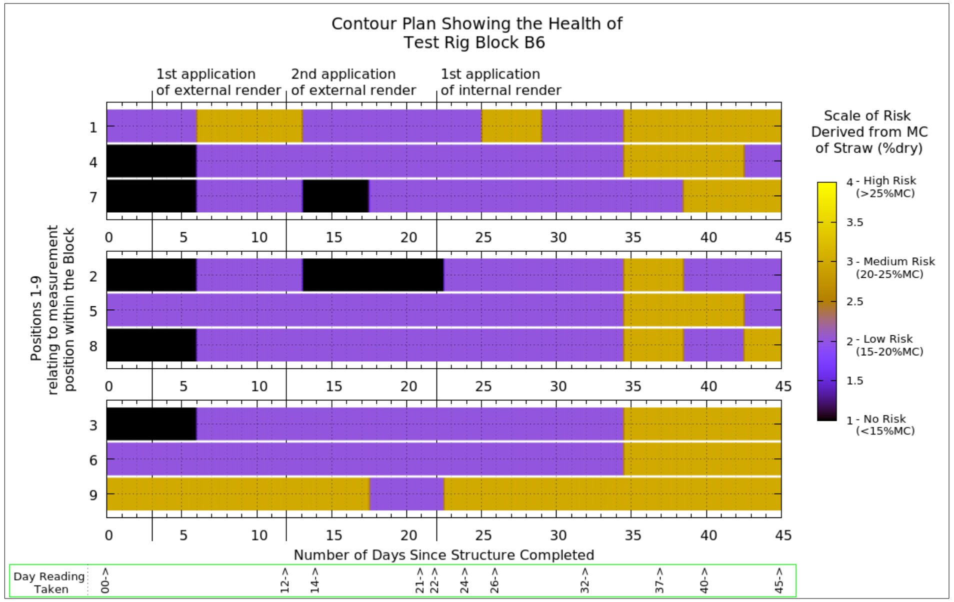

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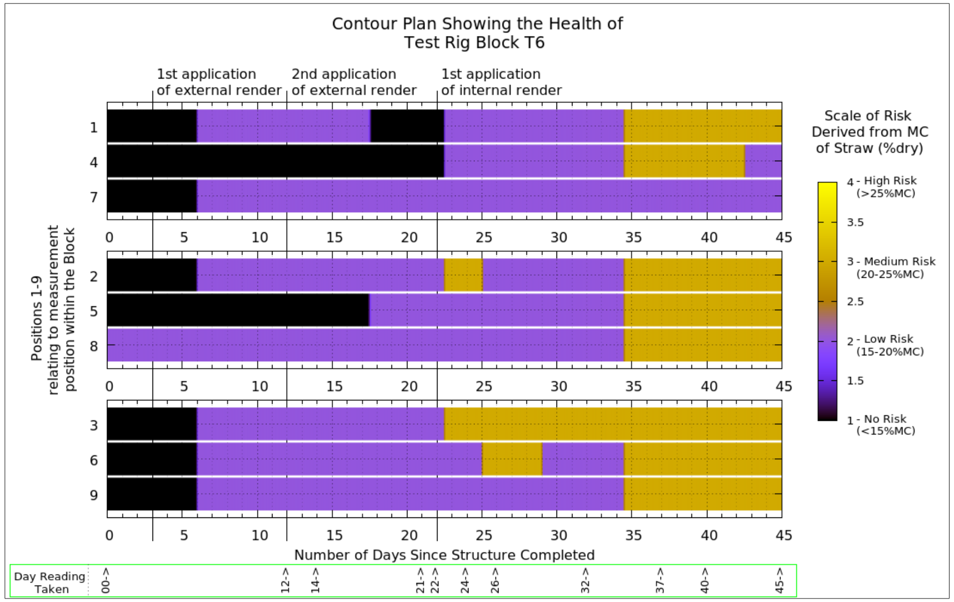


*Figure X.13: Preliminary Test Rig Data - T6*

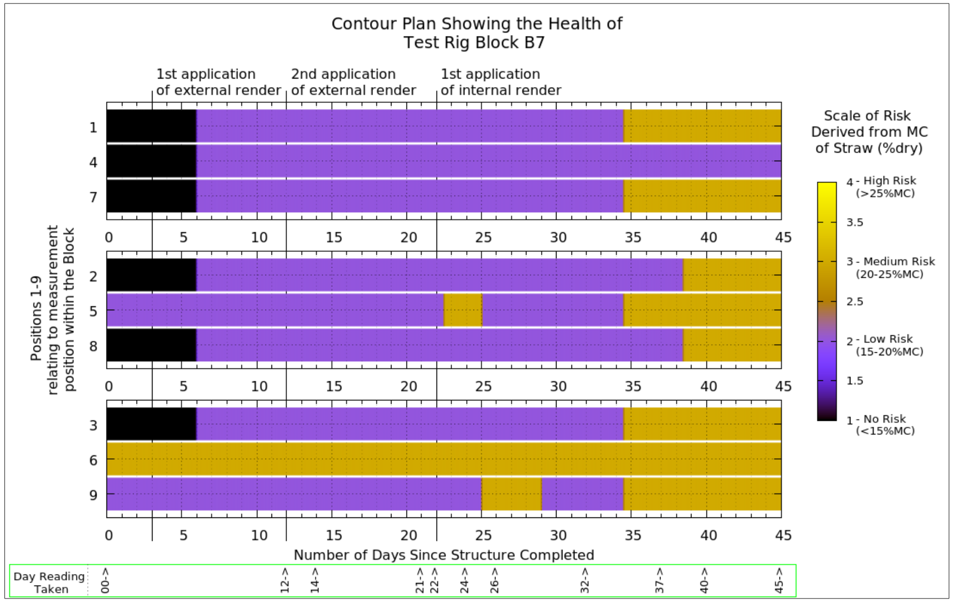


*Figure X.14: Preliminary Test Rig Data - B7*

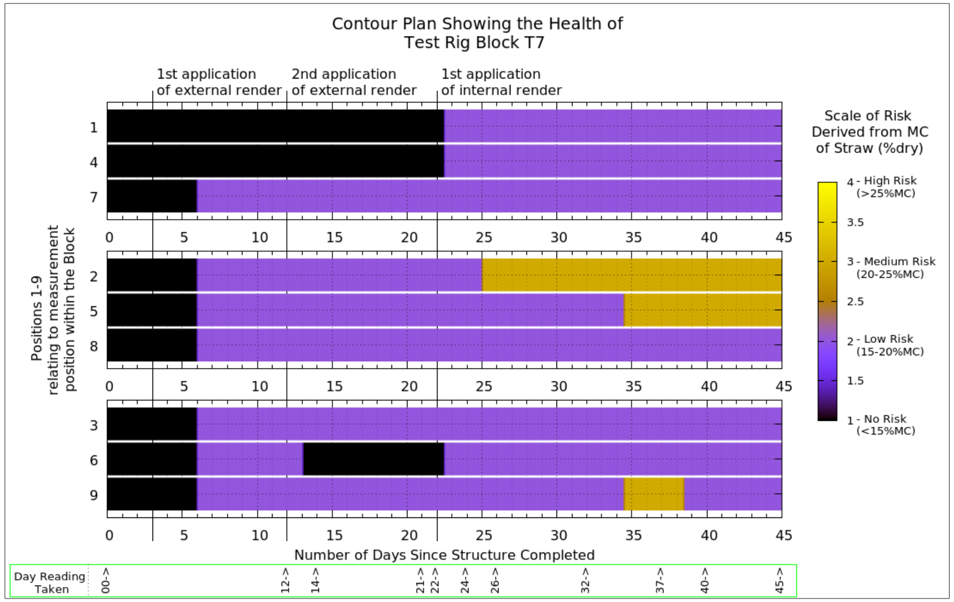


*Figure X.15: Preliminary Test Rig Data - T7*

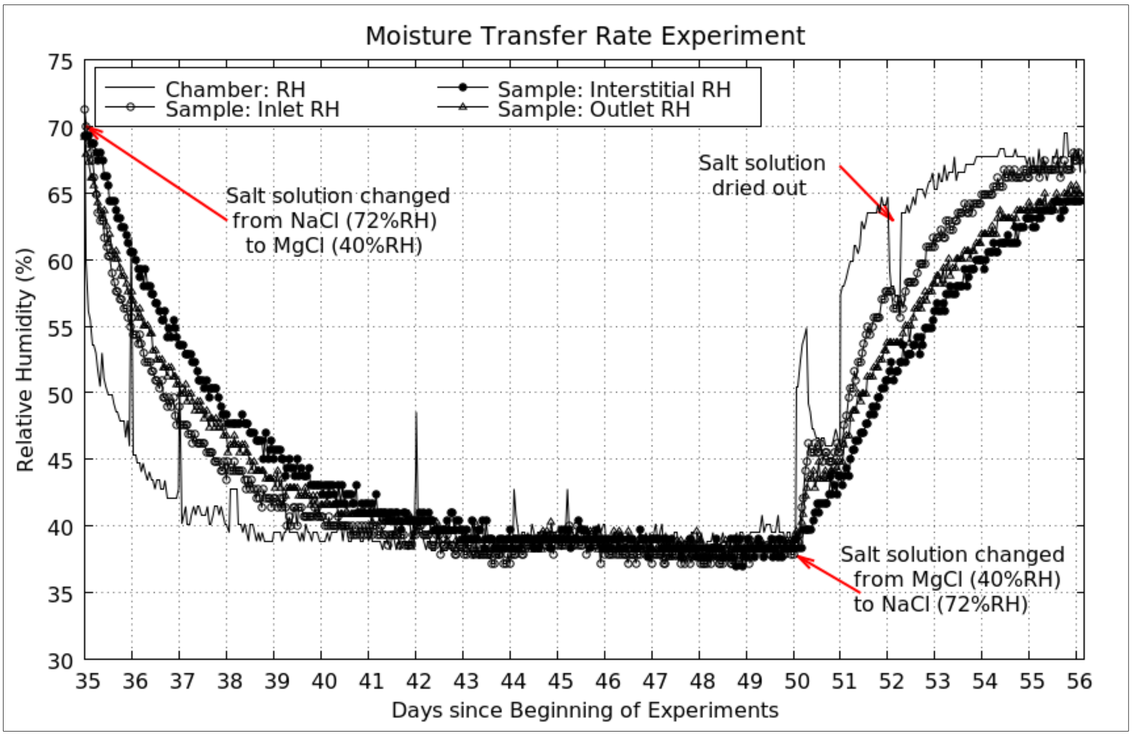
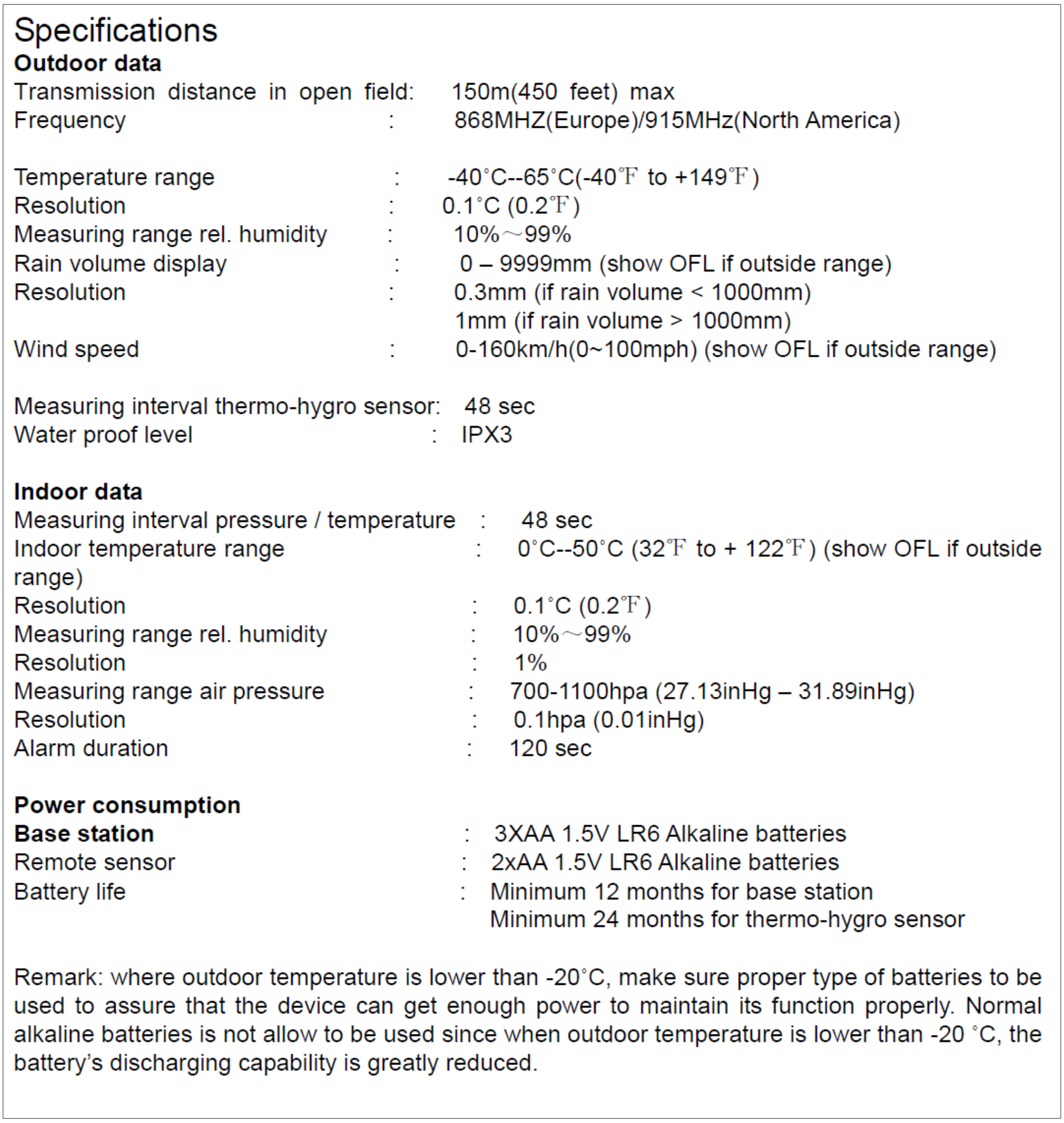


*Figure X.16: Moisture Transfer Laboratory Experiment*

# Chapter XI-Appendix B : Equipment

## XI.0.1-W-8681 Touch screen weather station



Specifications

**Outdoor data**

Transmission distance in open field: 150m(450 feet) max
Frequency : 868MHZ(Europe)/915MHz(North America)

Temperature range : -40°C--65°C(-40℉ to +149℉)
Resolution : 0.1°C (0.2℉)
Measuring range rel. humidity : 10%～99%
Rain volume display : 0 – 9999mm (show OFL if outside range)
Resolution : 0.3mm (if rain volume < 1000mm)
1mm (if rain volume > 1000mm)
Wind speed : 0-160km/h(0~100mph) (show OFL if outside range)

Measuring interval thermo-hygro sensor: 48 sec
Water proof level : IPX3

**Indoor data**

Measuring interval pressure / temperature : 48 sec
Indoor temperature range : 0°C--50°C (32℉ to + 122℉) (show OFL if outside range)
Resolution : 0.1°C (0.2℉)
Measuring range rel. humidity : 10%～99%
Resolution : 1%
Measuring range air pressure : 700-1100hpa (27.13inHg – 31.89inHg)
Resolution : 0.1hpa (0.01inHg)
Alarm duration : 120 sec

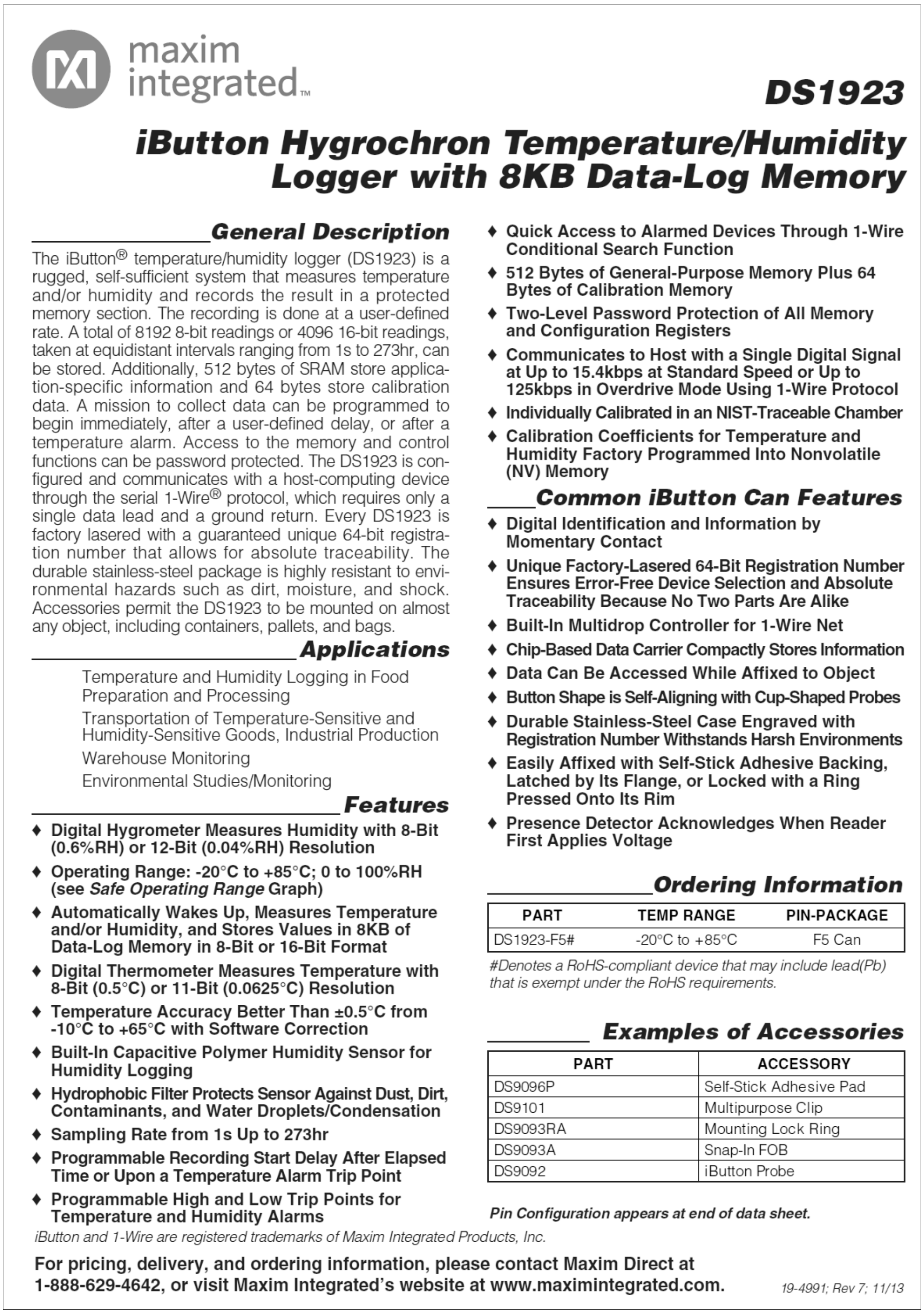
**Power consumption**

**Base station** : 3XAA 1.5V LR6 Alkaline batteries
Remote sensor : 2xAA 1.5V LR6 Alkaline batteries
Battery life : Minimum 12 months for base station
Minimum 24 months for thermo-hygro sensor

Remark: where outdoor temperature is lower than -20°C, make sure proper type of batteries to be used to assure that the device can get enough power to maintain its function properly. Normal alkaline batteries is not allow to be used since when outdoor temperature is lower than -20 °C, the battery's discharging capability is greatly reduced.

*Figure XI.1 W-8681 specifications (Maes Electronics No date)*

## XI.0.2-relative humidity iButton sensor



maxim integrated™

**DS1923**

# iButton Hygrochron Temperature/Humidity Logger with 8KB Data-Log Memory

## General Description

The iButton® temperature/humidity logger (DS1923) is a rugged, self-sufficient system that measures temperature and/or humidity and records the result in a protected memory section. The recording is done at a user-defined rate. A total of 8192 8-bit readings or 4096 16-bit readings, taken at equidistant intervals ranging from 1s to 273hr, can be stored. Additionally, 512 bytes of SRAM store application-specific information and 64 bytes store calibration data. A mission to collect data can be programmed to begin immediately, after a user-defined delay, or after a temperature alarm. Access to the memory and control functions can be password protected. The DS1923 is configured and communicates with a host-computing device through the serial 1-Wire® protocol, which requires only a single data lead and a ground return. Every DS1923 is factory lasered with a guaranteed unique 64-bit registration number that allows for absolute traceability. The durable stainless-steel package is highly resistant to environmental hazards such as dirt, moisture, and shock. Accessories permit the DS1923 to be mounted on almost any object, including containers, pallets, and bags.

## Applications

Temperature and Humidity Logging in Food Preparation and Processing

Transportation of Temperature-Sensitive and Humidity-Sensitive Goods, Industrial Production

Warehouse Monitoring

Environmental Studies/Monitoring

## Features

- ♦ **Digital Hygrometer Measures Humidity with 8-Bit (0.6%RH) or 12-Bit (0.04%RH) Resolution**
- ♦ **Operating Range: -20°C to +85°C; 0 to 100%RH (see *Safe Operating Range* Graph)**
- ♦ **Automatically Wakes Up, Measures Temperature and/or Humidity, and Stores Values in 8KB of Data-Log Memory in 8-Bit or 16-Bit Format**
- ♦ **Digital Thermometer Measures Temperature with 8-Bit (0.5°C) or 11-Bit (0.0625°C) Resolution**
- ♦ **Temperature Accuracy Better Than ±0.5°C from -10°C to +65°C with Software Correction**
- ♦ **Built-In Capacitive Polymer Humidity Sensor for Humidity Logging**
- ♦ **Hydrophobic Filter Protects Sensor Against Dust, Dirt, Contaminants, and Water Droplets/Condensation**
- ♦ **Sampling Rate from 1s Up to 273hr**
- ♦ **Programmable Recording Start Delay After Elapsed Time or Upon a Temperature Alarm Trip Point**
- ♦ **Programmable High and Low Trip Points for Temperature and Humidity Alarms**
- ♦ **Quick Access to Alarmed Devices Through 1-Wire Conditional Search Function**
- ♦ **512 Bytes of General-Purpose Memory Plus 64 Bytes of Calibration Memory**
- ♦ **Two-Level Password Protection of All Memory and Configuration Registers**
- ♦ **Communicates to Host with a Single Digital Signal at Up to 15.4kbps at Standard Speed or Up to 125kbps in Overdrive Mode Using 1-Wire Protocol**
- ♦ **Individually Calibrated in an NIST-Traceable Chamber**
- ♦ **Calibration Coefficients for Temperature and Humidity Factory Programmed Into Nonvolatile (NV) Memory**

## Common iButton Can Features

- ♦ **Digital Identification and Information by Momentary Contact**
- ♦ **Unique Factory-Lasered 64-Bit Registration Number Ensures Error-Free Device Selection and Absolute Traceability Because No Two Parts Are Alike**
- ♦ **Built-In Multidrop Controller for 1-Wire Net**
- ♦ **Chip-Based Data Carrier Compactly Stores Information**
- ♦ **Data Can Be Accessed While Affixed to Object**
- ♦ **Button Shape is Self-Aligning with Cup-Shaped Probes**
- ♦ **Durable Stainless-Steel Case Engraved with Registration Number Withstands Harsh Environments**
- ♦ **Easily Affixed with Self-Stick Adhesive Backing, Latched by Its Flange, or Locked with a Ring Pressed Onto Its Rim**
- ♦ **Presence Detector Acknowledges When Reader First Applies Voltage**

## Ordering Information

| PART | TEMP RANGE | PIN-PACKAGE |
|---|---|---|
| DS1923-F5# | -20°C to +85°C | F5 Can |

*#Denotes a RoHS-compliant device that may include lead(Pb) that is exempt under the RoHS requirements.*

## Examples of Accessories

| PART | ACCESSORY |
|---|---|
| DS9096P | Self-Stick Adhesive Pad |
| DS9101 | Multipurpose Clip |
| DS9093RA | Mounting Lock Ring |
| DS9093A | Snap-In FOB |
| DS9092 | iButton Probe |

***Pin Configuration appears at end of data sheet.***

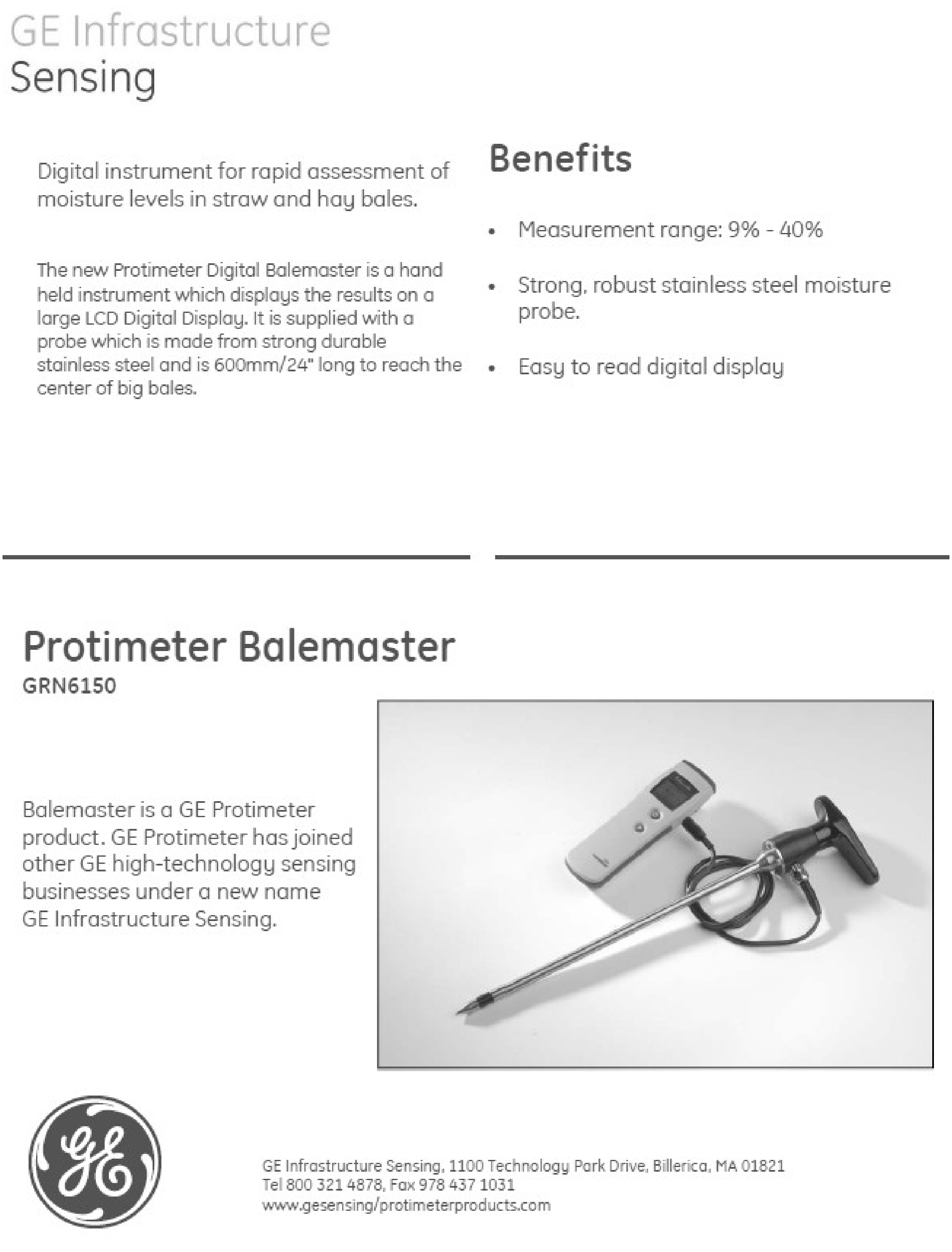
*iButton and 1-Wire are registered trademarks of Maxim Integrated Products, Inc.*

**For pricing, delivery, and ordering information, please contact Maxim Direct at 1-888-629-4642, or visit Maxim Integrated's website at www.maximintegrated.com.**

*19-4991; Rev 7; 11/13*

*Figure XI.2: The iButton sensor used to record temperature and humidity (Maxim Integrated Timbermaster 2014)*

## XI.0.3-Balemaster



GE Infrastructure
Sensing

Digital instrument for rapid assessment of moisture levels in straw and hay bales.

The new Protimeter Digital Balemaster is a hand held instrument which displays the results on a large LCD Digital Display. It is supplied with a probe which is made from strong durable stainless steel and is 600mm/24" long to reach the center of big bales.

**Benefits**

- Measurement range: 9% - 40%
- Strong, robust stainless steel moisture probe.
- Easy to read digital display

**Protimeter Balemaster**
GRN6150

Balemaster is a GE Protimeter product. GE Protimeter has joined other GE high-technology sensing businesses under a new name GE Infrastructure Sensing.

GE Infrastructure Sensing, 1100 Technology Park Drive, Billerica, MA 01821
Tel 800 321 4878, Fax 978 437 1031
www.gesensing/protimeterproducts.com

*Figure XI.3: Balemaster specifications (GE Measurement & Control 2014)*

## XI.0.4-Timbermaster

GE Infrastructure
Sensing

# Mini Specifications

**Calibration Chart**
150 commonly used species

**Plug in**
Extension pin probe (Included)

**Calibration**
Check device (Included)

**Case**
Pouch with belt loop (Included)

**Warranty**
One year parts and labor

**Options**
Hammer electrode
Deep wall probes

## GE Protimeter Mini

Low cost, analog pin-type moisture meter

**Range**
6% to 90% numerical label

**Display**
60 LEDs–green (dry), yellow (at risk) and red (wet)

**Part Number**
BLD2000

**Power**
9 V (Included)

## GE Protimeter Timbermaster™ Mini

Low cost, digital pin-type moisture meter

**Range**
7% to 99.9%

*Mini kit*

*Timbermaster Mini kit*

**Display**
Digital, resolution 1/10 of 1%

**Species Correction**
Nine species groups built in

**Part Number**
BLD5604

## Technical Specifications

**Weight, Including Batteries**
.330 lbs (150g)

**Dimensions**
7.02 in x 1.09 in x 1.91 in (180 mm x 28 mm x 49 mm)

**Batteries**
2 AA (Included)

**Measurement Range % WME**
6% to 90%

*Figure XI.4: Timbermaster specifications (GE Measurement & Control 2014)*

# Chapter XII-Appendix C : Glossary and Abbreviations

## ***XII.1-Glossary***

Bezier curve – A parametric curve used to model a smooth line

Basidiomycetes - “*any fungus of the phylum Basidiomycota (formerly class Basidiomycetes), in which the spores are produced in basidia. The group includes boletes, puffballs, smuts, and rusts*” (Collins 2014)

Degredation - “*a breakdown of a molecule into atoms or smaller molecules*” (Collins 2014)

Mycelium - “*the vegetative body of fungi: a mass of branching filaments (hyphae) that spread throughout the nutrient substratum*” (Collins 2014)

Polysaccharides - “*any one of a class of carbohydrates whose molecules contain linked monosaccharide units: includes starch, inulin, and cellulose. General formula:* $(C_6H_{10}O_5)_n$” (Collins 2014)

*Xerophilous - “(of plants or animals) adapted for growing or living in dry surroundings” (Collins 2014)*

## XII.2-Abbreviations

| | |
|---|---|
| BM | Balemaster |
| BMp | Balemaster with Balemaster probe |
| BMt | Balemaster with thermocouple |
| CMHC | Canadian Mortgage Housing Corporation |
| $CO_2$ | Carbon dioxide |
| CSP | Compressed Straw Probe |
| EWD | Expandable Wood Disc |
| FRAS | Fuzzy Risk Assessment System |
| GA | Gravimetric analysis |
| $kg/m^3_d$ | Dry Density-Kilograms per meter cubed |
| $kg/m^3_w$ | Wet Density-Kilograms per meter cubed |
| MC | Moisture Content |
| $MC_{dry}$ | Moisture Content Dry Basis |
| RH/T | Relative Humidity and Temperature |
| td | Time dependant |
| TM | Timbermaster |
| $TM_{20D}$ | Timbermaster adjusted for temperature and density |
| TMp | Timbermaster with Balemaster Probe |
| TMt | Timbermaster with thermocouple |
| WBP | Wood-Block probe |

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