Graduate School of the Environment,
Centre for Alternative Technology,
Machynlleth,
Powys,
SY20 9AZ.
United Kingdom

Tel: 01654 705981

And:

School of Computing and Technology,
University of East London,
Docklands Campus,
4-6 University Way,
London,
E16 2RD.
United Kingdom

Tel: 020 8223 3000

Frost Damage in Solid Masonry Walls Retrofitted with Internal Insulation

Dan Browne

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Author's contact details:

e-mail: dan@williamsandbrowne.co.uk

Contact: 07989 171784

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Preface

This thesis focuses on the issue of frost damage to external brickwork that can arise from high levels of additional internal wall insulation. Computer based simulations and real building studies have shown that adding insulation in this way can increase the risk of damage but no studies have focused on how this problem may affect the UK's solid walled housing stock.

The insulation of existing homes is essential if we are to reduce primary energy demand and associated green house gas emissions. This is particularly important as it is estimated that between 66% and 85% of the current building stock will be standing in 2050. Reducing heat loss in our solid walled housing stock is complicated but essential as these homes are often the worst thermal performers. Due to the preservation of the historical appearance of these buildings, external insulation may not always be possible.

The work presented here includes a review of current theory on moisture transfer mechanisms in building materials and examines the action of frost damage to brickwork. Through the use of WUFI Pro 4.2 hygrothermal simulation software this thesis investigates the changes to moisture content and temperature in five types of brick after application of additional internal wall insulation (IWI). Climate files are used from eight locations around the UK in order to establish areas that may suffer more severely than others. At each location the bricks are simulated with four different types of insulation to establish if any are better suited to internal application.

The WUFI simulations have returned many unexpected results and most importantly no instances of frost damage conditions have been found even at locations where bricks are known to fail. This is most likely due to the exclusion of extreme weather conditions by the climate files used. In all cases the bricks' moisture content rose significantly and an increased number of annual zero degree crossings are observed.

The thesis concludes that more research is needed into the detrimental effects of IWI and to create a new weather file that includes annual extreme events. The theories developed here play a small part in informing us on how best to proceed with reducing our national energy demand but also unfortunately raise many more questions.

Acknowledgements

I would like to firstly thank Mike Thompson for running such an inspiring and life changing course, Ruth Stevenson my tutor for all her support throughout the MSc and Jason Hawkes my thesis supervisor for being great and keeping me on track.

Special thanks Lawrence Brown for all his help and enthusiasm in developing my initial ideas into a thesis proposal and for all his encouragement when no one else cared or understood.

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I also wish to thank Dr. Andrew Smith and Professor Geoff Edgell for their help, advice and for the tour of their frost testing facilities at CERAM, Roger Sharp at Hanson Bricks for the values of Stewartby Flettons and Professor Peter Brimblecombe at the University of East Anglia for his endless patience and advice when writing an AWK programme to read my ASCII output files.

All of this would not have been possible without my grandparents, Elsa and Cyril, for financing the course and all the unconditional support from my mother Penny.

Last but by no means least extra special thanks to little Gracie for letting me study in her bedroom and for making me smile when it all got too much and to my girlfriend Chloe Pepper for her tolerance and patience when listening to nothing but frost damage for months on end and for supporting me and assisting in editing this thesis.

I hope that this small piece of work and the work of environmentalists all over the world will help to achieve in making this planet a better place for Gracie's generation and those to follow.

Contents

List of Abbreviations and Symbols

μ-value	Diffusion resistance factor [-]
A-value	Water absorption coefficient [kg/m²√s]
B-value	Water vapour buffer capacity [-]
K-Value	Thermal conductivity (lambda value) [W/m K]
Sd-value	Vapor diffusion thickness [-]
U-value	Thermal Transmittance [W/m^2 K]

BDA	Brick Development Association
BERR	Department for Business, Enterprise and Regulatory Reform
BRE	Building Research Establishment
BSI	British Standards Institution
CIBSE	Chartered Institution of Building Services Engineers
DCLG	Department for Communities and Local Government
DEFRA	Department for Environment, Food and Rural Affairs
DTI:	Department of Trade and Industry
EPS	Expanded polystyrene
EST:	The Energy Saving Trust
F_{MAX}	75% of free water saturation (frost damage threshold)
GHG	Greenhouse Gas
HTT	Hard To Treat homes
IBP	Fraunhofer Institute for Building Physics
IWC	International Weather for Energy Calculations (climate file)
IWI	Internal Wall Insulation
MC	Moisture Content
MtC	Million tonnes of carbon
MW	Mineral Wool insulation
NBT	Natural Building Technologies
NI	No Insulation
ODPM	Office of the Deputy Prime Minister
ONS	Office for National Statistics
OPSI	Office of Public Sector Information
PF	Phenolic insulation
POST	Parliamentary Office of Science and Technology
RH	Relative Humidity
SAP	Standard Assessment Procedure
TRY	Test Reference Year (climate file)
WAC	unknown (climate file)
WET	unknown (climate file)
Wf	Free water saturation
WF	Wood-fibre insulation
WRI	World Resources Institute
WUFI	Wärme und Feuchte instationär - Transient Heat and Moisture simulation software

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Introduction

It is clear that when compared to much of the world's population, the contemporary western lifestyles we lead are extremely wasteful. A major restructure of most of modern society is needed if we are going to be successful in meeting the commitments made by our governments to reduce greenhouse gas emissions. The United Kingdom, as part of the Climate Change Act 2008 has committed to an 80% reduction in carbon dioxide emissions by 2050 against 1990 levels (Office of Public Sector Information 2008, p.1 and 3).

With our modern lifestyles it is estimated that we now on average spend 90% of our time indoors (Oliver et al. 1996, p.10). Some of this time will be in the workplace but still, much of our life is centred around the 'home' and therefore much of the energy we use is wasted within them. According to 2006 figures, roughly 30% of the UK's final energy consumption is used by the domestic sector (BERR 2008b).

The systematic refurbishment of the majority of the UK's 25 million homes to reduce energy demand is an inevitable task. This undertaking is huge and very complicated, and in many ways it is no surprise that as a nation we will put it off to the last minute.

Annually, space heating has accounted for over half of all domestic energy used for the last 30 years (Utley & Shorrock 2008, pp.3 & 91). After adding loft insulation and fitting draft excluders, further measures to reduce energy loss like fitting new windows and adding wall insulation are very costly and disruptive. Unfortunately it is exactly these measures that will make the biggest difference to our household energy use. Our government is slowly implementing grants for cavity wall insulation and renewable energy technologies for our homes, but so far, reducing the energy demand of our 6.6 million solid walled (BRE 2008, p.6), pre 1930s housing stock has not been widespread.

The need to preserve our architectural history at the same time further complicates the problem. Whilst new double glazing can be made to closely match existing windows, external insulation changes the whole appearance of a building and some critics may deem this to be unacceptable. In many cases the only option will be internal wall insulation.

Internal wall insulation (IWI) is a necessary but disruptive solution to reducing the energy demand of our solid wall homes. There are many approaches and insulation choices but resolving issues of detailing to avoid problems with moisture are key to all of them. Whether it be surface condensation on thermal bridges, interstitial condensation or mould growth, careful planning and forethought need to be exerted to avoid damaging our buildings. Unfortunately many buildings have already been damaged by misguided and thoughtless attempts to improve them over the years (Griffiths 2007, p.13). The consequence of a failed nationwide retrofit of internal wall insulation to our solid wall housing stock is alarming. The wasted energy, money, time and materials would be colossal. We should be aiming for high quality retrofits with high levels of insulation so that refurbishments undertaken now would last right up to, and beyond our 2050 deadline.

We cannot afford to get this wrong. The upgrade of our housing stock with serious energy saving measures needs to happen only once between now and 2050.

This thesis examines one under-researched problem rarely associated with high levels of internal wall insulation - frost damage to external masonry. After internally insulating, the outward heat flow through external solid walls is reduced and exposes the bricks surface to temperatures low enough to potentially cause frost attack. The action of freezing water causing frost damage is not just dependant on low temperatures, the bricks themselves need to be of low frost resistance and a high water content on freezing is needed inside the bricks pore structure.

In order to test this quickly and at low cost, a computer programme that simulates transient heat and moisture flows in building envelopes is used. The programme, WUFI, has been developed by the Fraunhofer Institute for Building Physics and has been validated against real building testing over a number of years. The experiment uses measured weather data to simulate the changes that take place in a brick wall after adding internal wall insulation of different types.

The aim of this thesis is to answer the following questions:

- Do high levels of internal wall insulation have the potential to cause frost attack to vulnerable bricks?
- Are any types of insulation better at reducing this risk?
- Is the wind driven rain exposure zone of the wall a good indicator of the amount of risk?
- Will the threat of frost damage change our energy targets or approach to renovating the UK's solid walled homes?

In order to answer these questions and discuss frost damage within the context of reducing national greenhouse emissions, this thesis will take the following format:

Chapter 1 — *The Conservation of Energy and the Role of Building Refurbishment*, places UK emissions in a global context and highlights the savings to be made through reducing the energy consumption of our housing stock. This focuses on reducing space heating of solid walled homes.

Chapter 2 — Reviews literature on hygrothermal processes in building materials and highlights the negative issues of moisture as a result of refurbishing buildings.

Chapter 3 — Examines how frost damage occurs and what factors make bricks vulnerable to degradation. This type of masonry weathering is then discussed as an unforeseen side effect of internal wall insulation, with current topical literature reviewed.

Chapter 4 — Explores the boundaries of computer simulations and specifically WUFI Pro 4.2. Investigative experiments are run and analysed in order to establish the parameters needed to accurately simulate frost damage in bricks from additional internal wall insulation.

Chapter 5	*The Methodology* defines the boundaries of the experiment and the procedures involved in the numerical simulation. Material values are decided upon and the procedure for analysis of the results is outlined.
Chapter 6	Presents the results of five types of masonry internally insulated with four types of insulation. Experiments are simulated at a total of eight locations around the UK in different climatic conditions.
Chapter 7	Analyses the findings and the shortcomings of the experiment. The findings and implications are discussed and compared to current theory on the subject.
Chapter 8	Concludes the findings of the experiment and what this means for the building industry and suggests where future studies should be focused.

Throughout this thesis the word ‘moisture’ refers to water in its three states (vapour, liquid and ice) and the term ‘masonry’ refers to constructions of brick held together with mortar.

Chapter 1

The Conservation of Energy and the Role of Building Refurbishment

This Chapter looks into UK energy use and presents the problem of how to reduce the energy demand of the UK's poorest performing buildings.

1.1 UK Greenhouse Gas Emissions

Concerns over climate change, greenhouse gas (GHG) emissions and energy availability are forcing the developed world to address their energy consumption. It was estimated by the Department for Environment, Food and Rural Affairs (DEFRA) (2006, p.24) that the UK's emissions of the six greenhouse gasses covered by the Kyoto Protocol were in the region of 178.5 MtC in 2004[1]. In 2000 these emissions ranked the UK as the 34th largest per capita polluter in the world (World Resources Institute (WRI), 2008). In order to reduce these emissions the Climate Change Act 2008 has committed the UK to an 80% reduction in carbon dioxide emissions by 2050 with a 26% reduction by 2020 against a 1990 baseline (Office of Public Sector Information 2008, p.1 and 3).

1.2 Energy Use In Buildings

As seen in *fig. 1.1*, total primary energy consumption by the UK amounted to 232.3 million tonnes of oil equivalent (BERR 2008b) in 2006, of this, the domestic sector accounts for about 30%. Within this sector, the largest proportion of energy is used for space heating, which has annually been responsible for over half of all energy used in the UK housing stock from 1970 to 2006 (Utley & Shorrock 2008, p.3 & 91). Domestic energy for 2006 by end use is shown in *fig. 1.2*, with space heating accounting for 57%. According to the Parliamentary Office of Science and Technology (POST) (2005) the UK housing stock is considered to be some of the least efficient in Europe and total GHG emissions from homes were responsible for approximately 43.7 MtC in 2004, 24.5% of total emissions (DEFRA 2006, p.77).

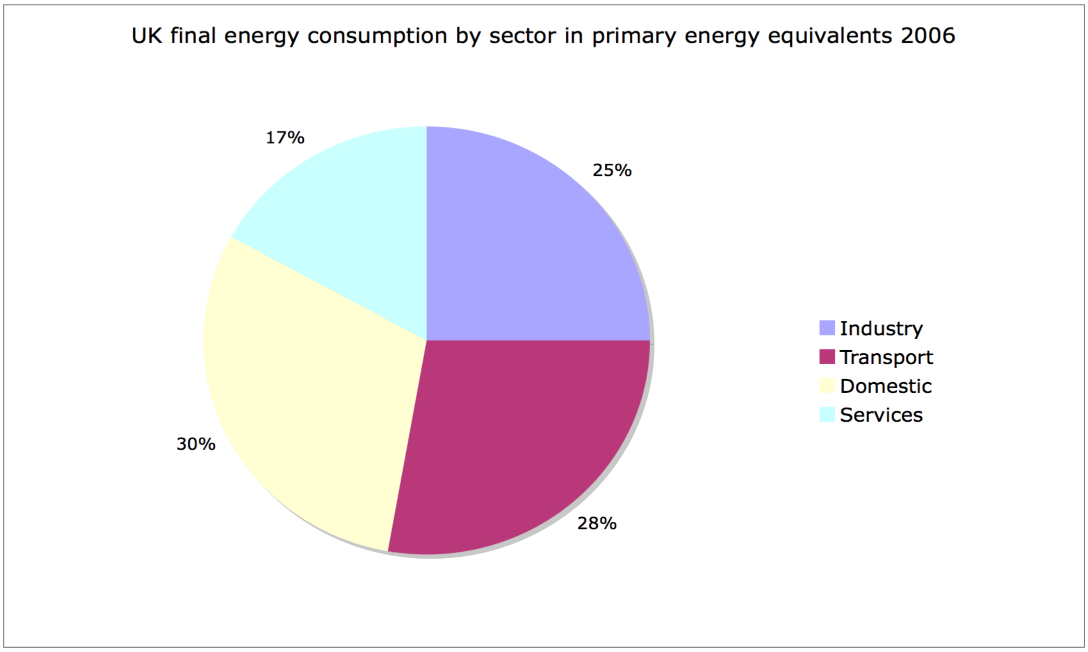


Figure 1.1. *Final energy consumption by sector, in primary energy equivalents for 2006. Total 232.3 million tonnes of oil equivalent (BERR 2008b).*

[1] Greenhouse gas emissions are expressed in million tonnes of carbon equivalent. One tonne of carbon is contained in 3.67 tonnes of carbon dioxide (DEFRA 2006, p.24)

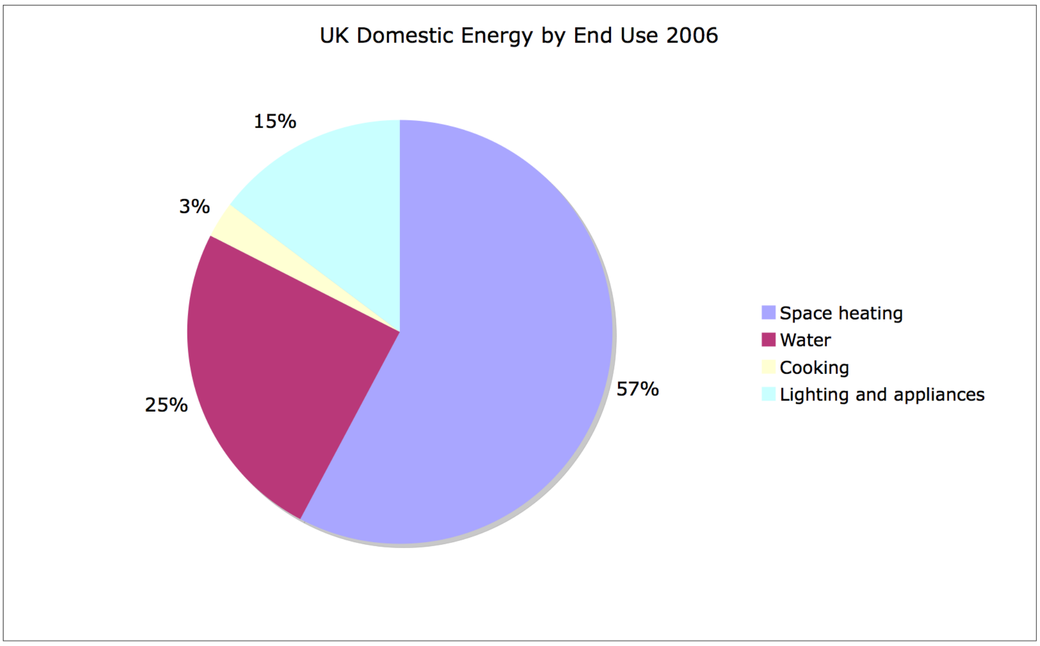


Figure 1.2. *Domestic energy by end use in 2006 (BERR 2008a).*

When considering that the majority of the housing stock has poor thermal performance compared to new build housing it is essential that the energy performance of these buildings is dramatically improved. Although arguably not strict enough, current building regulations and the higher standards laid out in the Code for Sustainable Homes ensure the heat loss in new housing is reduced. Improvements to the UK building regulations are set to be introduced in 2010 and 2013 with the aim of 'zero carbon' homes in 2016. With each new edition of Approved Document L1A, *Conservation of Fuel and Power in New Dwellings,* more thermal insulation will be required. Approved Document L1B, *Conservation of Fuel and Power in Existing Dwellings* is likely to also become tighter. Currently, when making changes to more than 25% of a thermal element in existing homes, the entire element is required to be upgraded where practically possible. This includes heating systems, windows, floors, roofs and external walls (ODPM 2006, pp.7 & 23).

The UK Government's Standard Assessment Procedure (SAP) is used to establish the energy performance of a building by rating it between 1-100, 100 being most efficient. Although SAP ratings have only recently been introduced, *fig. 1.3* uses the SAP to illustrate how the energy performance of housing has progressed since our pre 1919 solid walled stock.

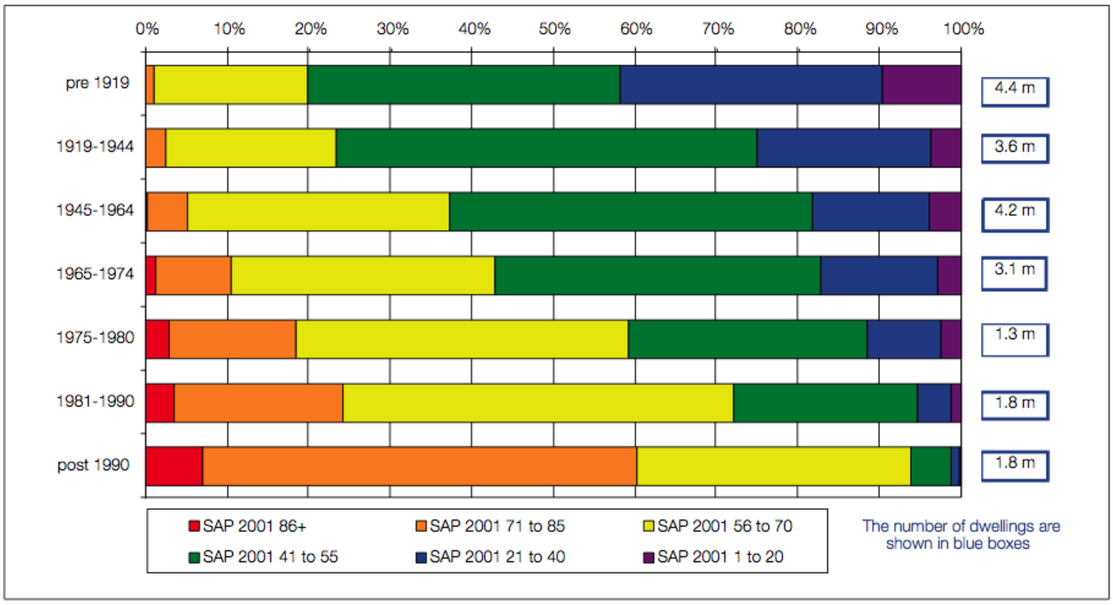


Figure 1.3. *Illustrates the progress in SAP ratings of the UK housing stock (DCLG 2006, p.5).*

1.3 The UK's Housing Stock

> "These old buildings do not belong to us only; that they have belonged to our forefathers, and they will belong to our descendants unless we play them false. They are not in any sense our property, to do as we like with. We are only trustees for those that come after us." (William Morris 1889 cited by Haskell 1993).

In 2006 the number of households in the UK is estimated at being in the region of 24.9 million (Office for National Statistics (ONS) 2007). The English housing stock accounts for the vast majority of these dwellings, approximately 21 million (BRE 2008, p.2). The diversity of this stock is huge, both in construction type and in age, with many buildings dating back hundreds of years.

1.4 Hard To Treat Homes

'Hard to Treat' (HTT) homes, as the name suggests, present a particularly difficult problem. They are defined as homes where it is complicated or not cost-effective to introduce energy efficient measures. As shown in *fig. 1.4* this includes solid walled homes, homes off the gas network, those with no loft space and high-rise flats (BRE 2008, p.1). In England, this amounts to approximately 9.2 million dwellings and according to the BRE, solid wall homes account for 72% of the HTT stock and 31% of England's total housing stock, approximately 6.6 million dwellings (BRE 2008, p.6). The regional distribution of these homes over England is shown in *fig. 1.5*. It is worth bearing in mind that the BRE's definition of solid wall homes includes 9" solid masonry walls, solid stone walls, solid concrete walls and walls made of metal or timber panels (BRE 2008, p.5).

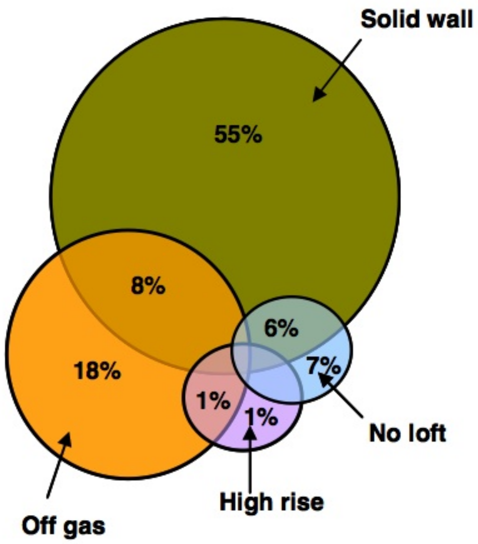


Figure 1.4. *Relationship between HTT home types labelled as a percentage of the total HTT stock 9.2 million homes. Percentages may not add up to 100% due to rounding (BRE 2008, p.7).*

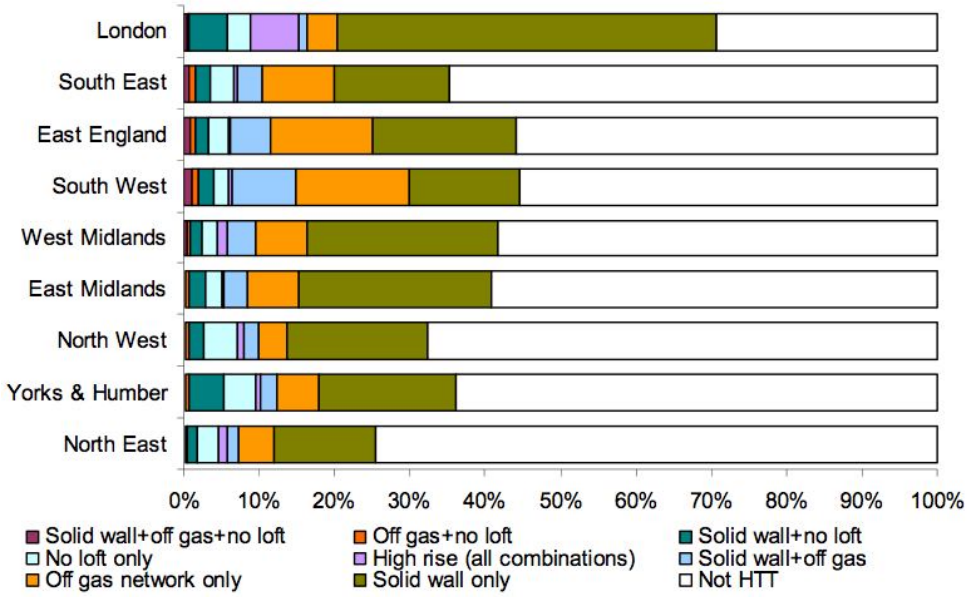


Figure 1.5. *Geographical location of HTT homes in England (BRE 2008, p.9).*

1.5 The Importance of Historical Buildings and Solid Walled Homes

Solid wall homes play a big part in defining our local and regional culture (Cook 2009, p.69) with many people preferring to live surrounded by architectural history. Buildings in some of the most beautiful areas in the world are protected, and improvements to their energy efficiency are either not permitted or are very complicated.

In the UK there are approximately 500,000 buildings of architectural or historical interest (CIBSE 2002, p.1) and many of them are made with solid walls. There are currently three main forms of statutory protection for buildings (CIBSE 2002, p.3); the last two categories contain many homes:

- Scheduled ancient monuments
- Listed buildings
- Buildings situated in conservation areas

Within building renovation there is often conflict between the building regulations and rules governing listed buildings and those in conservation areas. Apart from aesthetics, buildings may be important for many other reasons, e.g. method of construction, special structural features or associations with famous people, historic events, important architects or builders (CIBSE 2002, p.3). During the period between 1800 and 1911 about one third of the UK's existing homes were built (Cook 2009, p.66). The look of these buildings shapes our local environment and there is a strong argument that the aesthetic contribution of these buildings is hugely important both to our culture and to others observing it (Cook 2009, p.69).

1.6 Green Refurbishments of Solid Walled Homes

Solid wall buildings are very poor thermal performers, often having wall U-values of up to 2.3W/m^{2}K (McMullan 2001, p.44). Unfortunately the upgrading of this stock to reduce space-heating demand whilst preserving their historic fabric is a complicated task that poses a great challenge to the entire building industry. This challenge is especially important as it is estimated that between 66% (Energy Saving Trust (EST) 2006, p.3) and 85% (Griffiths 2009) of the current building stock in the UK will be standing in 2050. New homes only account for approximately 1% of the total stock each year (Department for Communities and Local Government (DCLG) 2006, p.4).

CIBSE (2002, p.2) identifies four principle aims for improving the sustainability of the existing building stock:

Aim 1: Preserve historic fabric

a) Adopt a respectful approach to the building and its fabric
b) Understand how air and moisture moves in older buildings
c) Avoid inappropriate and incompatible materials and allow the fabric to breathe

Aim 2: Extend the beneficial use of older buildings

a) Avoid building services that are expensive to run or maintain
b) Seek to provide modern standards of accommodation
c) Adapt existing buildings sympathetically and appropriately to modern demands and requirements

Aim 3: Reduce carbon dioxide emissions

a) Install efficient plant
b) Use cleaner fuels
c) Make higher health and comfort standards affordable without compromising the building or the environment
d) Reduce fuel bills
e) Improve the thermal performance of the building but in ways which do not conflict the historical features, the intended performance or health of occupants or users

Aim 4: Specify environmentally conscious materials

a) Assess the whole life cycle costs of new and existing materials before making changes
b) Assess the impact of new materials on the environment
c) Assess the impact of the new materials on the health of both those who install them and the users of the buildings

According to the BRE (2008, p.7), 55% of these HTT homes are made with solid walls and as illustrated in *fig. 1.6* below, approximately 25% of heat is lost through the roof of a home.

Figure 1.6. *Approximate proportions of heat lost from domestic buildings. Note that walls account for around 35%. (DCLG 2006, p.4).*

Rolling out loft insulation is relatively easy, not disruptive and has an estimated financial payback of around 2.7 years (DCLG 2006, p.8). After other cost effective measures such as draught proofing doors and windows, installing solid wall insulation and fitting new double glazed windows is significantly more costly with estimated financial payback periods of approximately 7.5 and 97.6 years respectively (DCLG 2006, p.8). Those payback periods will of course reduce if energy costs continue to rise.

Estimations suggest that in order to hit the UK's energy targets, nearly half a million homes would need to be refurbished every year (Cook 2009, p.32), nearly ten thousand homes a week. In 2000, excluding maintenance costs, the UK spent approximately £26.8 billion on refurbishments. Of this, £14.1 billion was spent on private and public housing (Riley & Cotgrave 2005, p.10). If there is to be a systematic 'upgrade' of our housing stock to reduce CO_2 emissions then it needs to be intelligently planned and detailed (Griffiths 2007, p.12). The cost of having to redo it would be vast. This is not only in financial terms, as damaging existing homes through the deployment of poorly thought through schemes would be an immense waste of energy, time and resources that the UK and developed world cannot afford.

1.7 Aiming High

When looking ahead to 2050 and understanding the reductions in heat loss needed to reach emissions targets, retrofits should receive the highest levels of thermal insulation possible. With minimum paybacks of around 7 years for basic solid wall insulation, a short-term view would not be sensible or cost effective. Given these points it would be foolish to go through a costly and disruptive nationwide installation of IWI to only achieve small reductions in heat loss. The Code for Sustainable Homes highlights a step change of insulation levels over the next six years (to 2016) to arrive at wall U-values of $0.15W/m^2K$ (EST 2008, pp. 4&10). This is specifically for new build homes but given the payback times it would be sensible to aim as high as possible and install IWI to 2016 levels now. If this is done properly, avoiding detrimental side effects and with a long-term view, quality retrofits undertaken now could take us right up to, and beyond our 2050 deadline.

Apart from being meticulously planned, the scheme for thermal renovations would of course need government backing and grants. In Germany the Kreditanstalt fur Wiederaufbau institution is responsible for financially assisting renovations that reach the same energy efficiency levels as those required of new-builds (Galvin n.d., p.3). This generally applies to external insulation and provides a good incentive to renovate to high standards with even further financial assistance being given to projects reaching levels 30% higher than their current new-build regulations (Galvin n.d., p.3).

This Chapter has outlined the reasons for thermally renovating our solid wall housing stock and has highlighted some of the problems associated with it. The following chapter focuses on understanding heat and moisture movement.

Chapter 2

Hygrothermal Processes

It has been established in Chapter 1 that there is an urgent need to refurbish our existing building stock. This will require energy saving measures such as additional internal wall insulation. The complications that come with this as a result of moisture related issues are complex. This chapter focuses on how heat and moisture moves through buildings in different ways and is important in order to understand the implications of thermal renovations.

2.1 Renovations and Changes in Moisture

> "Via its surfaces, every building component is undergoing hygrothermal interaction with its surroundings. That is, the surroundings are affecting the component and the component is affecting its surroundings" (IBP 2001).

Hygrothermal: *Hygro*- relating to moisture, *Thermal* - relating to heat (Oxford English Dictionaries 2009).

Before renovating a building it is important to understand all the interrelationships between the original materials and how introducing new ones will impact upon them. Solid walled buildings have survived for more than 100 years often without significant failure because the way they were constructed and detailed was appropriate for their climate and for the way they were lived in. This inter-compatibility of materials needs to be understood in order to avoid damaging mistakes from modern alterations. The issues of heat loss, ventilation, air infiltration, temperature, relative humidity (RH), condensation and air quality are all linked. Therefore changing any one of these impacts upon the others and an over simplified view can lead to potential dangers for the building fabric (CIBSE 2002, p.3). Sometimes the impact is insignificant and easily solved but at other times it can be severe and create 'sick buildings' or degrade structural elements of the building fabric. In many cases this degradation may occur inside the structure and therefore go unnoticed until it has grown into a serious problem.

Various changes over the last century to the way we live and heat our houses are now placing new demands on old structures. Some of these changes have been viewed in isolation and thus unforeseen problems have occurred. As a result, the issue of condensation as a problem is a relatively recent concern (McMullan 2001, p.107). The small quantities of water vapour produced by simple lifestyles of the past were able to escape through increased ventilation and evaporate from internal limewash finishes without causing decay to the building fabric (CIBSE 2002, p.15).

Unfortunately, out of all the familiar substances that surround us, water is the most complex and least understood (Brundett, 1990 cited by Oliver et al. 1996, p.4). This lack of understanding in the context of moisture and buildings means that through 'faulty design', moisture is now responsible for 70-80% of all damage in buildings. This makes understanding and controlling moisture the key to achieving durable, long lasting sustainable building design (Mumovic & Santamouris 2009, p.211; Riley & Cotgrave 2005, p.15; May 2005, p.34).

Adding internal insulation to an existing building presents many issues that are varied and complicated, where unfortunately the obvious solution may not be right. The original structure and the proposed changes to it will always vary slightly meaning that standard solutions cannot always be applied (Westfield et al. 1996, p.36). Wargocki (2009, p.181) predicts that problems with moisture will be widespread in the coming decades as we try to reduce our existing buildings' energy consumption and maintain thermal comfort.

2.2 Lessons to Learn from the Past

In many cases we have not learnt from the problems encountered with heat, insulation and moisture in the 19th and 20th centuries. The following account by Allen (1997, p.36) describes how seemingly logical changes have lead to complications.

> The first problems arose as household fuel changed from wood to coal and the size of fireplaces was reduced. Victorians made a requirement for all habitable rooms to have a direct air supply to provide adequate ventilation and to remove problematic water vapour. From 1945, in a move to reduce the heat lost up chimneys, fireplaces were commonly dropped to one per dwelling. Air-bricks were blocked up and suspended timber floors with air gaps were replaced with concrete floors directly on the ground. These changes increased thermal comfort and reduced heat loss but caused the first complaints of condensation. Trickle vents in windows were introduced but were also commonly sealed up by residents to reduce draughts.
>
> In the 1950s as economic and political pressures forced mass housing, concrete became an economic choice and fan-blown ducted warm-air systems were introduced. Significant problems were encountered as no fresh air was added to these systems, no ventilation was allowed for and the concrete structures inhibited the migration of moisture through the building envelope. RH rose dramatically and over three winters in the late 1960s condensation caused extensive damage and made headline news as walls, floors, ceilings, bedding, furniture, carpets and internal finishes became saturated. The costs were presumable huge. Every change that had occurred in building renovation and new building developments concerned with energy conservation had lead to a loss of means for water vapour to escape (Allen 1997, p.36).

2.3 Moisture in and Around the Building Envelope

Moisture is present on both sides of the building envelope in the form of ice, snow (on the outside), water and water vapour. Depending on the hygric properties of the materials involved, moisture will move through it in different ways.

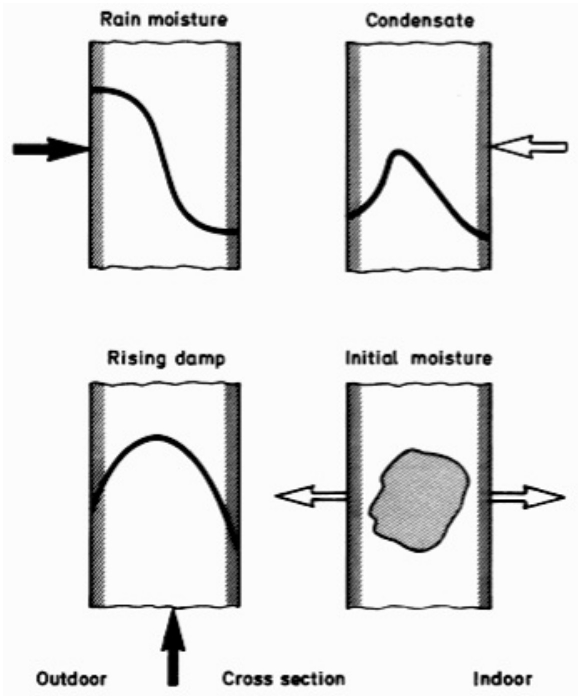


Figure 2.1. *Schematic diagrams showing the effect and distribution of moisture in an outside wall caused by rain moisture, condensation on the inside and at layer boundaries, rising damp and initial moisture from construction (Kunzel 1995).*

2.4 Externally Produced Moisture

The most significant source of external water to affect a building is from rain landing on the roof and from wind-driven rain hitting the walls and windows. The amount of driving rain incident on the side of a building is linked to its design and detailing, and to its height, orientation and local climate. Water striking the outside of a building needs to drain away quickly to avoid penetrating the structure. Once this water has found its way to the bottom of the walls it should be stopped from being drawn back up into the structure through damp proof courses in walls and damp proof membranes under solid floors. Failures in these precautions will result in rising damp.

2.5 Internally Produced Moisture

The amount of moisture produced by modern lifestyles inside our homes varies but it is estimated that the internal activities of a family of five produce quantities of moisture ranging from 10-20l per day (McMullan 2001, p.109). *Table 2.2* outlines the most common sources of this moisture.

Internal activity
Human breath, (usually the biggest contributor, relative humidity (RH) of close to 100%)
Cooking
Combustion moisture from cooking or heating with flue-less burners
Evaporation from washing and drying
Transpiration from plants
Humidification from air conditioning

Table 2.2. *Internal activities that contribute to moisture identified by Allen (1997, p.23).*

Moisture inside the building envelope interacts with internal items and the fabric of the building in different ways depending on their properties and will always seek to find equilibrium (Oliver et al. 1996, p.15). The 'moisture cycle' in buildings *(fig. 2.3)* refers to how internal moisture moves around different 'sources, sinks and reservoirs'. The term 'moisture sink' describes "a medium to which moisture can safely dissipate without adversely affecting the building" as opposed to a 'reservoir' that is an unwanted accumulation of moisture that does adversely affect the building (Oliver et al. 1996, p.16).

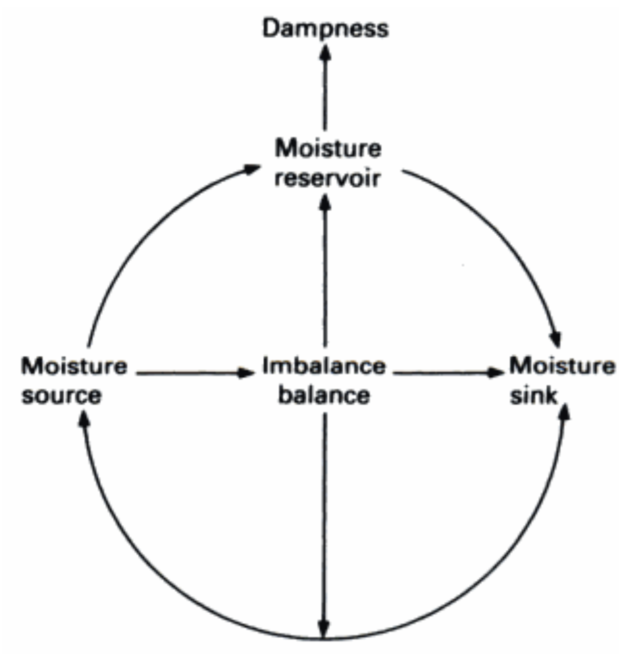


Figure 2.3. *Moisture transfer cycle (Oliver et al. 1996, p.16).*

2.6 Moisture Transport Mechanisms

Some of the theories discussed here on moisture transport form the underlying values of WUFI and are further covered in Chapter 4 - Explorations with WUFI.

Moisture migration through the building envelope happens as it seeks equilibrium. *Table 2.4* shows the different transport mechanisms and causes for liquid and vapour. The most relevant mechanisms of moisture transport within porous building materials are vapour diffusion, capillary conduction and surface diffusion (IBP 2001).

Phase	Transport mechanism	Driving potential
Water vapour	**vapour diffusion**	**vapour pressure**
	effusion	vapour pressure
	solution diffusion	vapour pressure
	convection	total pressure gradient
Liquid water	**capillary conduction**	**capillary suction stress**
	surface diffusion	**relative humidity**
	seepage flow	gravity
	hydraulic flow	total pressure differentials
	electrokinesis	electrical fields
	osmosis	ion concentration

Table 2.4. *Moisture transport mechanisms and their driving potentials (Kunzel 1995, p.5), main mechanisms and their driving potentials shown in* ***bold.***

Each of the drivers shown in bold (*table 2.4*) is affected by the constantly changing boundary conditions of the internal and external surfaces. Over the course of a day as temperature, relative humidity, rainfall, solar radiation and wind pressure fluctuate, so do the moisture driving potentials (De Freitas et al. 1996, pp.99-100).

2.6.1 Vapour Diffusion

Due to the temperature difference inside and outside the building (in winter it is usually warmer inside), higher indoor air and vapour pressures will cause water vapour in the air to be pushed through ‘vapour permeable’ parts of the structure to the outside (Kunzel 1995, p.13). This diffusion takes place in the air inside the pore spaces and is slowed or stopped where the pore structure is not present or connected, as in the case of vapour retarders or barriers (IBP n.d.).

Within a porous material the relative humidity of the air inside the pores relates to the total water content of the material. *Table 2.5 and fig. 2.6* below show numerically and graphically this relationship in masonry. The rise in water content can be seen to be slow and steady up until around 90-95% RH, at which point the water content of the material rises dramatically, also shown by the figures in **bold**.

% RH	Water content (kg/m³)
0	0.00
10	0.55
20	1.23
30	2.11
40	3.26
50	4.84
60	7.17
70	10.93
80	18.00
90	36.21
95	**63.09**
97	**87.07**
99	**137.08**
100	**190.00**

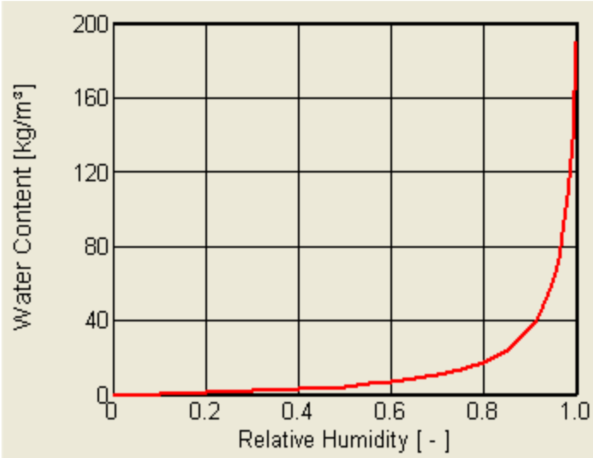


Table 2.5 and figure 2.6. *Numerical and graphically represented relationship between relative humidity and water content (WUFI 2009b).*

2.6.2 Condensation

Condensation is formed when the water vapour held in warm air meets a cold surface. This process can be traced through the use of the psychrometric chart of moisture and temperature shown in *figure 2-7* below.

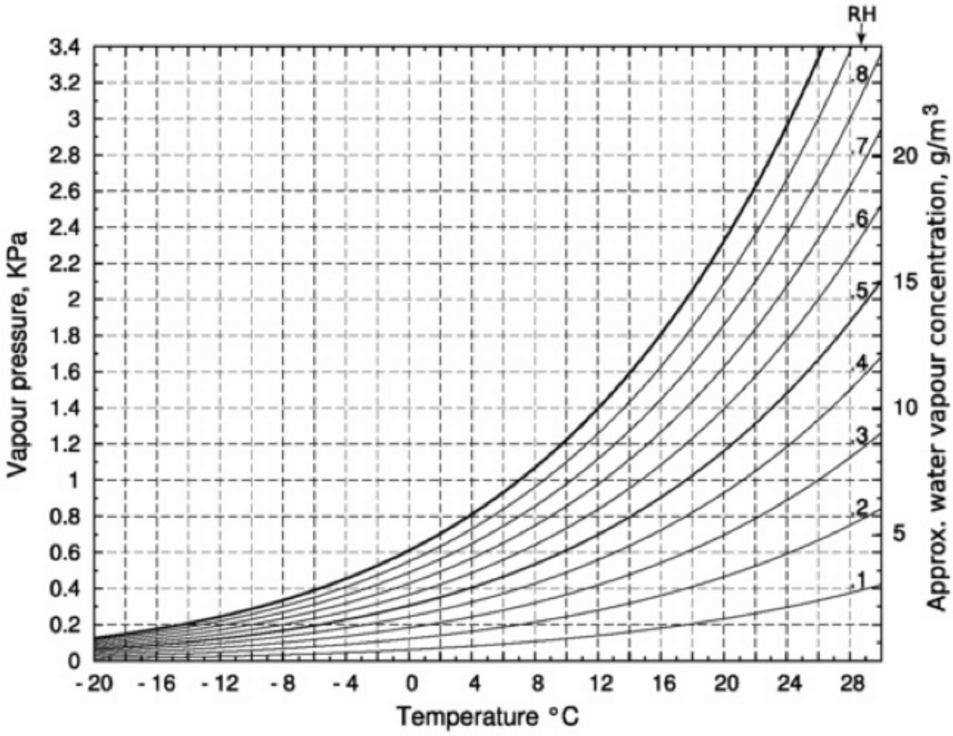


Figure 2.7. *Psychrometric chart of moisture and temperature (Padfield 2006, p.4).*

Using the above chart, find the intersection point between the vertical line representing 20°C and the curved line at 50% RH and follow this point horizontally all the way to the left curved line to find the dew point, shown on the X axis to be 10°C. This shows that when air at 20°C with 50% RH is cooled by meeting a surface that is 10°C or lower it will lose its ability to hold water vapour and condensation will form.

The temperature across a wall may range from 20°C inside to 0°C outside, so within the wall the temperature drops by 20°C. As the air diffuses through the structure it is cooled by the wall's decreasing temperature. When the temperature decreases, the RH of the air increases and eventually the 'dew point' is reached and moisture in the air cannot continue to be held as water vapour will condense onto any available surface. If this happens on the inside finish of the room it is called surface condensation and if that point is inside the wall, it is referred to as interstitial condensation (McMullan 2001, p.108). As the water vapour changes state to liquid water, capillary conduction can now take place if the material is porous. If the material is not porous the liquid will remain where it has condensed until it can evaporate or when other forces such as gravity allow it to escape. Where interstitial condensation occurs and is not able to dry out, it may accumulate and cause decay, mould growth or corrosion in the building (BSI 2005a, p.9).

The different materials used in the construction of a building vary in their ability to allow vapour diffusion *table 2.9 and 2.10.* It should be noted that vapour permeability is a very different property to a material's ability to admit liquid water and it is common to have a material that is closed to liquid but remains open to vapour (McMullan 2001, p.112). The degree to which materials are vapour open or vapour closed can be expressed in different ways:

Expression	Unit	Description
Vapour resistivity (r_V)	[GN s/kg m] or [MN s/g m]	r_V is a "measure of the resistance to the flow of water vapour offered by unit thickness of a particular material under standardised conditions" (McMullan 2001, p.112).
Vapour resistance (R_V)	[GN s/kg] or [MN s/g]	R_V "describes the resistance of a specific thickness of material" (McMullan 2001, p.113) calculated by the following formula: $R_V = r_V L$
	where:	R_V = vapour resistance of that material (GN s/kg) L = thickness of the material (m) r_V = vapour resistivity of the material (GN s/kg m)
Water vapour diffusion resistance factor (μ)	[-]	μ-value "is the factor by which the vapor diffusion in the material is impeded, as compared to diffusion in air. For very permeable materials, such as mineral wool, the µ-value is thus close to 1 (IBP n.d.).
Vapour diffusion thickness (sd)	[m]	the sd-value is "For a material layer with diffusion resistance factor μ and thickness s, the product µ·s thus gives the thickness which an air layer would need in order to have the same diffusion resistance" (IBP n.d.)

Table 2.8. *Showing the different ways of expressing to what extent a material is vapour closed or vapour open.*

Below are a list of common building materials and their water vapour diffusion resistance factor (μ-value). This shows how much vapour diffusion is impeded by the material when compared to the same diffusion in air (IBP n.d.). As a means of comparison, air has a μ-value of 1 and a vapour retarder has a μ-value of 20 000.

Material	Water vapour diffusion resistance factor (μ-value) [-]	
	dry	wet
Air	1	1
Building materials		
Alluminium	∞	∞
Argon	1	1
Bitumen	50 000	50 000
Concrete		
- medium density	100	60
- high density	130	80
- with expanded clay as predominant aggregate	8	6
- with >70% expanded blastfurnace slag aggregate	30	20
Fired clay	16	10
Glass	∞	∞
Gypsum plasterboard	10	4
Gypsum plastering	10	6
Granite	10 000	10 000
Lime/sand plastering	10	6
Limestone		
- semi hard	50	40
- extra hard	250	200
Mortar	20	10
Oriented strand board (OSB)	50	30
Plywood	220	90
Polythene	100 000	100 000
Polyurethane (PU)	6000	6000
Sand and cement render	10	6
Slate	1 000	800
Steel	∞	∞
Timber	50	20
	200	50

Table 2.9. *Showing the water vapour diffusion resistance factor (μ-value) of some common building materials according to BS EN 12524:2000 (BSI 2000).*

Material	Water vapour diffusion resistance factor (μ-value) [-]	
	dry	wet
Insulation materials		
Expanded polystyrene	60	60
Extruded polystyrene foam	150	150
Polyurethane foam, rigid	60	60
Mineral wool	1	1
Wood wool board	5	3
Wood fibreboard	10	5
Loose-fill expanded polystyrene beads	2	2

Table 2.10. *Showing the water vapour diffusion resistance factor (μ-value) of some common insulating materials according to BS EN 12524:2000 (BSI 2000).*

The above tables show to what degree some common building materials admit water vapour diffusion. The makeup of a typical solid wall construction of fired clay brick and mortar (μ 10-20) can be seen to be relatively vapour open when compared to concrete (μ 60-130) or even plywood (μ 90-220). In order to prevent interstitial condensation vapour barriers can be used to stop the migration of water vapour through the walls (McMullan 2001, p.118). These barriers (made of materials like polythene) have a μ-value of around 100,000, which is very effective at nearly completely reducing the diffusion of water vapour. Incidentally the sd-value is used to refer to the properties of vapour barriers and according to the IBP (n.d.) the value of a vapour retarder is sd ≥ 10 m and a vapour barriers sd ≥ 1000 m.

After installation of a vapour barrier, internally produced water vapour cannot diffuse to the outside of the building through the walls. Internal RH will rise if the internal air is not able to leave the building as a result of increased air-tightness measures (Allen 1997, p.36). Any breaches in the vapour barrier to the cold side of the building will experience increased levels of moisture that could build up and start to cause degradation (Slanina & Silarová 2009, p.1625; McMullan 2001, p.118; Phillips 1976, p.71). Furthermore, after internally insulating with the inclusion of a vapour barrier any structural elements that penetrate it such as timber joists will act as thermal bridges attracting condensation and should be considered in any assessment of hygrothermal behaviour (Slanina & Silarová 2009, p.1625).

2.6.3 Capillary Conduction

Capillary conduction is a function of the pores within a material and is the most efficient type of moisture transport within porous materials such as masonry. The curved surface of water in the pores is called the meniscus (from Greek *mēnískos* meaning 'crescent') (Oxford English Dictionaries 2009). This curvature creates tension and draws liquid through the pores, where pore diameters are smaller, higher suction pressures occur. When a wall is exposed to driving rain, the pores start to fill up, capillary conduction starts and liquid water is drawn into the wall (IBP 2001). The amount of capillary suction that a material has is described as the 'water absorption coefficient' (A-value) [$kg/m^2\sqrt{s}$]. There is also a relationship between capillary conduction and relative humidity as changes in the relative humidity of the pore air above the meniscus affect the capillary tension in the pore and define the rate of capillary suction (IBP 2001).

Under the term 'capillary conduction' two separate processes can be defined:

- liquid transport coefficient for suction' (Dws) [m^2/s]
- liquid transport coefficient for redistribution' (Dww) [m^2/s]

A greater explanation of these processes is included in Chapter 4 - Explorations with WUFI, as they are specific to modelling capillary conduction with numerical simulations.

2.6.4 Surface Diffusion

As previously stated by the IBP (2001) all building components are constantly undergoing hygrothermal interactions with their surroundings where both surroundings and materials affect each other. This is especially true when observing hygroscopic materials that change according to their surrounds through surface diffusion. This can be defined as:

> "moisture transport in the water molecule layers adsorbed at the pore walls in hygroscopic materials and in micro-capillaries" (Kunzel 1995, p.16).

As the relative humidity of the air changes, hygroscopic materials will adjust their moisture content in an attempt to reach equilibrium with their surroundings (Padfield & Jensen 2009, p.1). Some hygroscopic materials can effectively buffer changes in RH and, in cases where air tightness is high they will maintain a nearly constant internal RH as the internal temperature rises and falls (Padfield & Jensen 2009, p.1). Unfortunately measuring and describing a material's ability to buffer moisture presents some difficulty. Materials are often present in buildings at a specific thickness, for example gypsum plaster board will commonly be 12.5mm thick, spruce floor boards may be 20mm thick and a concrete floor 100mm thick. The amount of moisture they can buffer over a specific time needs to be defined in order to accurately compare them for use in building. A 100mm thick gypsum wall is not practical nor is a 12.5mm concrete floor. It would however be conceivable to have between 20 and 300+mm of a hygroscopic insulation that if appropriately covered could have some success in regulating internal RH. The chart in *fig. 2.11* below shows average moisture buffer values for the selected materials from the results of a study by (Rode 2005, p.30) using the proposed Nordtest method.

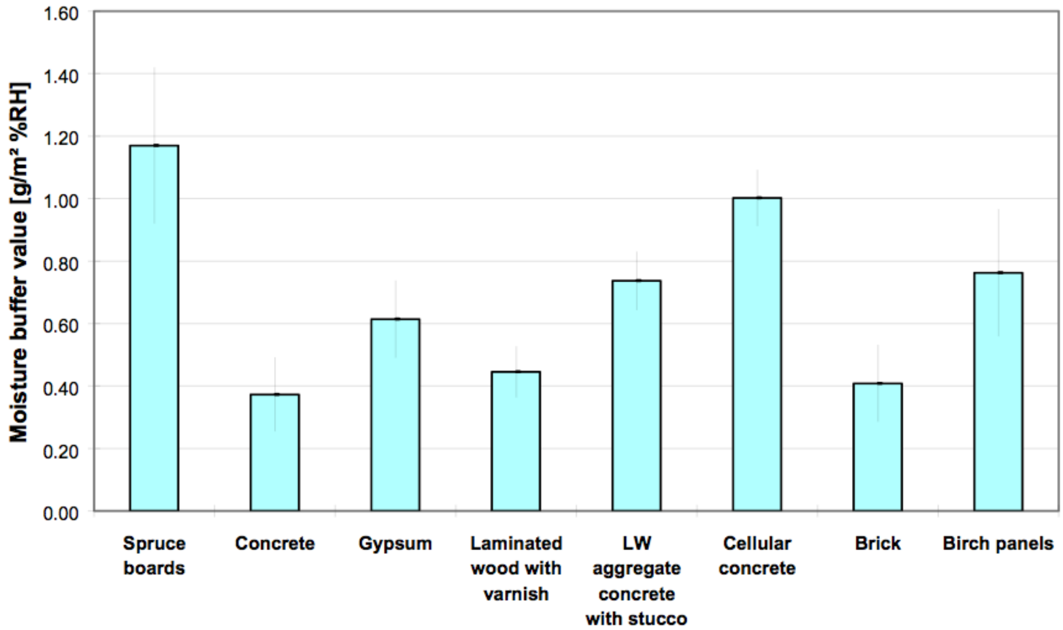


Figure 2.11. *Shows average 'moisture buffer values' [g/m^2 %RH] for eight building materials (Rode 2005, p.30) using the Nordtest method.*

Two commonly used methods for determining the moisture buffer capacity are defined by the Japenese standard JIS A 1470–1:2002 and the Nordtest method. They both measure the moisture passing through the surface of the material after a defined change in %RH and both express results as kg/m^2 %RH (Padfield & Jensen 2009, p.2).

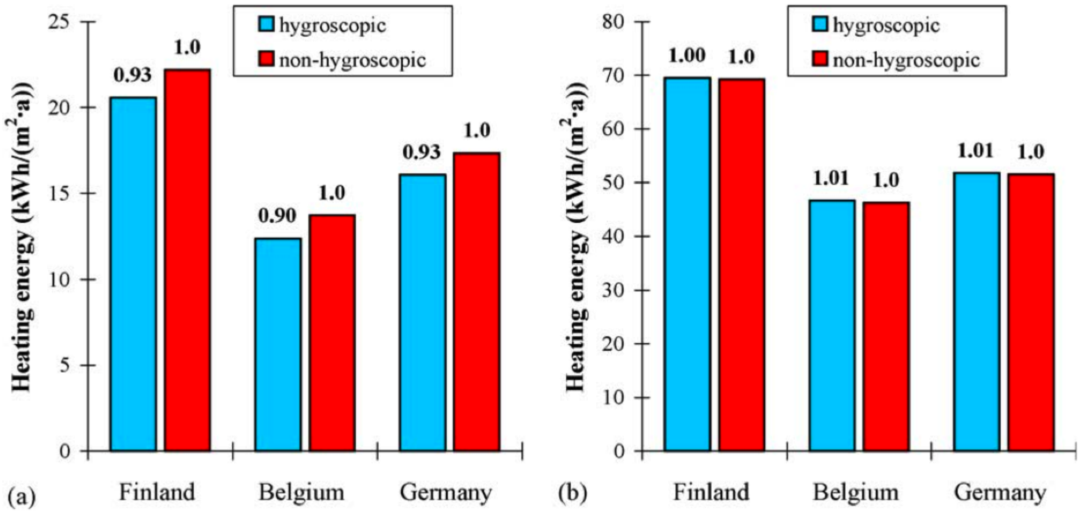
In their paper *Humidity buffer capacity of unfired brick and other building materials,* Padfield and Jensen present what they feel to be a clearer means of describing how a material reacts to changes in humidity. By using one indirect unit, the B-value [-], the response of a material is compared to that of the same volume of air. This unit roughly doubles for every 10°C drop in temperature (Padfield & Jensen 2009, pp.2-3).

Specimen description	Thickness [mm]	B-24 [-]	B-96 [-]
unfired massive brick	53	10	21
unfired perforated brick	53	27	58
unfired perforated brick	106	39	95
unfired perf. brick ventilated	110	61	108
End-grain wood	40	15	34
Cellular concrete	50	7	9
Fired perforated brick	52	-	-

Table 2.12. *shows the B-values after 24 and 96 hours for a selection of materials at 18°C (Padfield & Jensen 2009, p.8).*

Apart from regulating internal humidity a further function of a hygroscopic material is demonstrated in the wood fibre insulation 'Pavadentro'. The manufacturers claim that the hygroscopic action of the wood fibres draw any interstitial condensation in the insulation back to the inside of the room to be released as water vapour without any materials being damaged (NBT 2008, p.3). This insulation is specified to be used with an internal lime plaster finish. Lime is often wrongly referred to as being more breathable than gypsum. As seen earlier in *table 2.9* the μ-values of gypsum and lime are the same. It is their ability to hold moisture at a given relative humidity that differs significantly. At 50%RH and 80%RH gypsum has a water content of 3.6 and 6.3 kg/m^3 respectively, lime has a much greater capacity of 20 and 30 kg/m^3 respectively (WUFI 2009b).

Another observation of hygroscopic materials has been made by Osanyintola & Simonson (2006, p.1277) who found the heat generated by hygroscopic materials whilst absorbing moisture contributed to reducing heating bills by a small amount, although not significantly over the whole heating season *figs. 2.13 and 2.14*. Osanyintola & Simonson (2006, p.1281) show 2-3% direct savings for heating energy and more significantly 10-30% total cooling energy savings.



Figures 2.13 and 2.14. *Showing savings made from moisture absorbed by hygroscopic materials over (a) periods of occupation 22:00 - 7:00 and (b) the whole heating season (Osanyintola & Simonson 2006, p.1277).*

2.7 Simultaneous Heat and Moisture Transfer

It is possible for vapour diffusion and capillary conduction to take place in different directions across a wall at the same time. This is due to the different drivers and transport mechanisms for water and water vapour. In winter the warm internal water vapour will diffuse from high pressure to low pressure, from warm to cold. Conversely capillary conduction goes from moist to dry (IBP 2001). These processes also do not interrupt each other as they occur in different parts of the pore structure, liquid transport takes place in the micro pores and pore walls whilst vapour diffusion moves through the larger pores (Kunzel 1995, p.14). Whilst these processes are occurring heat is always being conducted out of the building. *Fig. 2.15* illustrates clearly how under normal winter conditions moisture moves across walls.

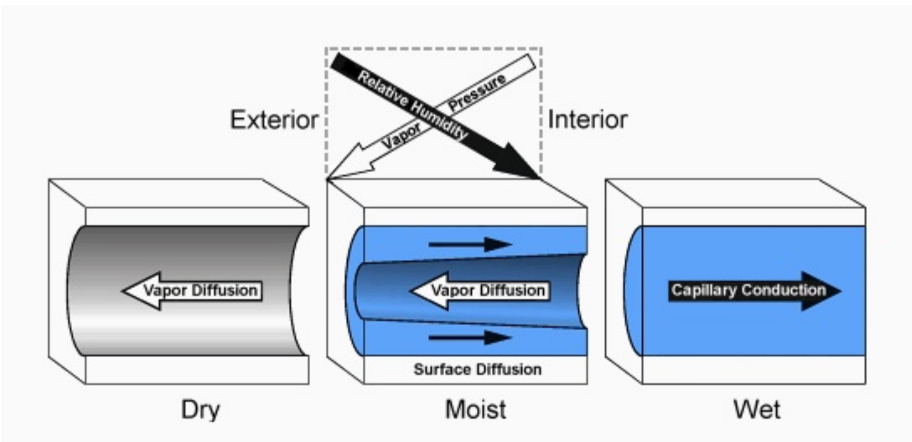


Figure 2.15*. Moisture transport phenomena in the pores across an exterior wall in winter with different moisture levels (IBP 2001).*

2.8 Special Conditions Occurring in Frozen Masonry

When masonry becomes saturated its thermal conductivity increases. This is further exaggerated if water in the pores becomes frozen. On freezing, the ice initially advances into the brick or mortar from the surface at a relatively slow rate. This rate then increases as freezing continues which may be due, as Laycock (2002, p.196) suggests to the difference in thermal conductivity (k-values) between ice and water. The k-values [W/mK] of water and ice are very different, for example water at 25^{o}C is 0.58 W/mK (The Engineering ToolBox 2005b), whereas ice at 0^{o}C has a k-value of 2.22 W/mK (The Engineering ToolBox 2005a). This suggests that the rate of freezing increases as the wall freezes, as the process of heat loss is sped up. The opposite is true on thawing as once the surface ice has melted its reduced thermal conductivity insulates the remaining ice further inside, and slows the whole thawing process (Laycock 2002, p.196).

Chapter 2 has covered many of the hygrothermal process that need to be understood in order to research moisture related subjects in building physics. The following Chapter discusses the mechanism of and drivers for frost attack to masonry.

Chapter 3

Frost Damage to Masonry

This Chapter thoroughly investigates the problem of frost damage to masonry and examines the changes brought about by internally insulating. The causes of frost damage are explored and the factors determining bricks' resistance to attack are presented.

3.1 The Mechanism of Frost Damage

Frost damage to brick units is one common type of weathering in the UK. Damage to susceptible units, also called ‘spalling’, causes their structure to degrade and become friable (Hammett 1998, p.29). Other types of weathering to masonry include sulphate attack and cracking from thermal expansion. Sulphate attack is caused when calcium aluminosulphate hydrate expands upon contact with water. This chemical is caused by a reaction between the tri calcium aluminate in cement and the water-soluble sulphates in bricks (Smith & Edgell 2009, p.11).

When a brick is exposed to liquid from driving rain, ground water or standing water the connected pores in the brick draw the liquid by capillary action into the material. This suction process is a basic property of all bricks and without it proper adhesion to the mortar would not be possible. It is unfortunately this property of the bricks that when combined with below zero temperatures can cause frost damage.

Figure 3.1. *Frost damage to brick masonry (Smith & Edgell 2009, p.4).*

Damage to susceptible brick units is caused when the water held within the pore structure expands on freezing. The density of ice is lower than that of water and therefore ice has a greater volume than the water it derived from, so upon freezing it expands. The volumetric expansion of ice by 9% on freezing exerts tensile stresses on the brick’s pores and causes damage when the stresses exceed the strength of the material (Lisø et al. 2007, p.3550).

This sort of damage in bricks is largely cosmetic but nevertheless, still very undesirable (Edgell 2005, p.32), particularly to buildings of architectural significance. If allowed, this process of degradation will continue with every wet-frost (freeze/thaw cycle of wet bricks) (Hammett 1998, p.29) and may gradually progress through the brick causing loss of strength and ultimately total disintegration (van der Klugt 1989 and Hewlett 1998 Cited by Larbi 2004, p.305). In a study by Maurenbrecher & Suter (1993), unchecked frost damage had a severe effect on the load bearing capacity of a building. Masonry in particularly exposed positions such as parapets, retaining walls, free standing walls and chimneys is most vulnerable and may become structurally unsound and need to be reconstructed (Edgell 2005, p.32).

3.2 Factors Determining Frost Resistance

The resistance of masonry to frost action depends on the characteristics of both the brick and mortar and most importantly relates to the conditions of exposure. Where brickwork is likely to remain wet for long periods, careful specification of both masonry units and mortar is needed (BSI 2005b, p.68).

In the USA the saturation coefficient is used to predict frost resistance. The saturation coefficient is the relationship between the brick's 'free water saturation' and 'maximum water saturation' and is calculated by a '24hr cold-soaked' water and a '5hr boiled' water absorption tests respectively (Edgell 2005, p.33). This coefficient theoretically shows if a brick has sufficient pore space available for the expansion of freezing water. Due to the lower diversity of clays used in brick manufacturing in the USA this coefficient is acceptable but is not a reliable definition of frost resistance for bricks made with the diverse range of clays in the UK that are sometime mixed and blended (Smith 2009). There are many cases of bricks with a sufficient pore spaces failing in severe conditions (Edgell 2005, p.33). This method relates to the theory that free water saturation or 'capillary saturation' is the maximum saturation level that a porous material can achieve through capillary suction alone. Higher saturation levels, (determined in the 5hr boil test to define 'maximum water saturation') can only be achieved by applying pressure, as in the case of expanding ice, or through water vapour diffusion in a temperature gradient (Kunzel 1995, p.6).

Aside from the saturation coefficient, within a brick there are many other properties that can make it vulnerable to attack. Many of these characteristics actually come from the original mineral make up of the clay that a brick has been made from and include the firing temperature and length of firing during its manufacture. Incidentally, poorly fired bricks, as well as having reduced frost resistance, can often be associated with having a high salt content which can lead to additional weathering from salt-attack (Cook & Hinks 1992, p.234).

The vast combination of clays and firing techniques used in the UK results in an enormous range of bricks with many varying properties (Edgell 2005, p.32) so making generalisations about a link between an easily measurable physical property and frost resistance is extremely difficult (Edgell 2005, p.34). When comparing two very different fully frost resistant bricks, such as a Staffordshire blue engineering brick and a hand made brick, it is clear why predicting failure or resistance is complicated. The engineering brick is dense and has low water absorption (~2-3%) and high strength (~150 N/mm^2). Conversely, the hand made brick has high water absorption (~20-25%) and low strength (~20 N/mm^2). The former is resistant because of its low water absorption and high strength, the latter because its open pore structure resists damage as ice expands (Edgell 2005, p.33).

The freezing of water within the bricks is also a complex process and is not only dependent on temperature. The dissolved salts and differing pore size and shape mean that in some cases the temperature at which the water freezes is not necessarily zero degrees C (Laycock 2002, p.196). *Fig. 3.2* illustrates how smaller radii freeze at lower temperatures.

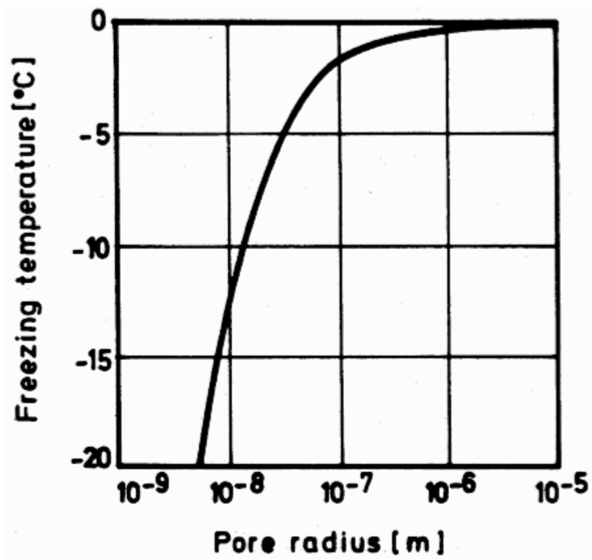


Figure 3.2. *The dependence between pore radius and freezing temperature of water in cylindrical capillaries (Neiss 1982 cited by Kunzel 1995, p.23).*

Even though the temperatures shown in *fig. 3.2* drop to -20°C, it is interesting to note that pores with a diameter below 1 µm (micron, 10^{-6}) are thought to exert the highest expansive forces on the pore structure when freezing (Forde 2009, ch. 35, p.4). As seen in *fig. 3.2* the temperature at which water begins to freeze in these pores is very close to 0°C.

In the table below Stupart (1989, p.42) attempts to identify all the critical properties of bricks with relevance to frost damage.

Critical properties of bricks relevant to frost damage
Pore size distribution
Moisture content (degree of saturation)
Elasticity (E value)
Tensile and compressive strength
Degree of firing
Presence of flaws such as laminations

Table 3.3. *Critical properties of bricks relevant to frost damage (Stupart 1989, p.42).*

In addition to the critical properties laid out in *table 3.3* the Building Research Establishment (BRE) have identified five pore types in clay bricks, *fig 3.4.* Of these types, loop, blind alley and pocket pores are predicted to be less likely to fracture when freezing, as the pore shape holds a small amount of air which provides the freezing water sufficient room to expand (Thomas 1996, p.119). Even though bricks with predominantly these types of pores may be more frost resistant than others, additional factors still influence susceptibility.

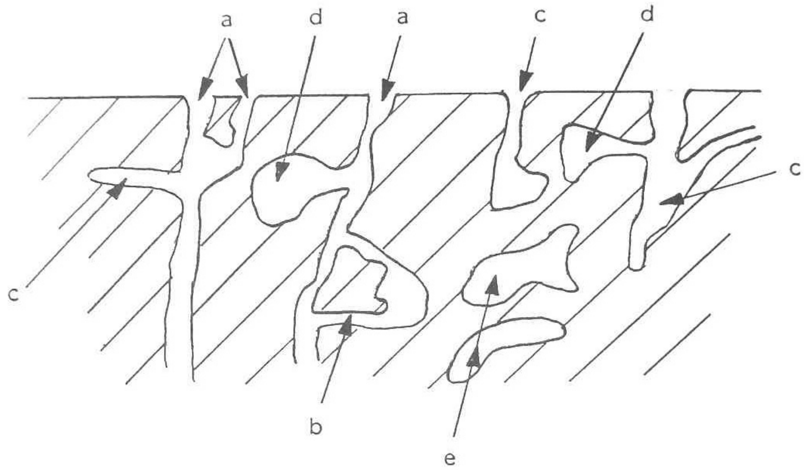


Figure 3.4. *The five different pore types in clay bricks identified by the BRE; (a) channel, (b) loop, (c) blind alley, (d) pocket, (e) sealed (Thomas 1996, p.120).*

It can be seen from the information presented here that predicting the frost resistance of a brick is very complicated. It is exactly this conclusion that is presented by Stupart (1989, p.47) in his extensive survey of 159 papers on frost damage where he concludes that it is unlikely for one set of measurements to ever accurately determine the frost resistance of all bricks due to the vast diversity in brick types available.

3.3 Grading Frost Resistance

All new bricks are graded in accordance with BS EN 771-1:2003 to define their resistance so that they can be correctly specified according to the geographical area and exposure position in the building, *table 3.5.*

Code	Definition	Description of Use
F2	Frost resistant	Can be used in all normal building situations and degrees of exposure[1]
F1	Moderately frost resistant	Durable except where they may remain saturated and are subjected to repeated freezing and thawing. Generally they can be used between dpc and eaves although caution should be exercised on sites in elevated, exposed locations. Should not be used below ground level dpc or for cills or other areas where high saturation /exposure can be expected e.g. coping/cappings, beneath cappings, in projecting details, exposed site locations or in landscaping[1]
F0	Not frost resistant	Should not be used externally[1] Masonry in external walls if provided with suitable protection, the extent of which depends on climatic conditions. In some parts of Europe, experience suggests that a thick layer of suitable external render provides such a protection. In situations where there is risk of wetting accompanied by freezing, the protection should take the form of an impermeable cladding[2]

Table 3.5. *Categories of frost resistance [1]IBSTOCK (2007, p.2) and [2] BSI (2005b, p.36).*

3.4 Assessment of Units for Frost Resistance

As it is clear that not one measurable material property can be accurately attributed to a brick unit being resistant, methods for determining resistance are all based around the actual freezing of water in a specific unit.

3.4.1 Proven Experience

The frost resistance of a clay brick is generally determined through experience of its use and according to Lynch (1994, p.97) there is no British Standard test. Accurately assessing the resistance of masonry to frost has long been a concern of manufacturers of bricks (Edgell 2005, p.32). Practical experience has shown many types of brick to fail in areas of severe weather and brick manufacturers are able to classify bricks solely from observing their condition in service (BSI 1985, p.1; BSI 2005, p.51). Without proper testing, predicting the failure of new bricks or existing bricks experiencing a change in hygrothermal conditions is difficult.

3.4.2 Accelerated Frost Testing

British Standard BS 3921:1985 and European Standard for the Specification for Masonry Units; BS EN 771-1 fail to outline a standard procedure to establish frost resistance but do allow resistance to be determined by the freeze panel test conducted by the British Ceramics Research Limited (now CERAM) (BSI 2005, p.51). *Fig. 3.6* shows the uni-directional accelerated frost test facility, developed by CERAM. The test involves subjecting a masonry panel that has been soaked in water for 7 days to 100 cycles of wetting, exposure to -15°C, +25°C and than re-wetting (Edgell 2005, p.40).

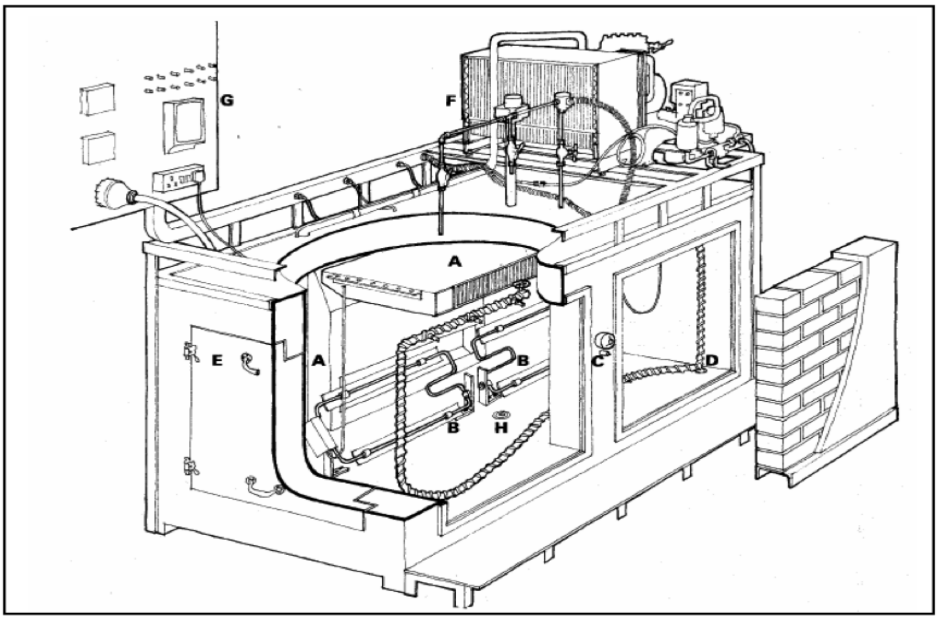


Figure 3.6. *CERAM's uni-directional accelerated frost test facilities: A, evaporators; B, electrical heaters; C, control thermometers; D, water supply protected with soil-warming cable; E, inspection panel; F, compressor; G, control panel; H, drain hole (Edgell 2005, p.40).*

The CERAM test is now universally used by the UK brick industry (Edgell 2005, p.41) but an official pan-European Standard for freeze/thaw testing has not yet been agreed on. Results from the CERAM freeze/thaw tests are defined as shown in *table 3.7*.

BS EN771-1 grade	No. of cycles	Observation
F2	100	No damage observed, fully frost resistant
F1	10-100	Damage observed between 10 and 100 cycles
F0	<10	Damage occurs before 10 cycles

Table 3.7. *BS EN771-1 grades relating to the number of freeze/thaw cycles in the CERAM accelerated frost test (Edgell 2005, p.41).*

Other tests that measure pore size distribution by mercury intrusion porosimetry have found a linear correlation between frost resistance and percentage of pores with a diameter bigger than 3μm (Maage 1984, p.345). Even though results from these tests can be successful have not been widely adopted by brick manufacturers (Edgell 2005, p.34).

3.5 The Correct Positioning of Bricks According to Frost Resistance

Correct detailing and positioning of bricks, *fig 3.8*, is important to reduce the amount of water that F0 and F1 bricks are exposed to. Some of the oldest bricks in service in England date back to around Roman times and demonstrate how a well-maintained, correctly detailed brick can be extremely durable (Brunskill & Clifton-Taylor 1977, p.13). Details like deep eaves will to some extent reduce the amount of wind driven rain striking the building. *Fig. 3.8 and Table 3.9* highlight particularly vulnerable positions where only F2 units should be specified.

Figure 3.8. *Guidelines on where to use different categories of frost resistant bricks in house construction (IBSTOCK 2007, p.2). Guidelines apply to buildings within low exposure zones of the UK.*

Vulnerable positions for frost attack
Chimney terminals, sills, copings and cappings. Freestanding and retaining walls, parapets and chimney stacks. Below damp proof courses at or near ground level and in foundations, manholes and inspection chambers. Conditions of highly mobile ground water.

Table 3.9. *Vulnerable positions for frost attack according to BS 5628-3:2005 (BSI 2005b, p.68).*

3.6 Climatic Conditions

The climatic conditions that are associated with causing frost damage can be assessed and defined in different ways. Since different bricks in service at the same site may not all react similarly, forecasting general failure is difficult. Annex A7 of BS 7543:2003 - *Guide to Durability of Buildings and Building Elements, Products and Components* is dedicated to correctly assessing and specifying building materials in relation to frost damage (BSI 2003, pp.15-16).

It states that:

> In the UK there are at present two approaches to identifying sites susceptible to frost damage.
>
> 1) One approach classifies a site as severely exposed to frost when all of the following factors apply.
>
> a) The average annual frost incidence is in excess of 60days.
> b) The average annual rainfall is in excess of1000mm.
> c) The altitude of the site is in excess of 91m above sea level.
>
> NOTE 1 The altitude factor is likely to reflect the greater liability to wind driven rain on higher ground.
>
> 2) The other approach contained in BS 5628-3 is based on driving rain only. It recommends that suitable grades of mortar, and of bricks or blocks, should be used in areas subject to severe driving rain as defined in the map of the all direction driving rain index drawn from BS 5628.

From the approaches presented in BS 7543:2003 two exposure maps have been produced for simple, systematic assessment.

In accordance with the meteorological criteria in the first approach, the London Brick map identifies severe exposure zones through postcode districts, *fig. 3.10.*

Fig 3.11 by the BRE has been compiled with the second approach using the quantity of wind driven rain only and refers to the method defined in BS 5628-3:2005*, table 3.12* below.

It can be seen when comparing the two maps that London Bricks ‘severe’ zone corresponds roughly to the BRE’s WDR zone 4.

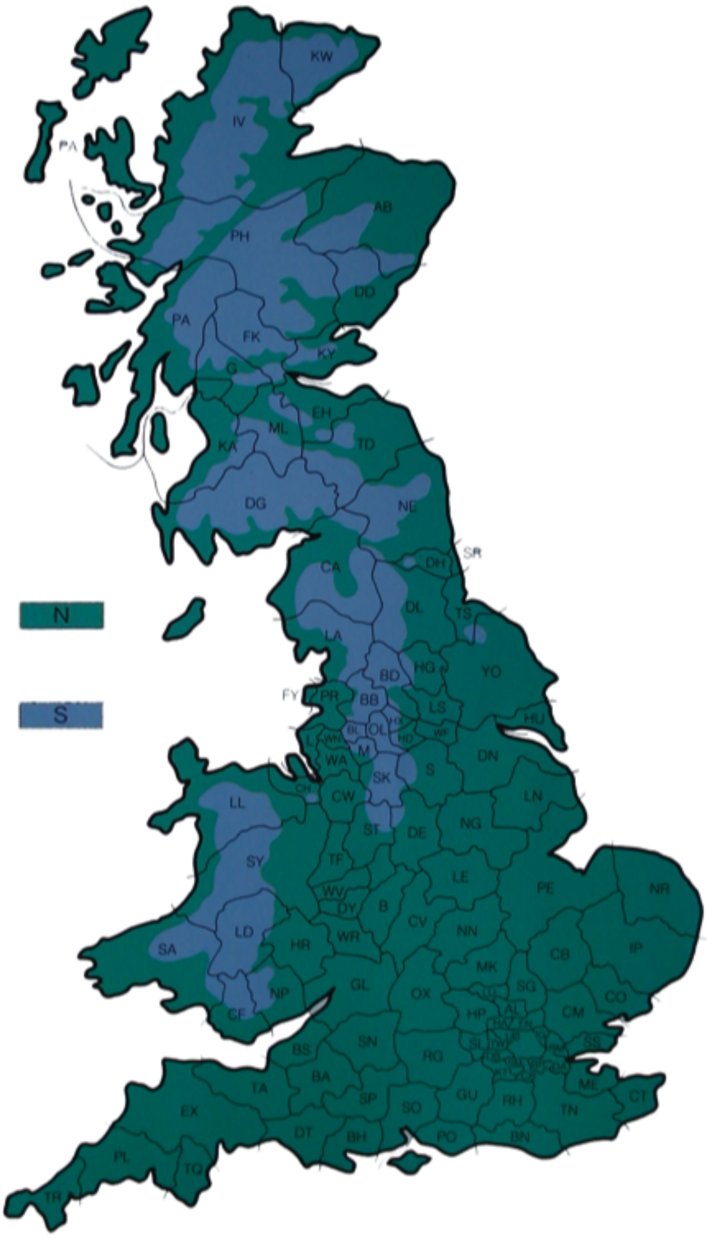


Figure 3.10. *Map showing areas of normal, N; and severe, S, exposure produced by London Brick (1990, p.3) in accordance with method 1 in BS 7543:2003 (BSI 2003, p.16).*

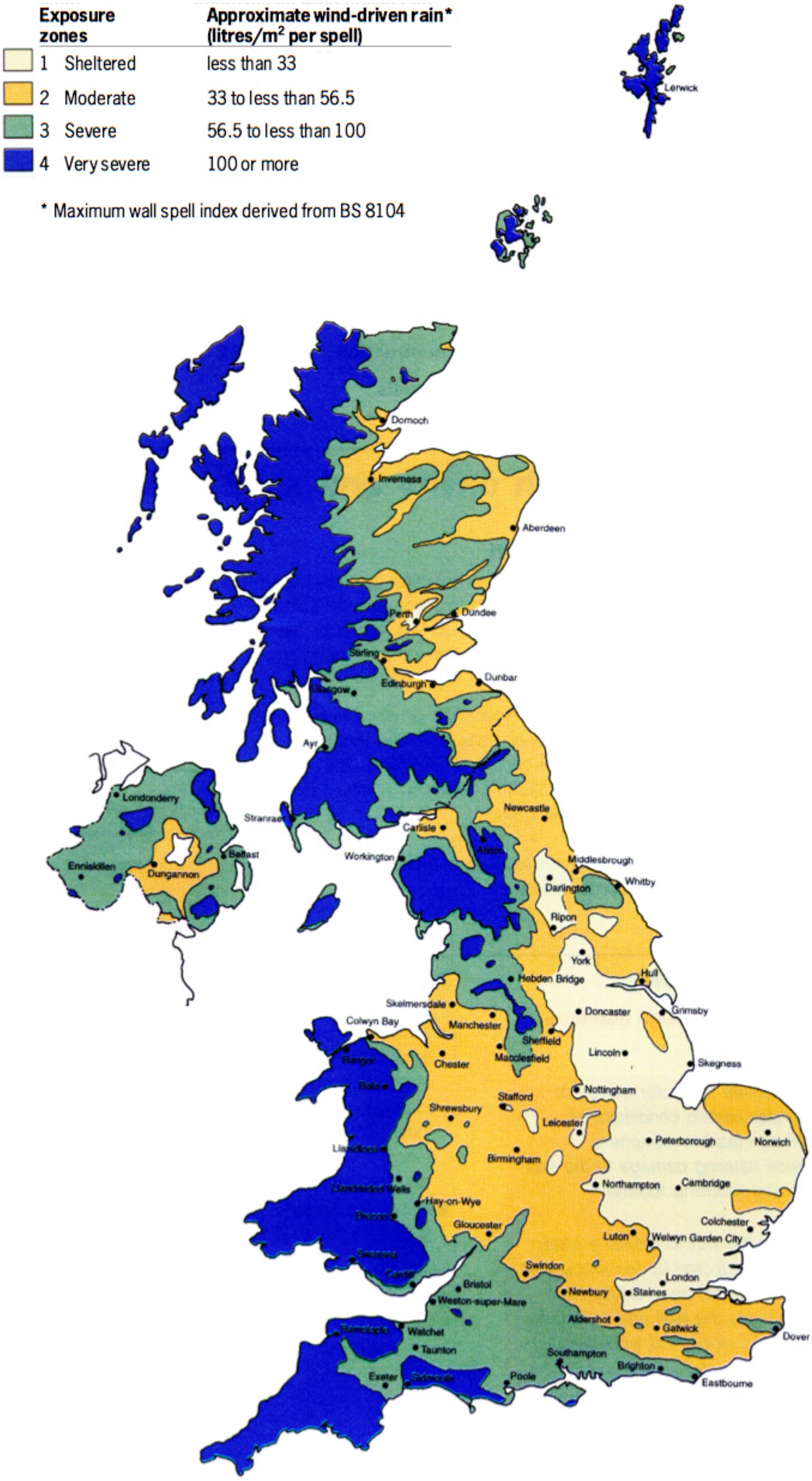


Figure 3.11. *Map showing the four UK exposure zones for wind driven rain (BRE 2002, p.27) in accordance with method 1 in BS 7543:2003 (BSI 2003, p.16).*

Category of exposure		Calculated quantity of wind-driven rain (l/m^2 per spell)
1	Sheltered	Less than 33
2	Moderate	33 to less that 56.5
3	Severe	56.5 to less than 100
4	Very Severe	Not less than 100

Table 3.12. *Categories of exposure to local wind-driven rain BS 5628-3:2005 (BSI 2005b, p.53).*

In addition to the methods above an alternative means of assessment is presented by Grossi et al. (2007, p.275) who use the term 'wet-frost' and suggest that the likelihood of frost damage to susceptible materials can be estimated by counting the number of freeze-thaw cycles and wet-frost days that they are subjected to. Wet-frost days are considered to be "rainy days with mean temperature above 0 °C followed immediately by a day with mean temperature below − 1 °C".

3.7 Frost Damage as a Result of Internal Wall Insulation

When insulating a solid masonry wall internally its hygrothermal behaviour is affected. Over the heating season the new insulation reduces heat flow across the wall to the outside, therefore lowering the temperature of the external masonry. In addition, the wall will eventually stabilise with a new higher moisture content and as a result its thermal resistance will be reduced (Hendry 2001, p.328). It is the combination of these factors that can increase the risk of frost damage conditions occurring.

The extent to which this may be a problem in the UK climate with the levels of insulation likely in retrofits is not known. According to Oliver et al. (1996, p.6) high levels of internal insulation can increase the risk of frost damage to the cold side of the building envelope. This still relies upon the units, either brick or stone, having low frost resistance. The various studies summarised below report on the effect that internal insulation has on both increasing freeze-thaw cycles or the increased incidence of frost attack.

> "Thermal insulation: the more a part of the structure is insulated, the warmer the internal surface will be for the same room heat input and, consequently, the risk of surface condensation or mould growth will be lower. However, layers to the outside of any extra insulation will be colder, and therefore more prone to interstitial condensation, and frost damage" (CIBSE 2007, ch.7, p.15).

3.7.1 Observations in Full- Size Buildings

Given that relatively few houses have been retrofitted with internal insulation the extent of the practical experience and knowledge of insulation and frost damage is not widespread. However, the addition of loft insulation is much more widespread and Thomas (1996, p.121) points out that frost damage can sometimes be seen on gable walls above eaves level where the loft floor has been highly insulated. This issue is also noted in clay roof tiles where roofs have high levels of insulation (Oliver et al. 1996, p.41). It is precisely for this reason that bricks in vulnerable parts of a building are required to be more frost resistant; they will suffer lower temperatures with a higher moisture content. The correct detailing of bricks according to their frost resistance is shown in *fig. 3.8.* An example of seemingly appropriate bricks failing is shown in *figs. 3.13* and *3.14*. In this example it can be seen that where the stair treads interact with the brick wall, localised frost damage is present. Water incident on the treads is being drawn into the adjoining bricks and their moisture content on freezing is increased to a damaging level (Smith & Edgell 2009, p.5).


Figures 3.13 and 3.14. *Localised frost damage in bricks. Pooling water on the stair treads has caused increased saturation on freezing (Smith & Edgell 2009, p.5).*

In a study by Saïd et al. (2003) hygrothermal performance monitoring took place over two years on a retrofitted four-storey masonry building in eastern Canada. The retrofit consisted of additional insulation and vapour barriers on the inside of the brick wall. The Canadian climate is particularly harsh and the outdoor air temperature dropped to -25°C which is not typical of average UK conditions. However, conclusions from the study showed that the insulated brick wall experienced 22 freeze-thaw cycles at -2°C compared to 9 cycles whilst uninsulated. The brick wall's interior surface was also exposed to 7 cycles as a result of the insulation retrofit. A south wall was used for the study as solar radiation increased the number of freeze-thaw cycles during 'below-zero days' (Saïd et al. 2003, p.451) The monitored wall was also shown to have an increased moisture content, partly due to the retrofit and the particularly wet weather experienced over the monitoring period. (Saïd et al. 2003, p.2).

3.7.2 Laboratory Testing

Laboratory testing has also shown how the addition of insulation can cause damage to masonry. Laycock (2002, p.199) reports on ten years of laboratory testing at Sheffield Hallam University where a climatic chamber was used to investigate the performance of construction materials. The findings show how increasing levels of internal insulation affect the number of freeze-thaw cycles and the length of time masonry stays below zero.

3.7.3 Numerical Simulations

The earliest numerical simulations found on the effects of internal wall insulation were conducted by Andersson (1979, p.9). Using numerical calculations it was shown that "internal additional insulation without a vapour barrier always results in an increased moisture content compared to before the insulation was applied", and the research recommends that vapour barriers are always used when insulating in this way. Nearly twenty years on from Andersson's experiment, Kunzel (1998, p.103) found the opposite using an early version of WUFI. *Table 3.15* shows the different values of vapour diffusion resistance for the types of insulation simulated. Expanded polystyrene (EPS) was the most vapour resistive insulation and Kunzel's findings show it to reduce the drying out rate and increase the moisture content of the wall the most.

	Brick	EPS	Mineral wool	Insulating plaster[1]
Vapour diffusion resistance factor [-]	10	30	1.3	8

Table 3.15. *Vapour diffusion resistance factors of materials simulated by Kunzel (1998, p.100).*

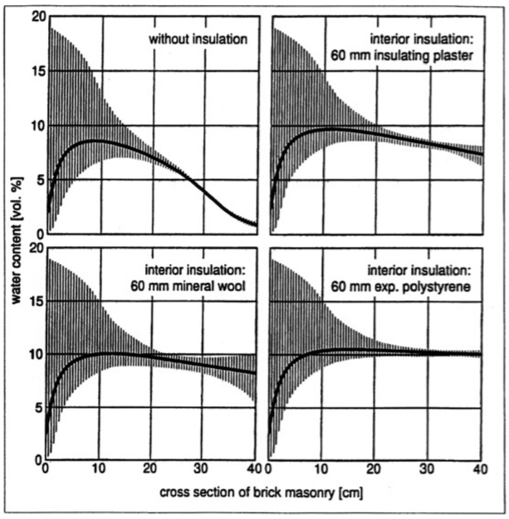


Figure 3.16*. Cross section of masonry showing water content. Solid line shows annual mean content and hatched area shows the amplitude of fluctuations throughout the year (Kunzel 1998, p.102).*

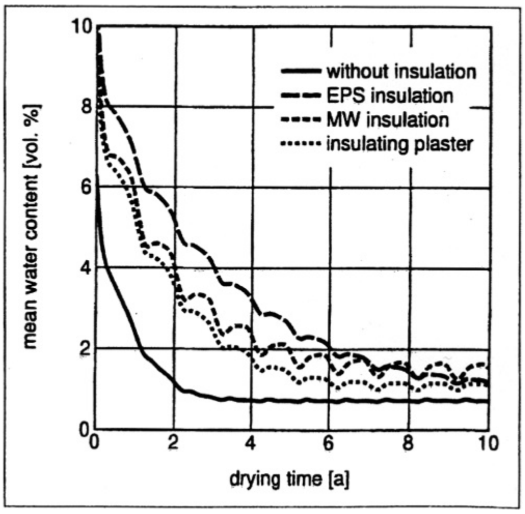


Figure 3.17. *Drying out times of un-rendered brick walls with and without different types of insulation (Kunzel 1998, p.102).*

This point is further reported on by the Fraunhofer Institute for Building Physics (IBP); the manufacturers of the WUFI software. According to the IBP (2007) the drying out ability of the wall is affected because it is now cooler and if the insulation

[1] The insulating lime-cement plaster contains particles of expanded polystyrene (Kunzel 1998, p.100).

is not ‘breathable’, drying out to the inside is not possible. These combined factors increase the wall’s moisture content and reduce its temperature, making freezing with a high moisture content more likely than before (IBP 2007).

3.8 Preventative Surface Treatments

One obvious option for reducing the potential for damage in susceptible units is by applying preventative surface treatments such as paint or silicone coatings. The use of this approach needs to be carefully considered as walls that are painted will take much longer to dry, should they become wet (Rousseau & Maurenbrecher 1990, p.9). It is this point that makes the treatment problematic. If surface treatments are well applied and maintained then the amount of rainwater absorbed into the brick is less. However, according to a report by the Brick Development Association (Hammett 1998, p.30) bricks cannot be treated to resist frost. Silicone surface treatments improve the shedding of water from a wall but increase the general flow of water over the surface which in turn subjects untreated areas and cracks in the masonry to greater quantities of water. These coatings also inhibit the drying out of saturated walls or wet areas and therefore can increase vulnerability to frost attack (Hammett 1998, p.31). This would increase likelihood of the sort of localised damage shown in *figs. 3.13 and 3.14.* The reduced ability to dry out was also observed by Kunzel & Sedlbauer (2000, p.278) whose study showed that an uncoated wall absorbed more moisture than a wall with defective paint but also dried out more quickly lowering the moisture content to non-critical levels by the time temperatures fell to freezing point. However, in a numerical experiment by Kunzel (1998, p.5) (received and accepted in 1996), four years before his study with Sedlbauer into moisture in painted and unpainted walls, he concludes that a water repellent impregnation or paint should be used prior to the installation of internal insulation to reduce potential frost damage.

3.9 Frost Damage in a Changing Climate

Climate change, including increased rainfall and temperature fluctuations has the potential to adversely affect the degradation of buildings with regard to frost damage. Within all climate change predictions there are obviously many uncertainties and given this, the World Heritage Committee (2006, p.35) has highlighted the potential risk of increased ‘wet frosts’ and freeze-thaw cycles as having a damaging impact on our cultural heritage. In a report for the Council of Europe by Sabbioni et al. (2008), the impact of these risks on Europe’s cultural heritage is assessed. The report focuses on the threat from water as intense rain, flooding, or storm surges (Sabbioni et al. 2008, p.3) in relation to the weathering of buildings.

Findings from the models in the report (Sabbioni et al. 2008, p.18) expect Europe in general to experience a reduction in frost damage to masonry, however in areas of permafrost such as far northern Europe, temperatures may rise to near zero and increase the frequency of freeze-thaw cycles and frost damage (Grossi et al. 2007, p.280). The Sabbioni report however identifies that parameters such as freeze-thaw cycles and wind driven rain are sensitive to small changes in climate modeling (Sabbioni et al. 2008, p.13) suggesting that predictions are not entirely reliable.

Chapter 3 has shown how frost damage to bricks from internal wall insulation can be a real concern. The mechanism of frost attack has been sufficiently covered in order to understand how best to proceed in designing an experiment that will indicate the significance of the problem.

Chapter 4

Explorations with WUFI

This chapter discusses the use of simulation software in building science and examines some of the functions of WUFI. Exploratory simulations are run with WUFI in order to establish how it can be most accurately used to detect frost damage in bricks and to ascertain some of the material parameters needed for assessment.

4.1 Simulation Software in Building Science

Within building science the ability to predict the behaviour of a wall or building component is highly valuable. Various approaches are available to the technician including laboratory testing, research using test cells and full-scale testing on specifically designed or real buildings. However, the great expense often associated with these approaches makes simulation software an appealing alternative.

Simulation software has an obvious advantage in that results are returned quickly and cheaply. This enables the researcher to easily re-run experiments and quickly explore many different iterations. Variables can be exaggerated to highlight trends that would be difficult to orchestrate in real life. Input values can be changed to understand a variable's degree of consequence and effects can be observed in isolation.

Real life material testing can be relatively simple. Consider a basic experiment to establish a brick's frost resistance:

Leave a brick exposed to real weather conditions for a number of years and monitor it.

To simulate this very basic experiment numerically, a large number of processes need firstly to be understood. The relevant variables including drivers and mechanisms need to be defined, the external climate has to be correctly measured and accurately reproduced. All the relevant properties of the brick need to be identified, measured and validated through prior experimentation. Each one of these processes and the effects they have on each other has great potential for error making the accurate simulation of apparently simple processes extremely complicated.

Hygrothermal simulation programmes, like the one used in this experiment, are based on years of research and on reasonably well-understood processes in building science, but even though the underlying formulas may be correct, the sheer volume of variables involved may prove some results to be questionable (Straube & Burnett 1998, p.83). Additional errors may also be present when we consider the possibility of human error in data input. To minimise this the researcher should have a good knowledge of the physics involved and be competent enough to analyse the results and recognise any anomalies within them.

Simulation tools are simplified versions of reality so the results will also be simplified and suggest trends rather than specific outcomes (Meadows 2005). They should therefore be used as part of a larger approach that draws on other methods of building testing. When used correctly and validated against real building tests, the software can be a convenient and important tool in helping to suggest general trends in building.

4.2 The Glaser Method

Many methods for estimating heat and moisture transfer across building envelopes exist. BS EN ISO 13788:2002 - *Hygrothermal performance of building components and building elements - Internal surface temperature to avoid critical surface humidity* *and interstitial condensation - Calculation methods,* includes a well known method of the calculation often referred to as the 'Glaser method' (BSI 2002, p.13).

The Glaser method is used to assess the annual moisture balance of a wall and calculate interstitial condensation using the following method:

> "Starting with the first month in which any condensation is predicted, the monthly mean external conditions are used to calculate the amount of condensation or evaporation in each of the twelve months of a year. The accumulated mass of condensed water at the end of those months when condensation has occurred is compared with the total evaporation during the rest of the year. One-dimensional, steady-state conditions are assumed. Air movements through or within the building elements are not considered" (BSI 2009, p.12).

However, this calculation does not "provide an accurate prediction of moisture conditions within the structure under service conditions, and is not suitable for calculation of drying out of built-in moisture" and "should be regarded as an assessment rather than as an accurate prediction tool" (BSI 2002, p.12).

Most importantly, the method does not take into consideration a number of important material properties relevant to this study (BSI 2002, p.4):

- the dependence of thermal conductivity on moisture content
- the release and absorption of latent heat
- the variation of material properties with moisture content
- capillary suction and liquid moisture transfer within materials
- air movement through cracks or within air spaces
- the hygroscopic moisture capacity of materials

and therefore should not be used for assessment of structures where the above effects are significant (BSI 2002, p.4).

Factors affecting hygrothermal behaviour are complex and result in the heat and moisture contents of the wall changing on an hourly basis in response to internal and external conditions. A key aspect to this study is hygroscopic and capillary liquid transport within the porous materials simulated, neither of which are considered by Glaser's model (Ficker 2003, p.5175). For these reasons, isothermal, steady-state models like Glaser's cannot be used.

4.3 WUFI Pro 4.2

WUFI Pro 4.2 (Wärme- Und Feuchtetransport Instationär - Transient Heat and Moisture) is a detailed computer based hygrothermal simulation tool and is considered to be one of the most advanced hygrothermal programs commercially available (Straube & Burnett 1998, p.87; Straube & Schumacher 2006, p.206). The programme was developed by Hartwig M. Kunzel and is supported by the work of K. Kiessl, M. Krus and others at the Fraunhofer Institute for Building Physics. It has demonstrated its accuracy through validation against full-scale field tests over many years (Straube &

Burnett 1998, pp.87-88). WUFI Pro 4.2 is a one-dimensional simulation tool that allows users to build external walls with many layers. Materials can either be taken from WUFI's extensive materials database or added using measured values from new materials.

Once the materials and their properties have been decided upon, climate files are assigned to the external and internal environments. Measured weather data is combined with geographical knowledge of the location such as altitude. Wall height, orientation and inclination need to be defined for WUFI to simulate additional climatic conditions including driving rain and radiation loads incident on the wall (IBP n.d., p.24). With the inputs defined WUFI then calculates the heat and moisture transport processes in the materials using the coupled differential equations shown in *fig.4.1.* The left side of both equations defines storage terms for heat and moisture. The right side describes transport terms for heat, liquid and vapour diffusion (IBP 2001).

$$\frac{\partial H}{\partial \vartheta}\frac{\partial \vartheta}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial \vartheta}{\partial x}\right) + h_v \frac{\partial}{\partial x}\left(\frac{\delta}{\mu}\frac{\partial p}{\partial x}\right) \quad \text{Heat transport}$$

$$\rho_w \frac{\partial u}{\partial \varphi} \cdot \frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial x}\left(\rho_w D_w \frac{\partial u}{\partial \varphi}\frac{\partial \varphi}{\partial x}\right) + \frac{\partial}{\partial x}\left(\frac{\delta}{\mu}\frac{\partial p}{\partial x}\right) \quad \text{Moisture transport}$$

D_w [m²/s]	Liquid transport coefficient
H [J/m³]	Enthalpy of moist building material
h_v [J/kg]	Evaporation enthalpy of water
p [Pa]	Water vapor partial pressure
u [m³/m³]	Water content
δ [kg/msPa]	Water vapor diffusion coefficient in air
ϑ [°C]	Temperature
λ [W/mK]	Heat conductivity of moist material
μ [-]	Vapor diffusion resistance factor of dry material
ρ_w [kg/m³]	Density of water
φ [-]	Relative humidity

Figure 4.1. *Equation showing the basis of the WUFI non-steady state heat and moisture transport processes in building components (IBP 2001).*

Along with temperature, wind-driven rain is the most important meteorological factor influencing frost damage and WUFI's ability to simulate this factor makes its use particularly appropriate for this experiment.

When inputting new materials WUFI requires the following: density [kg/m^3], free water saturation, [m^3/m^3], total porosity [m^3/m^3], specific heat capacity [J/kgK], thermal conductivity [W/mK] and the diffusion resistance factor [-] (IBP 2007). With these values WUFI is able to generate the materials' moisture storage function and with the water absorption coefficient (A-value), [kg/m²√s] liquid transport coefficients for suction and redistribution can be estimated (IBP 2007; Schmidt 2009). The exact values assigned to materials and the calculation criteria used are displayed in Appendix A.

4.4 Meteonorm External Climate Files

Accurately representing the external climate is of great importance, particularly when such specific events as wet-frosts are concerned. As previously discussed, for frost damage conditions to occur a number of external climatic variables have to coincide. This is further complicated by factors such as incident solar radiation and night-time long-wave radiation which are both capable of increasing zero degree crossings when air temperatures are below or above zero. Detailed climate files can therefore only be used when simulating wet frost conditions.

METEONORM is a collection of climate databases from around the world, combined with a large number of computational models developed in international research programmes (Meteonorm 2008, p.1). In order to create a climate file for a specific location, data from the nearest weather stations is interpolated (Meteonorm 2009, p.30).

The METEONORM software encompasses an extensive range of climatic parameters which makes it highly appropriate for this study, measurements include the following: monthly means of global radiation, temperature, humidity, precipitation, days with precipitation, wind speed and direction, sunshine duration (Meteonorm 2009). Once the climate file has been generated it is saved as a .TRY file for WUFI to read. The .TRY files exported from Meteonorm use data collected between 1996-2005 and are saved without driving-rain data, but with wind speed and precipitation. Driving-rain is then calculated within WUFI (Meteonorm 2009, p.95). Details of weather stations and definitions of hourly outputs saved in .TRY files can be seen in Appendix B. The exact locations of the climate files used are shown in Chapter 5 *table 5.3.*

4.5 Stewartby Fletton Bricks

Due to the diversity of brick units in service around the UK, the simulation of one brick type in this experiment cannot possibly claim to represent all units in the country. In order to give this research the most relevance possible it is necessary to define the properties of a widely used brick that will represent a large proportion of our housing stock.

One such brick is the 'Fletton', which made up a substantial proportion of the total UK brick output (Brick Development Association 1974) and until recently has been the most widely sold brick in the UK (Sharp 2009). Flettons were first made in the 1880s and became popular in the early part of the 1900s and particularly in the 1920s when many solid walled houses were still being built. In 1898 the London Brick Company's Fletton brick-yard installed Europe's largest Hoffmann kiln (circular continuous kiln), consisting of 40 chambers, each with a capacity of 50,000 bricks (Lynch 1994, p.25).

Flettons are named after a village in Cambridgeshire and are made from Lower Oxford Clay extracted from three different sites across Bedfordshire, Buckinghamshire and Cambridgeshire (Brick Development Association 1974). Although the clays derived from different sites the properties of the actual bricks vary relatively little (Smith 2009). Stewartby in Bedfordshire was the most active site manufacturing Flettons between 1880 and 1930. The values used in this experiment (*table 4.2*) are taken from bricks manufactured with clay from the Stewartby site and will be similar to bricks actually used between 1880 and 1930 (Sharp 2009) when many solid walled homes were made.

Stewartby Flettons	
24hr cold water absorption (W_F)	278.4 kg/m^3
5hr boil water absorption (W_{MAX})	330.6 kg/m^3
Saturation coefficient	0.85
Thermal conductivity	0.47 W/mK
Density (net)	1740 kg/m^3
Initial rate of water absorption	1.5-2.0 kg/m^2/min
A-Value	0.26
Frost resistance class	F1

Table 4.2. *Typical values for Stewartby Fletton (Sharp 2009).*

The London Brick Company produced Stewartby Flettons[1] and the exposure map (*fig 3.10* chap 3) was partly developed to serve as a guide to where Flettons could be appropriately used in house building (London Brick 1990, p.1; Sharp 2009). Flettons are not particularly frost resistant (F1) and commonly fail in freeze-thaw tests after 15 cycles (Smith 2009). This lack of frost resistance may make them vulnerable to the sort of hygrothermal changes brought about by internal wall insulation. These factors make the use of their values in this simulation particularly relevant.

With the values in *table 4.2* provided by Sharp (2009), moisture storage and moisture transport functions can be estimated by WUFI. The '24hr cold water' and '5hr boil' absorption figures are taken as 'total free water saturation' and 'total porosity' respectively. WUFI then generates the material's 'moisture storage function' curve by plotting RH against water content at free water saturation and total porosity. *Fig. 4.3* shows the moisture storage function for Stewartby Flettons, which is very steep at around 97% RH.

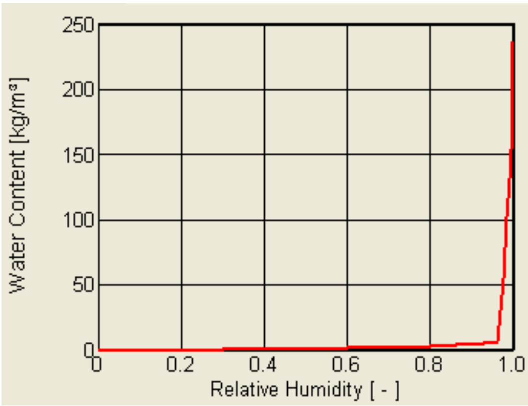


Figure 4.3. *The moisture storage function of a Stewartby Fletton generated in WUFI.*

[1] Now Hanson part of Heidelberg Cement Group

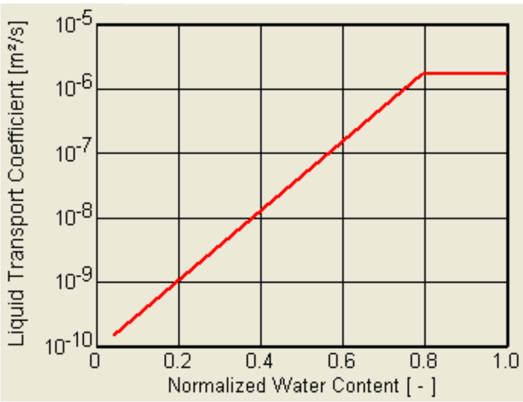
4.6 Liquid Transport Coefficients

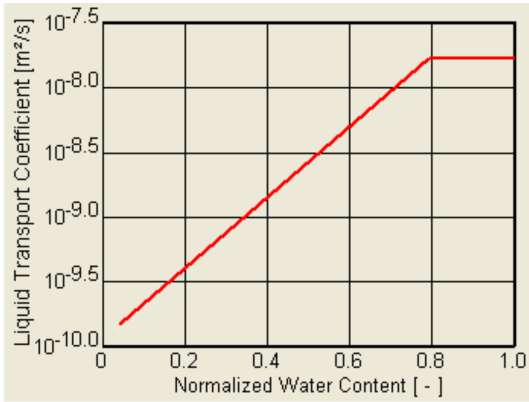
In order to correctly simulate different types of capillary suction WUFI uses the two following coefficients that are calculated from the water absorption coefficient (A-value):

The '**liquid transport coefficient for suction' (Dws) [m^2/s]** describes the uptake of water by capillary suction when the materials surface is completely wet. In the context of brick this is happening during a driving-rain event. The type of suction happens mostly in the larger capillaries where there is lower resistance to flow (IBP 2001).

The '**liquid transport coefficient for redistribution' (Dww) [m^2/s]** describes the process of redistributing the water drawn from the surface after the rain has finished. This mostly takes place in the smaller capillaries as they have a higher capillary tension that draws water from the larger capillaries. These smaller capillaries have a higher flow resistance which makes the redistribution process slower than initial suction (IBP 2001).

Both of these processes are moisture dependent as shown below in *table 4.4 and 4.5.*





Figures 4.4 and 4.5. *Left, liquid transport coefficient for suction in masonry and Right Liquid transport coefficient for redistribution. Both can be seen to be moisture dependant (WUFI 2009b).*

Since liquid transport coefficients are not available for most materials they can be worked out using the following equation:

$$D_{ws}(w) = 3.8 \cdot (A / w_f)^2 \cdot 1000^{(w / w_f) - 1}$$

D_{ws}	[m²/s]	:	liquid transport coefficient for suction
A	[kg/m²√s]	:	water absorption coefficient
w	[kg/m³]	:	moisture content
w_f	[kg/m³]	:	free water saturation

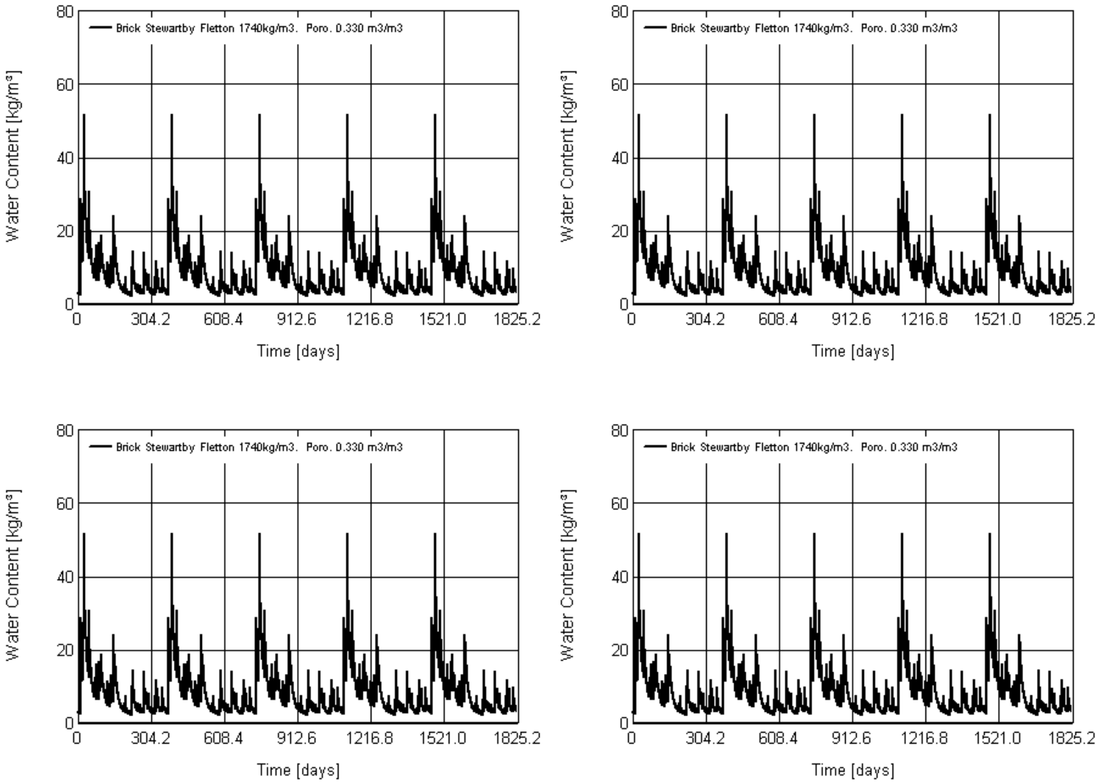
This is automatically calculated by WUFI on input of the A-value.

4.7 Establishing the μ-value for Stewartby Flettons

The values provided by (Sharp 2009) for the Stewartby Flettons do not include a 'water vapour diffusion resistance factor' (μ-value). "The μ-value states by how much the diffusion resistance of the material in question is higher than that of stagnant air" (IBP n.d.).

In order to establish how much the diffusion resistance factor affects the water content of the brick, simulations are run with just 215mm of brick and μ-values of 1, 8, 16 and 32.

4.7.1 Sample Outputs



***Figures 4.6 to 4.9**. Showing no changes in water content (kg/m^3) in the Stewartby Fletton wall when simulated with four different μ-values; 1(top left), 8(top right),16 (bottom left) and 32 (bottom right).*

4.7.2 Analysis

Results show the water content (kg/m^3) of the whole brick wall not to be affected by varying the water vapour diffusion resistance factor between 1, 8, 16 and 32. Even though this value has little or no effect on the water content of the wall, a value still needs to be defined. As Stewartby Flettons have similar basic values to 'hand formed' and 'historical' bricks both from the WUFI database *table 4.10* a μ-value of 16 is assigned.

Brick type	Porosity [m^3/m^3]	Density [kg/m^3]	Heat. Cap. [J/kgK]	Ther. Cond. [W/mK]	Diff. Res. Fac [-]
Solid Brick Masonry	0.24	1900	850	0.6	10
Stewartby Fletton	0.33	1740	1000	0.47	16
Extruded	0.41	1650	850	0.6	9.5
Hand-formed	0.38	1725	850	0.6	17
Historical	0.31	1800	850	0.6	15

Table 4.10. *Comparing values of Stewartby Flettons to other Bricks in the WUFI materials database in order to define a diffusion resistance factor.*

4.8 Establishing Monitor Positions

Following a driving rain event the water content of the brick will be highest towards or at the external surface. To accurately read conditions inside the wall, WUFI enables the user to set monitor positions that record temperature, relative humidity and vapour pressure, but not water content. It is however possible to establish the water content from RH using the brick's moisture storage function graph (*fig. 4.3*), but due to the steepness of the curve around 97% RH, readings may be inaccurate (Straube & Schumacher 2006, p.212).

This approach may also be misleading as readings are taken from a single point in the wall where freezing water may have room to expand into emptier neighbouring pores. A more accurate approach is to create a thin layer of brick within the wall and monitor its overall water content. In this case the freezing water has no room to expand as all the surrounding pores within the layer have also reached their critical percentage of free water saturation. During calculations WUFI simulates the wall as a continuous 215mm thick brick wall with no joints between layers of brick.

In order to establish where to place the layer within the wall, simulations are viewed in WUFI as a 'film'. This enables the researcher to see how diurnal and seasonal changes in external climate affect the hygrothermal behaviour of the wall. This approach establishes the general area at which the highest water contents occur.

4.8.1 Sample Outputs

Figure 4.11 captures the water content in a cross section through the wall during the simulation. The external 20mm of the wall (left side) has been divided into ten, 2mm layers. The actual water content at the time of pausing the film can be seen as a dark blue line, whilst the light blue shaded area shows the amplitude of fluctuations in water content throughout the simulation. Two more snapshots were taken six and twelve hours later, *figs. 4.12 and 4.13.* The external face of the wall is on the left of the snapshot, internal on the right. The units at the bottom refer to the thickness of the layers of brick in cm. The total thickness of the wall adds up to 21.5cm.

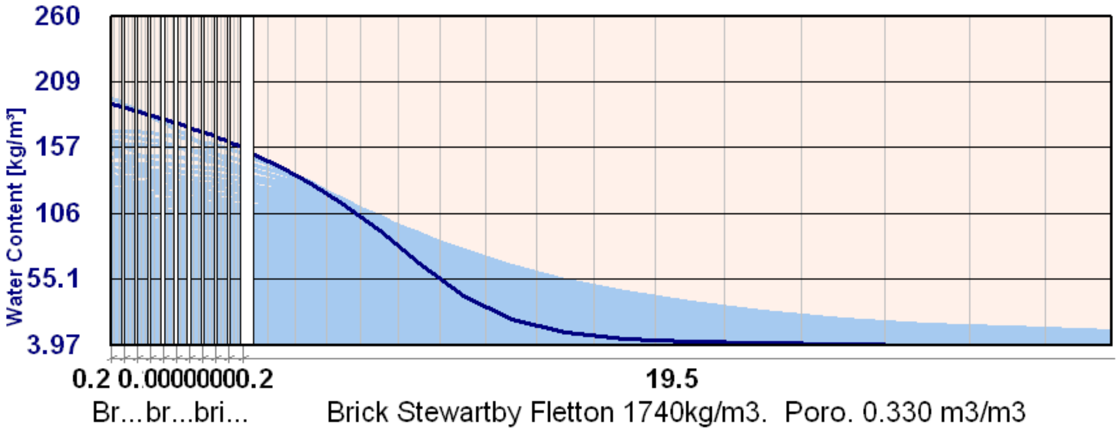


Figure 4.11. *Snapshot showing water content through a cross section of the wall in WUFI. Film paused at 12am midnight 8.10.2005.*

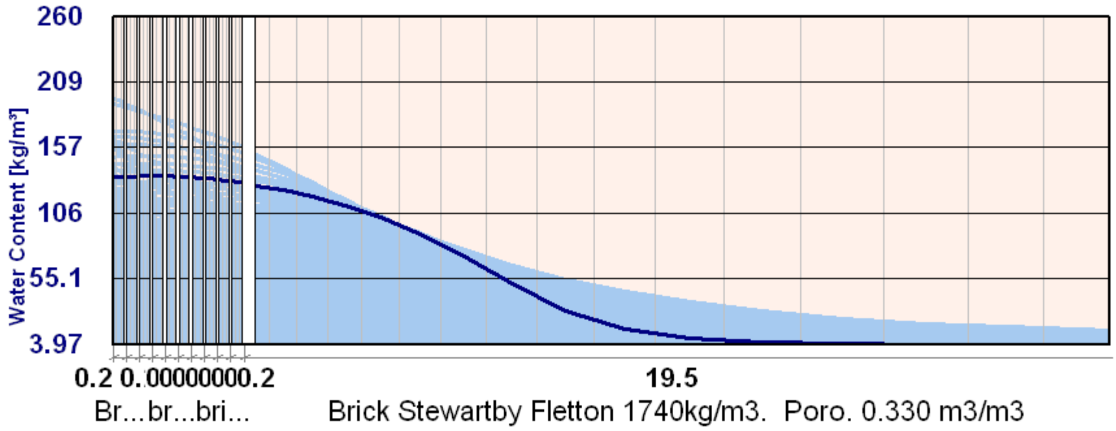


Figure 4.12. *Snapshot showing water content through a section of the wall in WUFI. Film paused at 6am 8.10.2005.*

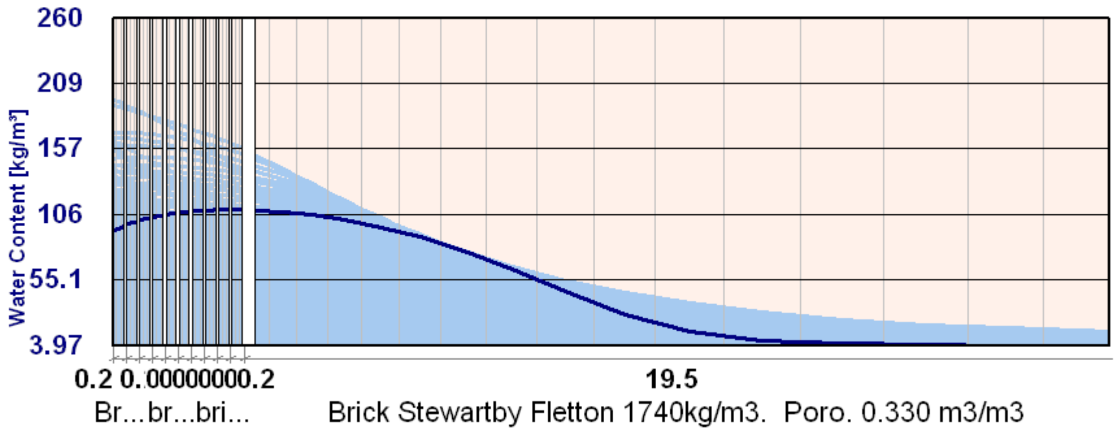


Figure 4.13. *Snapshot showing water content through a section of the wall in WUFI. Film paused at 12pm midday 8.10.2005.*

Figs. 4.12 and 4.13 show the surface water content to quickly drop after driving rain has ceased. The highest water content is now further into the wall, between 4 and 20mm. The water content around halfway into the wall has also risen.

4.8.2 Analysis

The dark blue line in *fig. 4.11* shows the highest water content to have occurred in the first two millimetre thick layer at 12am on 8.10.2005. However, this is the first layer to start drying out after driving rain stops just after midnight (*figs.4.12 and 4.13)*. At 6am, before sunrise when the coldest temperatures are often experienced, the highest water content is seen 4-8mm from the surface. 12 hours later at midday, the highest water content is at around 20mm from the external surface.

The rapid drying of the external brick face poses a problem when defining a monitor layer. As there is no way of knowing the time lag between a driving rain spell and a freezing event the correct position of the monitor layer will have to be estimated. Due to the speed at which drying out is shown to take place it can be assumed that after a matter of hours the water content of the brick is not high enough to suffer frost damage when freezing. Further details on the exact water contents that denote potential for frost damage are discussed later in Chapter 5. However, in relation to the simulations above using Stewartby Flettons (*figs. 4.11 to 4.13)* the critical water content for frost damage is 208 kg/m^3. *Figs. 4.11 to 4.13* show that for freezing to occur with this high water content the temperature would have to drop very soon after rain had stopped as after 12 hours the water content has approximately halved at the external surface. At a depth of 20mm where the highest water content is now shown levels are still far to low for frost damage to occur.

Given the speed of drying out observed in *figs. 4.12 and 4.13* the region of 0-10mm from the external surface is chosen for monitoring. A monitor for temperature is placed in the middle of this layer, 5mm from the external surface.

This Chapter has succeeded in providing the necessary background research needed in order to accurately produce a methodology for the experiment.

Chapter 5

Methodology

This chapter presents the methodology used to simulate the hygrothermal changes in a solid brick wall after adding internal insulation. Additionally, the processes are defined for determining whether or not frost damage conditions are reached in the bricks.

5.1 Object of the Exercise

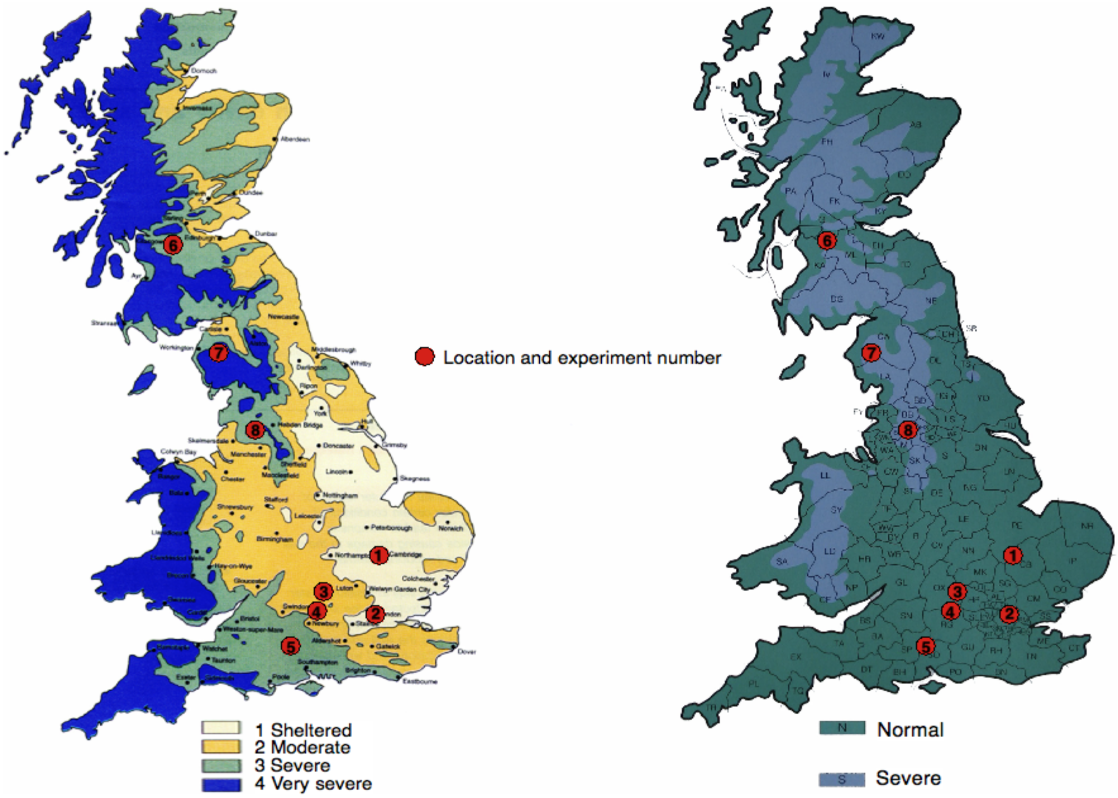
This experiment aims to establish whether high levels of internal insulation have the potential to heighten the exposure of brickwork to frost damage conditions. This is most relevant for bricks in frost resistant categories: F0 - not frost resistant and: F1 - moderately frost resistant. The experiment simulates four types of insulation, each possessing different moisture transport properties, to establish their effect on the water content and temperature of the wall. The results should indicate whether the threat of frost damage to brickwork with low/moderate frost resistance will limit the depth of retrofitted internal insulation and establish if certain types of insulation are better suited for this type of application.

Through the use of WUFI Pro 4.2 software, walls with four types of internal wall insulation are simulated to U-values compliant with the Code for Sustainable Homes level 5&6. The walls are simulated at various locations around the UK that each fall within a different wind-driven rain exposure zone as defined by the BRE (2002, p.27). At each location a solid wall with no insulation is modelled as a control. In order to validate the experiment a location is used where frost damage conditions are known to be highly likely (Sharp 2009b).

5.2 Exposure Zones

Each location simulated in this study falls into a different wind-driven rain (WDR) exposure zone as defined by the BRE (*fig. 5.1*). All locations apart from Keswick and Rawtenstall fall within ‘normal’ conditions according to the London Brick map (*fig.5.2*). Rawtenstall has specifically been chosen as an area where Stewartby Flettons have been known to fail (Sharp 2009b).

The BRE wind driven rain exposure zone map is derived from BS 8104 that contains large-scale maps and correction factors. Where buildings are sited in exposed areas such as open hillsides, one zone can be added and in protected areas one can be subtracted (BRE 2002, p.27). The London Brick map has been compiled with conditions defined in BS 7543:2003 - *Guide to Durability of Buildings and Building Elements, Products and Components* and combines data on wind, rain, frost and topography; areas are split into ‘normal’, ‘severe’ and ‘exceptionally severe’, with the latter only being determined through a site visit. Severe locations are defined as those experiencing an average annual frost incidence of more than 60 days, average annual rainfall more than 1000mm and at an altitude of more than 90m (London Brick 1990, p.2). *Figs. 5.1 and 5.2* show that the exposed areas of both maps are roughly in agreement. The climatic conditions and exact locations of weather stations chosen for this experiment are shown below in *table 5.3.*



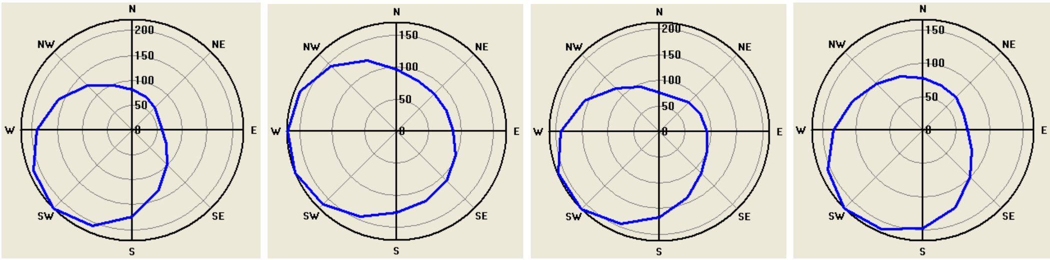
Figures 5.1 and 5.2. *Locations chosen for this study in relation to the wind driven rain exposure zones map (left) defined by the BRE (2002, p.27) and the London Brick (1990, p.3) map (right) showing areas of 'normal' and 'severe' exposure.*

Exp no.	Location and region	Grid Ref.	Altitude [m]	Normal rain sum [mm/a]	SW driving rain sum [mm/a]	BRE WDR zone	London Brick zone
1.	**Cambridge,** Cambs. East England	0.18°E 52.20°N	54	470	225	1	Normal
2	**London,** SE England.	0.17°W 51.50°N	36	500	160	1	Normal
3	**Grendon Underwood,** Bucks. SE England	1.02°W 51.90°N	70	538	210	2	Normal
4	**Wallingford,** Oxon. SE England	1.17°W 51.60°N	50	474	160	2	Normal
5	**Boscombe Down,** Wilts. SW England	1.75°W 51.16°N	124	606	240	3	Normal
6	**Glasgow,** Lanark. Scotland	4.43°W 55.86°N	8	758	225	3	Normal
7	**Keswick,** Cumbria, NW England	3.15°W 54.61°N	81	1017	215	4	Severe
8	**Rawtenstall,** Lancashire, NW England	2.29°W 53.70°N	168	614	260	4	Severe

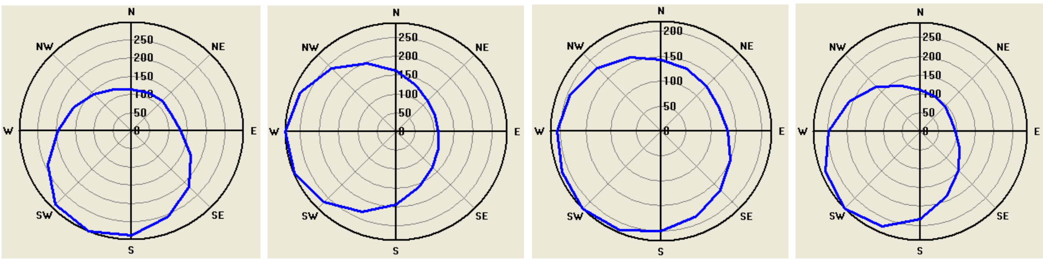
Table 5.3. *Details of the eight locations in the study showing exposure zones defined by the BRE and London Brick.*

5.3 Construction of the Simulated Wall

For this study a 10m high wall is modelled to represent a two-story home with a south-west orientation to face the prevailing wind-driven rain. This was determined by analysing the annual sum of driving rain [mm/a] for each of climate files used, *figs 5.4 to 5.11*. Due to the lack of driving rain on a north-facing wall the chances of frost damage following driving rain are lower. For this reason a north wall will not be simulated.



Figures 5.4 to 5.7. *Intensity of driving rain [mm/a]. From left to right; Cambridge, London, Grendon Underwood, Wallingford (WUFI 2009a).*



Figures 5.8 to 5.11. *Intensity of driving rain [mm/a]. From left to right; Boscombe Down, Glasgow, Keswick, Rawtenstall (WUFI 2009a).*

Additionally solar radiation during the winter months incident on a south-west facing wall may have the potential to increase the number of freeze thaw cycles on below zero degree days. Results will then suggest the most severe conditions a wall of any orientation will suffer. *Fig. 5.12* shows the insulated 215mm solid wall with 15mm of internal lime plaster.

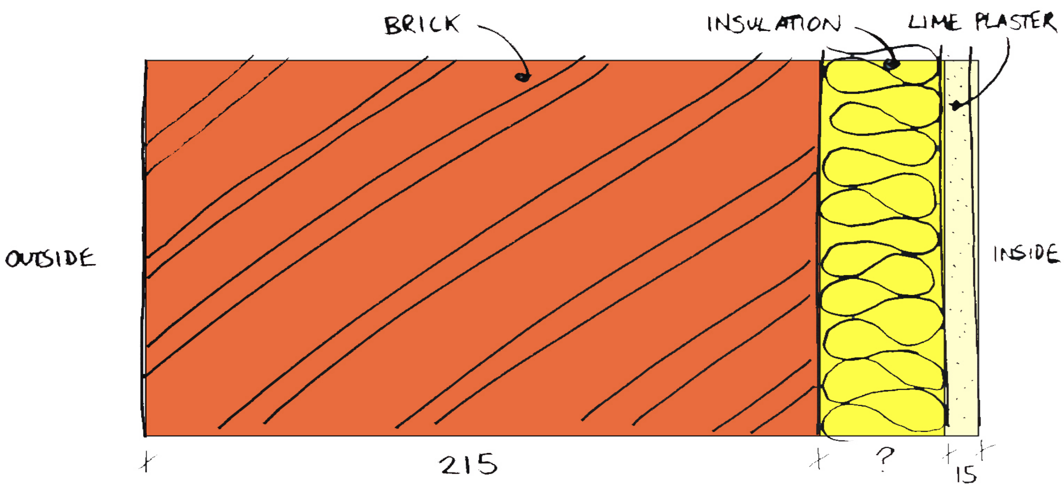


Figure 5.12. *Diagram of the simulated wall showing the 215mm brick wall with internal insulation and 15mm of internal lime plaster.*

5.4 Internal Climate

In order to represent internal conditions an indoor climate file is assigned. The algorithms are defined by BS EN ISO 13788:2002. This standard specifies test methods for thermal and moisture related properties of building materials and products (BSI 2009, p.3) Humidity class two has been defined, which is appropriate for dwellings and an indoor temperature of 17°C is assumed. With external temperatures below 0°C a moisture load of 4g/m^3 is used. When external temperatures exceed 20°C WUFI assumes that doors and windows will be opened therefore no moisture load will exist. For temperatures between 0°C and 20°C each moisture load function decreases linearly from its cold value to zero (IBP n.d., pp.33-34).

5.5 Calculation Period

To simulate conditions within the wall as accurately as possible the experiment is run for 5 years to let the wall establish a new moisture balance. The increased peak moisture content of the whole wall can be seen to repeat on the third year, *fig. 5.13*. Individual elements within the wall may take up to five years to establish a new balance.

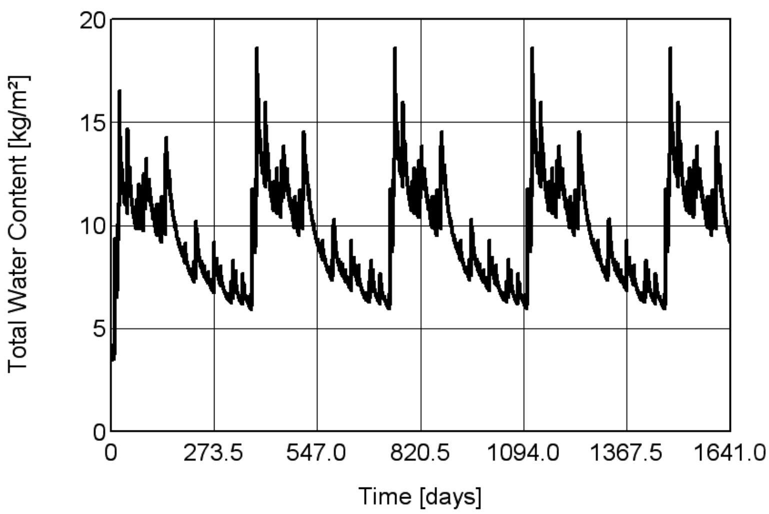


Fig. 5.13. *Shows annual fluctuations of moisture content in the whole wall construction repeating themselves after two years.*

5.6 Defining Frost Damage Conditions

In order to make conservative estimates of frost damage conditions, freezing events are defined as when the temperature in the brick drops from above to below 0°C. With regards to water content, the level can be estimated as a percentage of the brick's free water saturation. Literature on the subject presents a range of figures; Stupart & Phillipson (1998, p.16) estimate this to be 80-90% of free saturation, Saïd et al. (2003, p.451) suggest >75% and Straube & Schumacher (2006, p.212) recommend between 75-94%. As a cautious limit, it has been decided that 75% of free water saturation denotes potential for frost damage conditions.

5.7 Material Choices

5.7.1 Brick

For reasons (discussed earlier in Chapter 3) concerning the different material properties of brick types it would be misleading to present the results of one brick type as being representative of the performance of all UK bricks in service. In the WUFI material database several brick types exist. The following types have been chosen because together they hopefully represent the wide range of material properties of bricks in service. Any trends shown in the results can therefore be more generally applied to buildings in the UK. The table below (*table 5.14*) shows basic values for the chosen brick types.

Brick type	75% of free water sat. [kg/m3]	Free water sat. [kg/m3]	Porosity [m^3/m^3]	Density [kg/m^3]	Heat. Cap. [J/kgK]	Ther. Cond. [W/mK]	Diff. Res. Fac [-]
Solid Brick Masonry	143	190	0.24	1900	850	0.6	10
Stewartby Fletton	208	278	0.33	1740	1000	0.47	16
Extruded	278	370	0.41	1650	850	0.6	9.5
Hand-formed	150	200	0.38	1725	850	0.6	17
Historical	173	230	0.31	1800	850	0.6	15
Lime plaster	-	-	0.3	1600	850	0.7	7

Table 5.14. *Basic material properties of the bricks chosen for investigation.*

5.7.2 Plaster

In modern construction gypsum plaster is commonly used to finish internal surfaces. This is either applied as wet plaster or in the form of plasterboard. Lime plaster with a thickness of 15mm has been chosen as the internal finish for this study, primarily as traditionally it would have been used in the constructions of many solid walled homes. The values for lime plaster are included in WUFI's default material database and are shown in *table 5.14.* Lime plaster is also recommended for use with the wood fibreboard simulated in this study and may be considered to give this experiment some bias.

5.7.3 Insulation

From analysis of the material properties in the WUFI database, four types of insulation have been chosen because of their different moisture transport and storage properties. Each of these materials is also commonplace in modern construction with the exception of wood fibreboard which has a growing interest due to it being a natural product and because of the way it manages interstitial condensation. Additionally, as it has a comparatively high density it increases the thermal mass of the room more than other insulations. This helps to retain the rooms heat in the winter and reduce overheating in the summer. Its performance in this study is of particular interest. The different properties of the chosen insulations are shown below.

- Wood-fibre has a low μ-value (μ 3.3), a high moisture storage function. It is capillary active with good liquid transport mechanisms for suction and redistribution (WUFI 2009b). Being made of wood its hygroscopic performance is also good (Rode 2005, p.30).

- Mineral wool also has a very low μ-value (μ 1.3) offering almost no resistance to water vapour, it has no moisture storage abilities, nor any liquid transport properties and therefore no hygroscopic ability (WUFI 2009b).

- Expanded polystyrene (EPS) has a higher μ-value (μ 30) and also has no moisture storage, liquid transport mechanisms or hygroscopicity (WUFI 2009b).

- Phenolic board (PF) itself has a μ-value of 30, however due to its foil faces this is increased to μ 20 000. The PF itself offers no moisture storage or liquid transport and because of its foil face it's an effective retarder/barrier to both. Again no hygroscopic properties are present (WUFI 2009b).

Together the properties of these four materials represent the main types of insulation available on the market, with regard to vapour diffusion, moisture storage and transport. Each specific brand of insulation available will of course possess its own individual hygrothermal properties. However, this experiment hopes to observe general trends in moisture storage and transport between insulation types after insulating with relevance to the moisture content of the brick.

In this experiment the values for wood fibre insulation are supplied by Bartlome (2009)[1] and are specific to Pavatex Pavadentro internal insulation. The total build up of Pavadentro includes a thin 'mineral functional layer' that slows vapour diffusion whilst still allowing capillary conduction. The functional mineral layer is contained within the thickness of the insulation and is always located 20mm from the back face, regardless of the overall thickness of the insulation (NBT 2008, p.2). The values for PF board are approximated from Kingspan, K18 (Kingspan 2009). Each face of the simulated board is coated with a vapour retarder of the same sd-value as the foil surface of Kingspan K18. WUFI's standard values are used for mineral wool and EPS. All insulation values are detailed in Appendix A.

Due to each insulation type possessing a different thermal conductivity, thicknesses are chosen to comply with the U-value proposed for new homes built to level 5&6 of the Code for Sustainable Homes (*table 5.15*) (EST 2008, p.15).

[1] Co-inventor of Pavadentro (IPEXL 2009)

Insulation type	Thermal conductivity [W/mK]	2013 Code level 5&6 [1] U-value 0.15 W/m^2K
Wood-fibre [2]	0.042	250mm
Mineral wool [3]	0.040	240mm
EPS [3]	0.040	240mm
PF [4]	0.021	125mm

Table 5.15. *Insulation types with specified thickness to comply with the wall U-value for code level 5&6 of the Code for Sustainable Homes [1] (EST 2008, p.15). Wood-fibre values have been taken from Pavatex Pavadentro [2] (Bartlome 2009), mineral wool and EPS [3] from the WUFI database and PF is Kingspan K18 [4] (Kingspan 2009).*

Special attention needs to be paid to the water content of the insulation. As insulation becomes saturated with water from wind-driven rain or interstitial condensation its thermal performance is reduced (WUFI 2009b). This is also particularly relevant to wood-fibre insulation as sustained periods with the water content at or above 20% can cause rot and mould growth (IBP 2007, p.39; Bartlome 2009). The simulated insulation will be monitored for excessively high levels of moisture, however, an in depth analysis of this important factor is beyond the scope of this study.

5.8 Analytical Techniques - The AWK

With the correct monitor position defined from Chapter 4 and the critical temperature, and water content established, it is necessary to devise methods for accurately reading WUFI's outputs. Standard results graphs presented in WUFI give a general overview of hygrothermal conditions over the 5-year calculation period, but are not sufficiently detailed for the type of accurate analysis needed in this study. Results can be exported for analysis in programmes like Microsoft Excel, but due to the large amounts of data other methods are more favourable.

In order to accurately establish the presence of frost damage conditions, WUFI's results are output as ASCII files for further investigation. These large files consist of 39,409 rows of hourly readings over the 5-year calculation period. This data is then examined in a specifically written AWK programme that scans each line of the output data, searching for a zero degree crossing, when this event occurs the values for temperature and moisture content are recorded. Results can then be easily presented in graph form. This analytical approach is consistent with methods used by Brimblecombe (2009). A section of an ASCII file can be seen in Appendix C along with the AWK programme.

The analysis using the AWK programme is possible through the 'Terminal' application in an Apple Macintosh MacBook. This application is a command-line access to UNIX and allows the user to "access the complete UNIX environment using standard commands, tools and scripting languages" (Apple 2010). A sample of the commands used is also shown in Appendix C.

This Chapter has presented a comprehensive methodology for determining and then assessing incidents of frost damage to brick masonry using WUFI Pro 4.2. The results from the experiments are shown in the next Chapter.

Chapter 6

Results

The results from the experiment defined in the last chapter are presented in the following pages. The interpretation of them is covered in Chapter 7.

6.1 Results

Figs. 6.1 to 6.5 show the moisture content (MC) on freezing of the external 10 millimetres of each brick type. Within each graph the MC of an uninsulated wall is compared to walls with four different types of insulation with a new wall U-value of 0.15W/m^{2}K. Each brick type is simulated at eight locations that cover all of the BRE's wind driven rain exposure zones and both of the London Brick's zones.

75% of free water saturation is the defined critical frost damage limit and it can be clearly seen that no frost damage conditions are reached in any of the walls. The water content of the masonry always rises after adding internal wall insulation (IWI) but to nowhere near critical frost damage levels. This trend can be observed across all brick types, with all insulation types and at all locations. Additionally the type of insulation used does not significantly effect the maximum level of water recorded in each wall.

6.2 Results Charts

The left Y-axes show maximum water content reached on freezing [kg/m^3] and the right Y-axes show the percentage of free water saturation (Wf) up to 75%.

Insulation types are as follows; NI – no insulation, WF – wood fibre, MW – mineral wool, EPS – expanded polystyrene, PF – phenolic board (foil faced).

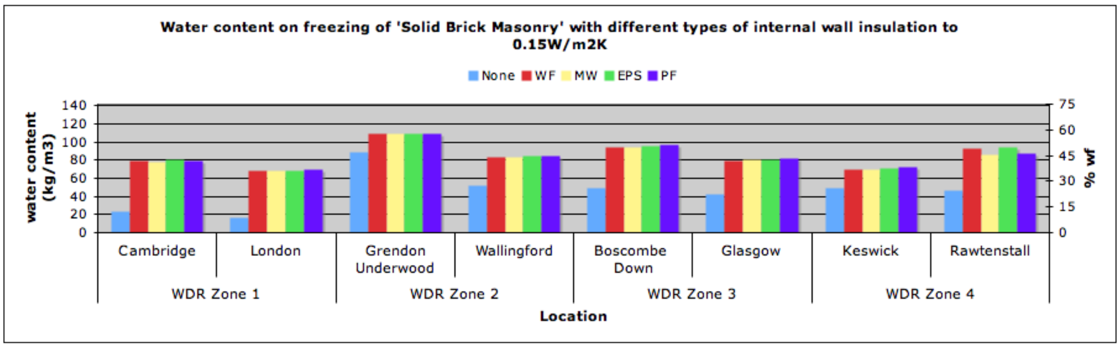


Figure 6.1. *- 'Solid Brick Masonry' - water content of external 10mm of brick on freezing with different types of internal wall insulation at eight locations.*

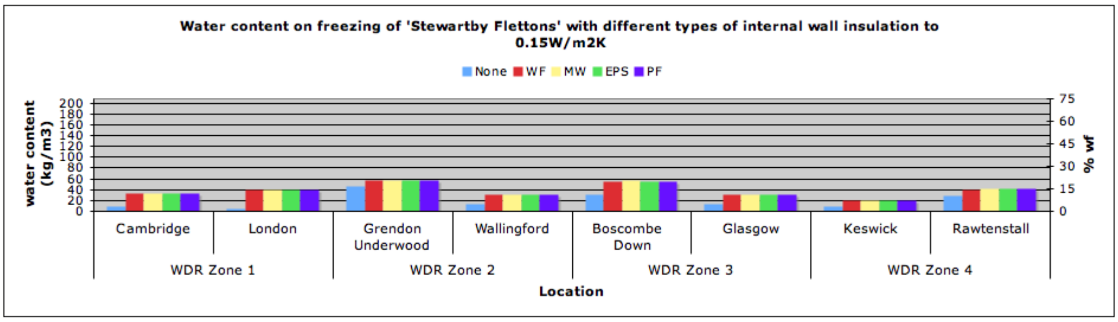


Figure 6.2. *- 'Stewartby Flettons' - water content of external 10mm of brick on freezing with different types of internal wall insulation at eight locations.*

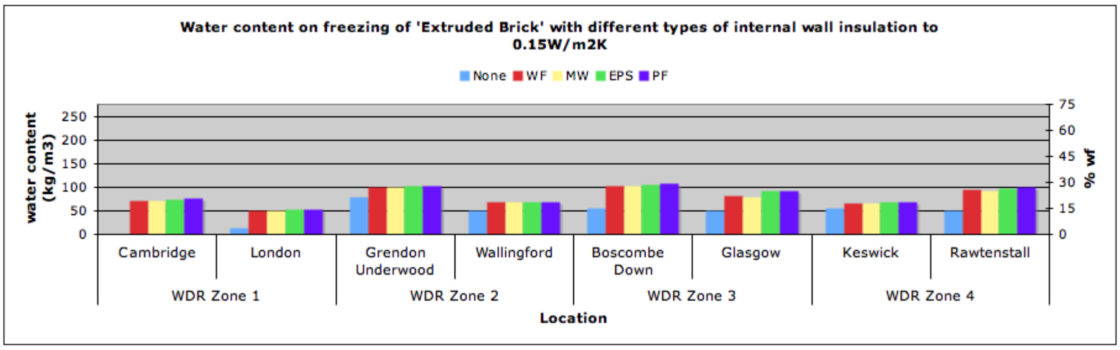


Figure 6.3. *- 'Extruded Brick' - water content of external 10mm of brick on freezing with different types of internal wall insulation at eight locations.*

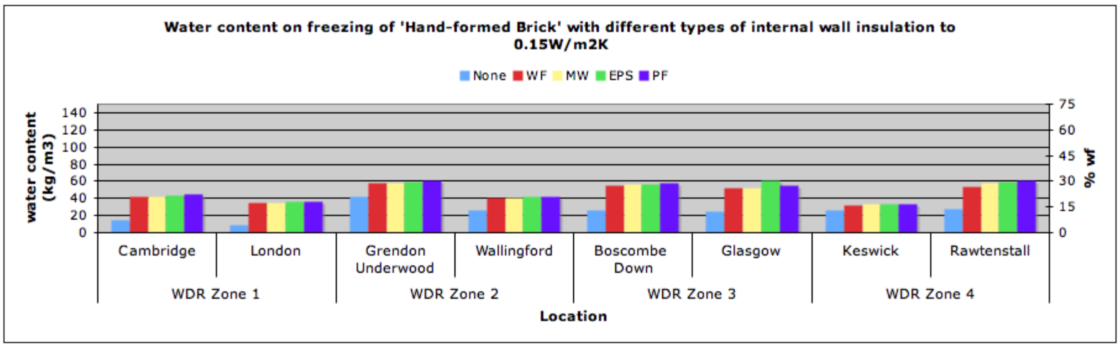


Figure 6.4. *- 'Hand-formed Brick' - water content of external 10mm of brick on freezing with different types of internal wall insulation at eight locations.*

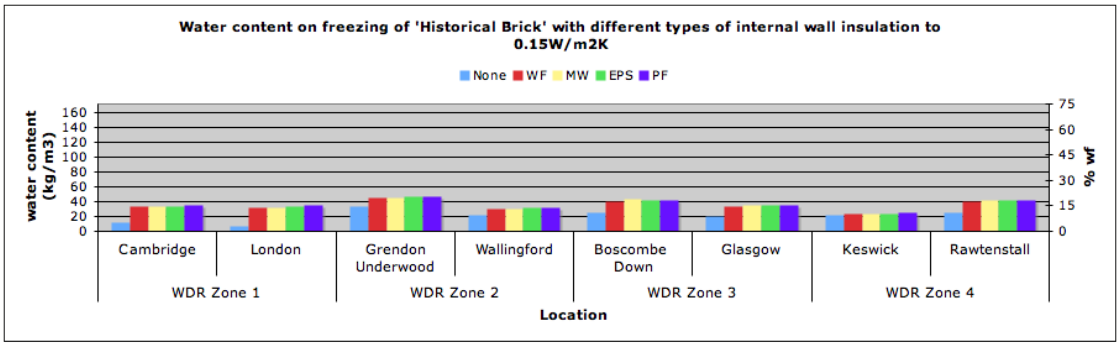


Figure 6.5. *- 'Historical Brick' - water content of external 10mm of brick on freezing with different types of internal wall insulation at eight locations.*

Chapter 7

Analysis and Discussion

This Chapter will analyse the WUFI and AWK results, discuss their accuracy and relevance, observe trends and compare the findings to similar research. The significance of these findings for the building industry is also discussed.

7.1 Analysis and Discussion

WUFI pro 4.2 has been used to predict the behaviour of solid masonry walls retrofitted with internal wall insulation. 200 simulations have combined each of the five brick types with four types of insulation and have been run using weather data from eight sites around the UK. The walls have been specifically monitored to establish whether or not frost damage conditions are created in the external 10mm of brickwork as a result of insulating. Frost damage conditions have been defined as moisture levels reaching 75% of free water saturation combined with a zero degree crossing in the brick.

The simulations were conducted in sets for each of the five types of masonry brick. Each set contains a control wall with no internal wall insulation and two locations where the likelihood of frost damage to an uninsulated wall is perceived to be high.

The experiment has been designed to highlight any potential problems with frost damage after renovating our existing housing stock with high levels of internal wall thermal insulation in order to reduce national energy demand and associated GHG emissions.

7.2 Analysis

From the results of all the simulations there are no instances where moisture levels have reached the defined critical level (F_{MAX}) for the brick to suffer frost damage upon freezing. However, in all cases the moisture level on freezing has risen after insulating when compared to the uninsulated control wall, but only up to around 20-30% Wf and not enough to cause frost attack. The exception here is with ‘Solid Brick Masonry’ which rose to just over 50% Wf, with the control wall peaking at around 25% Wf. This is significantly higher than in any other brick type but still not sufficiently high to cause damage.

Results also show the type of insulation to make little difference to the moisture content of the external brick. This result is unexpected, a variety of insulation types were chosen specifically because of the range of, or entire lack of, moisture storage and transport mechanisms. From research presented by Kunzel (1998, p.102) these dissimilarities were expected to produce greater contrast than seen here. Even though the results show all types to be very similar across all experiments some trends can be seen on closer inspection. Wood fibre and mineral wool tend to produce slightly lower results than EPS and PF. This is not hugely significant to this study as the water content only varies by up to around $1kg/m^3$, which equates to a one litre increase of water in a 10mm thick layer of brick measuring 10m x 10m.

This suggests that the outward migration of internally produced water vapour is not relevant to frost attack. Interstitial condensation derived from water vapour that has passed through vapour open insulation has no effect on increasing the MC of the external 10mm of brick. This is also true for the theory that saturation levels past free water saturation are possible from vapour diffusion in a temperature gradient (Kunzel 1995, p.6). Either the vapour flux is not high enough or the temperature gradient is not severe enough. In any case, the use of vapour open materials show that this sort of saturation is not accountable for increasing the water content of the bricks’ surface.

Vapour closed IWI does not limit the drying out of WDR to the inside of the building enough to create critical frost damage levels anywhere in the masonry. Insulations like wood fibreboard that are vapour open with hygroscopic and capillary action, do not affect the amount of moisture drawn from the bricks' surface into the wall after a driving rain or hold any significant amounts of moisture derived from internal sources to affect the MC of the external brick on freezing. When comparing the quantities of moisture derived from driving rain to that from internal moisture sources the latter is insignificant with regards to frost attack.

7.3 Potential Errors

Whilst the results presented here are informative and the methodology used to obtain them is well based, their accuracy should be further questioned for a number of reasons. Errors could be present in the following areas:

- Choice of locations
- Nature of a .TRY file
- The accuracy of the hygrothermal properties of masonry
- The exclusion of mortar in construction

7.3.1 Choice of Locations

In order to validate the experiment, climate files were used from two severe locations, Keswick and Rawtenstall, where Stewartby Flettons are expected to fail even with no insulation. These extreme locations are sited in the BRE's WDR exposure zone 4 and Hanson Brick's 'severe' weather zone where Flettons would not ever be specified and where failures to Flettons have been reported (Sharp 2009c). Results from these locations show moisture levels to peak on freezing at between 3.5% Wf and 10% Wf, nowhere near high enough to cause damage. The highest moisture level recorded on freezing for Stewartby Flettons is 56.75kg/m^3 (20% Wf) at Grendon Underwood, WDR zone 2.

It is possible that the location of Rawtenstall is incorrect as it was chosen by selecting a town in one of the postcode areas provided by Sharp (2009). Keswick may also be unrepresentative of WDR zone 4 and have a particularly sheltered microclimate. In this case the BRE's WDR map may not be detailed enough to show small areas with irregular weather conditions.

Earlier simulations run at only four different locations also returned similar results, the highest again for Flettons was in WDR zone 2. These were initially viewed as incorrect, with possible errors arising when interpolating data from weather stations to create the climate files. Due to these confusing results, eight new climate files were chosen. Two locations were simulated for each WDR zone to see if similarities could be seen within each zone and demonstrate how useful the zones are at indicating the potential for frost damage. The new locations presented in graphs *6.1 to 6.5* (Chapter 6) are the actual sites of the weather stations themselves, thus avoiding any errors from interpolating data. Rawtenstall is the only exception where interpolated data is still used.

As seen in the results graphs *6.1 to 6.5* there is not a strong correlation between high MCs and the severity of the WDR zone. The table below shows some consistency between peak moisture content and location when viewed across all brick types.

	Lowest MC on freezing					highest MC on freezing		
SBM	Lon	Kes	Cam	Glas	Wal	Rawt	Bos	Gren
	Z1	Z4	Z1	Z3	Z2	Z4	Z3	Z2
Fletton	Kes	Wal	Glas	Cam	Lon	Rawt	Bos	Gren
	Z4	Z2	Z3	Z1	Z1	Z4	Z3	Z2
Extruded	Lon	Kes	Wal	Cam	Glas	Rawt	Gren	Bos
	Z1	Z4	Z2	Z1	Z3	Z4	Z2	Z3
Hand-formed	Kes	Lon	Wal	Cam	Glas	Bos	Rawt	Gren
	Z4	Z1	Z2	Z1	Z3	Z3	Z4	Z2
Historical	Kes	Wal	Lon	Cam	Glas	Rawt	Bos	Gren
	Z4	Z2	Z1	Z1	Z3	Z4	Z3	Z2

Table 7.1. *From left to right: the locations of the lowest to highest moisture contents measured for each brick type.*

Table 7.1 reveals patterns to moisture levels measured. Keswick (Z 4) is surprisingly always at the lower end of the table, London, Cambridge and Glasgow group from low to middle (Z 1, Z 1 and Z 2 respectively) and Grendon Underwood, Boscombe Down and Rawtenstall (Z 2, Z 3 and Z 4 respectively) all group towards the top.

Earlier simulations found that ‘Oakley’ near Oxford in WDR zone 2 had the most severe weather conditions for frost damage. When looking at the exact geographical location of Oakley, it can be seen that Grendon Underwood and Wallingford are 15-25km away, *fig. 7.2* Data from the severest location, Grendon Underwood, was most likely interpolated with data from the other local stations to create the climate file for Oakley. This could mean that data from Grendon Underwood is unsound as it is not representative of the climatic conditions associated with WDRZ 2, it is also not in line with results from nearby Wallingford. Nevertheless, it is known for weather conditions to significantly vary within a relatively small geographical area and Beardmore & Ford (1986, p.3) advise the cautious use of data from weather stations to anywhere but the station itself.

Figure 7.2. *Locations of weather stations in WDR zone 2 marked with red and blue dots and Oakley whose climate file was interpolated from the most local stations.*

7.3.2 Nature of a .TRY File

> "In most simulations the aim is to test alternative design possibilities against relatively short period data that characterises typical or extreme weather conditions for the location in question" (Clarke 2001, p.202).

Climate files can be imported into WUFI in a number of different file formats; .WET, .TRY, .WAC and .IWC. From the aforementioned files the .TRY format (Test Reference Year) was chosen for this investigation mainly because it was the only WUFI compatible file type immediately available. The files were created by the Meteonorm programme that has data from a vast number of weather stations across the UK that measure the relevant parameters required by WUFI.

Even though .TRY files have no standard international procedure for creating them, they all tend to contain averaged weather data where extreme events are omitted (Clarke 2001, p.205). It is these extreme events, like the three winters from 1977 to 1980, where frost damage occurs (Stupart 1989, p.42; Beardmore & Ford 1986, p.3), and therefore the use of the .TRY files has not accurately represented real exposure conditions. This may be one explanation as to why no instances of frost damage are seen in the control walls at Rawtenstall or Keswick. Further research into WET, .WAC and .IWC (International Weather for Energy Calculations) files may establish which is more representative of extreme weather events. It would also be possible to continue using the .TRY format but replace the parameter columns for wind direction, wind speed, precipitation and air temperature with measured data from a more severe year like one of the winters from 1977 to 1980.

7.3.3 The Accuracy of the Hygrothermal Properties of Masonry

It is in this area where many errors could be present. Access to the complex hygrothermal properties of materials is often difficult to obtain or has never been actually tested. For this reason most of the brick types used in this study were taken from WUFI's own internal material database. The exact similarity between these bricks and those used in solid walled buildings throughout the UK is unclear, but there is enough range within the selection to highlight any trends. It was for this reason that attempts were made to include a widely used UK brick, the Stewartby Fletton. At the time of research only the basic material properties needed by WUFI to simulate the Fletton were available. As WUFI is capable of generating the complete set of values needed from these basic values no further information was sought. It is possible that these basic values or the extrapolation of them by WUFI is incorrect and has resulted in no frost failures being seen. Full hygrothermal testing of the Fletton or other brick by the Fraunhofer Institute's material testing facilities would be integral to any further studies.

7.3.4 The Exclusion of Mortar in Construction

> "The durability of masonry with regard to frost action and sulfate attack depends on the characteristics of both the masonry units and the mortar in relation to service conditions" (BSI 2005b, p.68).

WUFI PRO 4.2 is a one-dimensional programme and therefore cannot clearly account for different materials occupying the same cross sectional space. Within this experiment this presents a problem when modelling the mortar joints in the brick. Solid Brick Masonry (SBM) is 'brick masonry' in the WUFI material database and it is the only brick that has had its values adjusted to account for mortar joints (WUFI 2009b). Although mortar is not the only factor that has an effect on the hygric behaviour of masonry it has been shown in laboratory testing for frost attack that the type of mortar can affect the results (Edgell 2005, p.39) and therefore its influence should not be ignored.

7.4 Relationship of Masonry Facade to the External Climate

With insulation to such high levels the external 10mm of brick follows the external temperature more closely than before. The insulated wall is losing 12 times less heat than the uninsulated wall yet the difference this makes to the external 10mm is minimal, less than two degrees difference near freezing. In a climate such as the UK's that can fluctuate around zero degrees over winter this finding is significant. If any building defects have caused there to be saturated bricks then frost damage is now a real possibility. This is most relevant to geographical areas where historically frost damage has not been a concern and therefore the built environment is more likely to be built from bricks with low frost resistance. Appendix D contains graphs comparing external air temperature and external brick temp for the insulated and uninsulated walls over 14 days in the middle of February. Over this same period *table 7.3* shows how the act of insulating the wall causes the number of zero degree crossings to roughly double.

	London	Grendon Underwood
Uninsulated zero crossings	0	2
Insulated zero crossings	2	5
Air temp zero crossings	2	7

Table 7.3. *Covers a two weeks period in February and shows an increase in zero degree crossings in the external brick after insulating.*

Bricks in the south-west facing wall are now experiencing conditions that they were not specified for. These conditions are becoming more similar to areas where F2 bricks would be specified such as freestanding and parapet walls (BSI 2005b, p.68) The amount of rain water hitting the brick has not increased but its ability to resist freezing is diminished.

Across all of the locations and brick types that have been simulated, freeze thaw cycles of the external 10mm of masonry increase significantly. *Table 7.4* shows the increased incidence of zero degree crossings after additional IWI for SBM and Stewartby Flettons.

Brick type	Zero degree crossings at each location							
	Cam	Lon	Gren	Wal	Bos	Glas	Kes	Rawt
Uninsulated SBM	2	1	15	13	6	13	7	10
Insulated SBM	10	6	21	28	20	21	20	20
Uninsulated Fletton	6	1	16	16	11	13	14	12
Insulated Fletton	11	6	26	29	26	24	19	22

Table 7.4. *Annual zero degree crossings before and after IWI.*

7.5 Pushing WUFI to Create Frost Damage Conditions

Further simulations have been run in an attempt to create frost damage conditions. A moisture source was placed 5mm in from the external brick surface and produces 1% of the wind driven rain incident on the wall's surface. This was later pushed to 2% and then 10% of wind driven rain. This could represent moisture ingress from defects in construction, mortar pointing, cracks in bricks or gaps around service pipes, windows, doors or other openings (Fraunhofer Institute for Building Physics and British Board of Agrément cited by (May 2009b, p.40).

Table 7.5 shows the increase in moisture content for SBM when simulated at Grendon Underwood with 1%, 2% and 10% driving rain penetration.

Rainwater penetration	% Wf
None	57.6
1% of WDR	58.0
2% of WDR	58.4
10% of WDR	61.6

Table 7.5. *Increase in % of free water saturation with different quantities of moisture ingress.*

With 10% WDR penetration the moisture content on freezing only rose by 7.6 kg/m^3 to 61.6% Wf. This is still not sufficiently high enough for the brick to suffer damage. 25 litres more rainwater is needed per m^3 to reach F_{MAX}.

7.6 Comparison of Results to Topical Research

Despite not detecting actual frost failures this experiment has achieved in producing similar results to other studies, confirming that the general methodology and findings are sound. The most notable ones are that the moisture content of the wall significantly rises and that the temperature of the wall decreases, often to increase the number of zero degree crossings in the external brick (Andersson 1979, p.9; Hendry 2001a, p.328; Kunzel 1998, p.103; Laycock 2002, p.199; Saïd et al. 2003, p.446; Straube & Schumacher 2006).

One of the most in-depth studies using WUFI to assess the hygrothermal changes within a solid masonry wall after IWI is by Hartwig M. Kunzel (1998). Kunzel, the developer of WUFI (Straube & Burnett 1998, p.88) believes that the moisture content of the internally insulated wall rises due to its new lower temperature, which has the effect of reducing its drying out potential. Kunzel (1998, p.5) concludes that when using IWI, vapour open surface treatments should be used to reduce the risk of frost damage and greater protection from wind driven rain should also be sought. The vapour resistance of the insulation used does not affect the drying out ability of the masonry as the main moisture flux is still to the outside. Importantly he states that a vapour barrier is not needed, but that there is a need to stop the warm internal air penetrating the space behind the insulation, risking a build up of interstitial condensation (Kunzel 1998, p.103). As WUFI cannot take into consideration moisture carried by the convection of air this was not calculated and an air gap between the masonry and insulation was not included. This goes against the building regulations where according to Approved Document C, an air cavity should exist to break the passage of moisture (ODPM 2004, p.31).

7.7 Overcoming Simulation Errors

It is clear that the data needed for realistic hygrothermal modelling needs to be highly accurate and that there is a need for the development of two-dimensional models that can include the mortar joint. Most essentially there is a need for a climate file format for extreme events. The definition and time frame of these events would have to be established, maybe a range of files that represent the sort of events likely every year, every five years, 10 years and so on. The need to run the experiment for 5 plus years to establish new equilibrium water contents is not unique to this study so the creation of a five-year climate file including extreme events would be sensible. The Energy Conservation in Buildings and Community Systems (ECBCS) project established by the International Energy Agency has highlighted the lack of appropriate climate files for hygrothermal modelling software. The programme has been set up to provide research and development and to support activities relating to energy efficiency of the built environment (ECBCS 2010). Annex 24 of the ECBCS also recognises that there is a need for developing new climate data and has produced a methodology for a Moisture Durability Reference Year (.MDRY) (Hens 2002, p.15). In this case the

.MDRY would not be appropriate as it is specific to moisture not impacted by driving rain. The need for new files has been recognised and the Test Meterological Year (.TMY) and Weather Years For Energy Calculations (.WYEC) have been created to overcome some of the failings of a .TRY file (Clarke 2001, p.205).

As just using one method of determining a buildings behaviour is not recommended, future studies with numerical simulations should also contain observations made in real buildings. This study has highlighted the need for a UK map showing where masonry in solid walled vernacular architecture is of low frost resistance. This task would be vast and undertaken by organisations such as the Brick Development Association or the Building Research Establishment.

The current map of wind driven rain exposure zones is not particularly useful in determining resistance when compared to the .TRY files as few trends can be observed between rainfall patterns and the severity of the zone. As established earlier this may be due to the exclusion of extreme event by the .TRY files. Nonetheless, one would expect annual rainfall figures to be reasonably well represented in a .TRY file.

7.8 A Globally Changing Climate

Given the desired lifespan of a building even an annual event that degrades its structure is unacceptable. Brimblecombe & Grossi (2007, p.17) show the frequency of freeze-thaw events have been declining in England since 1750, *fig. 7.6* and suggest that these events will become fewer in years to come.

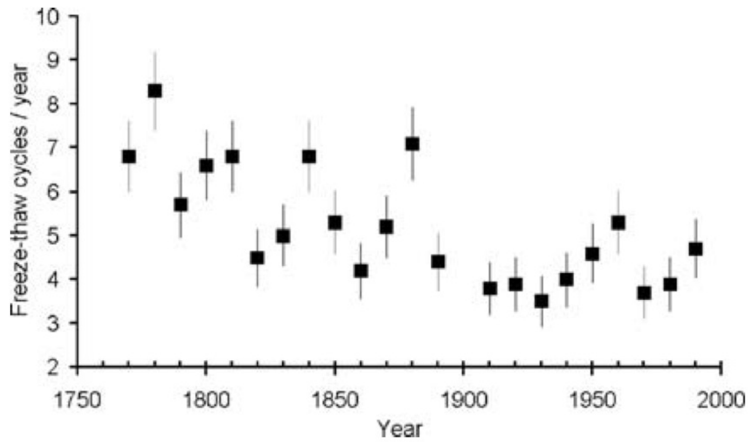


Figure 7.6. *Frequency of freeze-thaw cycles/year from 1750 to 2000 in central England (Brimblecombe & Grossi 2007, p.17).*

This is echoed in further work by Grossi et al. (2007, p.273) using climate data from the Hadley HadCM3 Model (A2 scenario, 1961 to 2099). As Europe warms, Grossi et al. forecast a continued reduction in these events and therefore a reduced risk of frost damage to our built heritage, *fig. 7.7.*

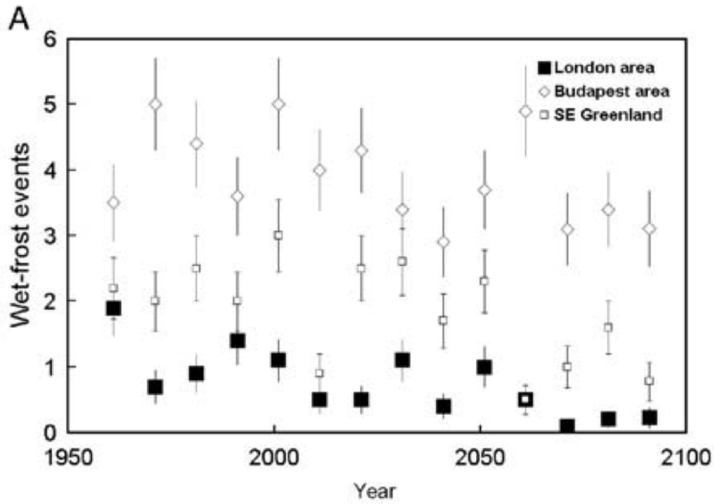


Figure 7.7. Declining wet-frost events over London, Budapest and SE Greenland using the Hadley HadCM3 Model (A2 scenario, 1961 to 2099) (Grossi et al. 2007, p.278).

7.9 Further Issues

Is only within the constraints of this experiment that the type of insulation specified is unimportant. The general approach taken when refurbishing buildings should still be holistic and consider the robustness and thermal performance of the insulation along with the effect it has on the rest of the building and the quality of the environment in it. The embodied energy of the materials and the environmental impacts of its manufacture and disposal should also be considered. This complicated decision making process can be helped by studies such as the BRE's Green Guide to Specification (Anderson et al. 2009) and the Ecology of Building Materials (Berge et al. 2001). These guides help to point the industry in the right direction but have received some criticism especially the BRE's guide by the Good Homes Alliance. May (2009a, p.3) from the Good Homes Alliance points out that giving all cement and brick masonry wall constructions an A+ rating (the highest) gives the industry no incentive to improve their environmental rating. Additionally, all the brick and cement masonry walls get the highest rating regardless of the environmental impact of insulation type used (Anderson et al. 2009, p.131).

Unfortunately it is a real concern that all these wider environmental issues will rarely be taken into account as cost, ease of application, energy performance (lambda value) and resulting U-value per loss of floor space will dominate.

7.10 The Future of Green Refurbishments

From the results presented it is clear that adding IWI has the potential to increase the chances of frost damage, if only from reducing the temperature of the external wall. Due to the use of averaged weather data this study can only claim to have highlighted the there is an increased chance of frost damage after adding IWI only where building faults and poor detailing allow bricks to become saturated on freezing.

The implications of this for energy efficient refurbishments are not insignificant. When planning IWI retrofits, to the estimated 6.6 million, solid wall, Hard to Treat Homes (BRE 2008, p.6) a great deal of caution should generally be applied and not only where frost damage is concerned. The inability of this experiment to create frost damage conditions does not suggest that this type of weathering is rare. All around us there are examples of frost-damaged masonry; architects, builders and homeowners should be aware of the effects IWI could potentially have.

The use of WUFI for simulating this process brings with it complications - namely correct material properties and representative climate files. This procedure may also be inaccessible to most builders, architect or homeowners as using WUFI requires a good understanding of building physics and currently costs €1950 for the one-dimensional programme and €3000 for the two-dimensional version (IBP 2010). With specific regard to frost damage, simple calculations such as the Glaser method may enable an estimation of the new external temperature of brickwork.

Thorough building surveys prior to refurbishment should be a matter of course to prevent bad details and any potential damage from unwanted moisture in the structure. Vulnerable brickwork should be picked up by a good survey that inspects brickwork in exposed positions such as below damp proof courses, in cappings and in chimneys. One possible way of assessing the frost resistance of a brick would be to inspect areas of the wall with hard cement based pointing. As hard cement pointing traps water from driven rain it can cause increased saturation on the edges of brick and lead to localised frost attack (Robson 2005, pp.135-136). This approach is widely applicable as many traditional solid wall buildings have been re-pointed with hard cement mortars. Surveyors should be careful not to confuse this damage with other types of weathering such as salt damage (Holmes & Wingate 2002, p.62).

If due to high levels of IWI an increased incidence of zero crossings is likely and brickwork is perceived to be of low frost resistance then there are still insulation options available. The first is in the form of external insulation, which may not be possible for a variety of reasons often surrounding aesthetics and planning permission. Other practical issues exist such as manholes and drains that are situated very near the external surface. If IWI is the only option then additional surface treatments could be researched combined with re-detailing to avoid saturated bricks or just installing lower levels of insulation to keep the external walls surface generally above zero °C.

The suggestion of including surface treatments in an overall IWI strategy seems a sensible and easily solution, however both the Brick Development Association (Hammett 1998, p.30) and Maurenbrecher & Suter (1993) suggest that it is not a satisfactory means of preventing damage to vulnerable bricks and should be applied with caution. This highlights the need for more research into the development of permanent and suitable surface treatments.

It is highly likely that technology will find solutions to reduce heat loss like Vacuum Insulated Panels (VIP) twinned with Mechanical Ventilation with Heat Recovery (MVHR) to regulate internal air quality. The use of products like VIP on internal walls can result in extremely high levels of insulation with minimal disruption to internal space (Simmler & Brunner 2005, p.1). In this situation it is inevitable that frost damage will be seen as a related problem in areas of poor detailing where bricks remain saturated after rainfall.

It is clear that we need to aim high in order to dramatically reduce heat loss and we should learn from schemes like those funded by the Kreditanstalt fur Wiederaufbau institution in Germany. The German scheme focuses on external insulation and has presumably had to make complicated decisions about changing the aesthetics of buildings. However, their process poses some difficulties, namely that there is a defined financial budget for thermal refurbishments In energy terms the money is better spent on insulating more buildings to a lower standard than far fewer to the highest standard (Galvin n.d., p.7). This is to do with the law of diminishing returns that applies to insulation (Nicholls 2006, p.113) but unfortunately may mean that buildings will have to be renovated again before the 2050 deadline. Galvin (n.d., p.9) argues that requiring everyone to renovate to such high standards will result in a smaller national energy reduction as the energy demand from those buildings that haven't yet been renovated is still very large. This further complicates an already very complicated problem. The Germans are raising the minimum refurbishment standards, which will potentially avoid them having to improve the energy performance of homes again in the near future. However, if upgrading the thermal upgrade can be designed so that it is not about starting afresh with new materials and requires only adding to those already there then maybe a two-phase approach is most sensible.

Many of the real effects of high levels of internal wall insulation are not apparent from this study and are clearly very complicated to accurately model. Even though relatively few renovations with IWI have been conducted, those over 10 years old should be observed intrusively to highlight any real issues before the mistakes are replicated, only to become general knowledge in another 10 years. This may be the only way of predicting widespread problems. It would also be naive to think that a task so complicated as a nationwide energy efficiency retrofit would not harbour any long-term problems. However with well-directed research into more accurate computer simulations and the pathology of already retrofitted buildings some of the larger more damaging mistakes could be avoided.

Chapter 7 has explored the meanings of the results and shown how the building industry can potentially move forward to reduce the energy demand of solid walled homes. The need for a significant amount of further research has been highlighted.

Chapter 8

Conclusion

The United Kingdom has committed to reduce CO_2 emissions by 80% from 1990 levels. Due to the large proportion of energy used in the domestic sector for space heating, internally insulating our solid walled housing stock to high levels is becoming necessary. The pressure to deliver energy reducing solutions is great, however, poorly thought through schemes may actually damage our homes and require a further use of energy and resources to repair them.

This thesis has tried to establish to what extent insulating the UK's 6.6 million solid walled homes with internal wall insulation will increase the potential of frost damage to the external bricks. Damaging the appearance and possibly the structure of pre 1930s solid wall buildings could be seen as unacceptable as they often have strong cultural associations.

The problem of frost damage has been investigated here using the hygrothermal simulation programme WUFI Pro 4.2. This software is a well-established one-dimensional simulation tool used for studying building envelopes. The programme has been developed alongside real building testing and has been used by its developers to study frost action after internally insulating.

South-west facing walls made from five different types of brick have been simulated at eight locations all around the UK in different wind driven rain exposure zones. These zones are defined by the Building Research Establishment. Four types of insulation were used to determine if any are better suited to internal application. Additionally an uninsulated control wall was included at each location. Walls are highly insulated to a new U-value of $0.15W/m^2K$ in line with level 5&6 of the Code for Sustainable Homes.

The experiment compared the moisture content of the external 10mm of brick of insulated walls to uninsulated walls. In every case adding internal wall insulation increased the water content of the wall on freezing when compared to the uninsulated wall and no significant difference was seen between the different types of insulation used. In over 50% of the walls the water content roughly doubled on freezing but was never high enough to cause damage. The critical limit set for frost damage conditions was 75% of free water saturation (Wf) and the highest water content recorded on freezing was just over 50% Wf. Even though the water content on freezing was never high enough to cause damage, the bricks' external surface was exposed to more annual zero degree crossings than before insulating. In London zero degree crossings rose from 1 per year to 6, Cambridge 2 to 10 and in Glasgow from 13 to 21. Where poor detailing or building faults leave bricks exposed to higher levels of saturation there will be an increased risk of damage to low frost resistant bricks. In many cases this could be a problem as bricks of low frost resistance have established their appropriate use in relation to their specific climatic conditions. Reducing the heat loss through the wall and therefore lowering its temperature will cause it to freeze more often than it ever has done.

The methodology used in this experiment is well based but has failed to return any specific incidences of frost damage even in locations where frost damage is expected to an uninsulated wall. This is most likely due to the type of weather file used. The Test Reference Year (.TRY) files used here exclude extreme weather events like those that can cause frost damage, heavy driving rain followed immediately by below zero degree conditions.

This research set out to additionally establish if the BRE's wind driven rain exposure zone map is appropriate for quick assessment of risk to frost damage from internal wall insulation. The guide map is not specifically designed for this purpose and when compared to results from the insufficient weather files, showed little correlation between the severity of the zone and the increase in water content on freezing.

Certain recommendations arise from this research namely the need for climate files that accurately represent extreme conditions. The .TRY files produced by Meteonorm draw on data from dozens of weather stations in the UK and can presumably be produced to include extreme events. For this to be consistent across the building industry clear methodology for creating these files needs to be internationally established. The files should be used with newly developed two-dimensional hygrothermal software.

This thesis has also shown a requirement for thorough building surveys to pick up vulnerable brickwork prior to insulating. This is not only for issues relating to frost damage and should include all of the complications associated with thermal renovations. This cautious approach would ideally follow a nationwide survey of buildings that have been internally insulated or thermally upgraded to highlight any resulting building faults before they are widely replicated. Further research would also include the development of reliable surface treatments to reduce rainwater absorbed into masonry.

Having a long term view of the energy saving changes we make to buildings is essential, however slowly renovating buildings to U-values like 0.15W/m^{2}K will save less energy than using the same available funds to insulate many more homes to a lesser extent. This further complicates an already very complicated problem. If bettering the thermal upgrade is not about starting again with new materials and requires only topping up the insulation already there then maybe a two-phase approach is most sensible.

If nationally we decide that we value our solid wall stock then a well-planned thermal renovation strategy with government grants needs to be implemented soon. As heating fuel becomes more expensive, living in solid walled buildings will become less desirable and the buildings will inevitably fall into a state of disrepair. Here-in lies the complication, obviously the perfect scenario is that we can quickly and cheaply reduce the energy demand of buildings with long lasting methods that don't degrade our stock. If this is not possible something suffers; either our environment from associated emissions to heat our inefficient homes, our environment from the general pollution and emissions involved in re-deploying and assimilating the waste from a failed retro fit, or our built heritage from uninhabitable homes or severe moisture related issues. These issues rather favour a two-phase approach; giving us more time to understand the issues surrounding moisture and to ensure that by 2050 we all have healthy low-energy homes to live in.

Appendix A

A.1 Input Values for WUFI

Standard calculation values	
Brick total thickness	215mm
Insulation thickness	Variable
Int. lime plaster thickness	15mm
Monitor layer for moisture	0-10mm from external surface
Monitor position for temp	5mm from external surface
Wall orientation	South west
Wall inclination	90°
Wall height	≤ 10m
Ext. surface heat resistance	0.0588 m^2K/W
Short-wave radiation absorptivity	0.68
Long-wave radiation emissivity	0.9
Rainwater absorption factor	0.7
Int. surface heat resistance	0.125 m^2K/W
Internal Climate	BS EN ISO 13788:2002
Humidity Class	2
Initial relative humidity	60%
Initial temperature	20°C
Internal temp	17°C
Calculation period	1.OCT.2005 - 31.MAR.2010
Time steps	Hourly

Table A.1. *Standard values for the WUFI calculations.*

Material	Density. [kg/m^3]	Free water sat. (kg/m3)	Porosity [m^3/m^3]	75% of free water sat.	Heat. Cap. [J/kgK]	Ther. Cond. [W/mK]	Diff. Res. Fac [-]
Stewartby Fletton	1740	278	0.33	208	1000	0.47	16
Solid Brick Masonry	1900	190	0.24	143	850	0.6	10
Solid Brick, extruded	1650	370	0.41	278	850	0.6	9.5
Solid Brick, hand-formed	1725	200	0.38	150	850	0.6	17
Solid Brick, historical	1800	230	0.31	173	850	0.6	15
Lime plaster	1600	-	0.3	-	850	0.7	7

Table A.2. *Basic values for bricks and lime plaster.*

Material	Density. [kg/m^3]	Porosity [m^3/m^3]	Heat. Cap. [J/kgK]	Ther. Cond. [W/mK]	Diff. Res. Fac [-]
Wood-fibre (Pavadentro)	180	0.883	2100	0.045	3.3
Pavadentro functional Layer	1500	0.400	850	0.930	450
Mineral wool	60	0.950	850	0.040	1.3
EPS	15	0.950	1500	0.040	30
PF Kingspan K18	43	0.950	1500	0.021	30
Kingspan foil face	130	0.001	2300	2.300	20000

Table A.3. *Basic values for the four insulation types simulated.*

Insulation type	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Wood-fibre (Pavadentro)	Brick	Pavadentro (20mm)	Mineral layer	Pavadentro	Lime plaster
Mineral wool	Brick	Mineral wool	-	-	Lime plaster
EPS	Brick	EPS	-	-	Lime plaster
PF (Kingspan K18)	Brick	Foil face	PF	Foil face	Lime plaster

Table A.4. *Layers of insulation included in the simulation.*

Appendix B

B.1 Additional Climate Information

Format	Header lines	Parameters	Units
.TRY	24	Nr, dm, m, h, DD, FF, FFv, Wc, RR, p, Ta, RH, Bh, Dh, L_G, G_{Lin}, G_{Lup}	[°], [m/s], [mm], [hPa] [°C], [%], [W/m^2], [lux]

Table B.1. *Definition of TRY file hourly output columns: number and sequence of parameters. Symbols: dm: day in month, m: month, h: hour, DD: Wind direction, FF: Wind speed (10 m above ground), RR: Precipitation, p: Atmospheric pressure, Ta: Air temperature (ambient temperature), RH: Relative humidity, Bh: Direct radiation on horizontal surface, Dh: Diffuse radiation (horizontal),* L_G*: Global illuminance ,* G_{LIN}*: Average hourly longwave horizontal radiation impinging (longwave incoming),* G_{Lup}*: Average hourly, longwave horizontal radiation emitted (longwave outgoing).*

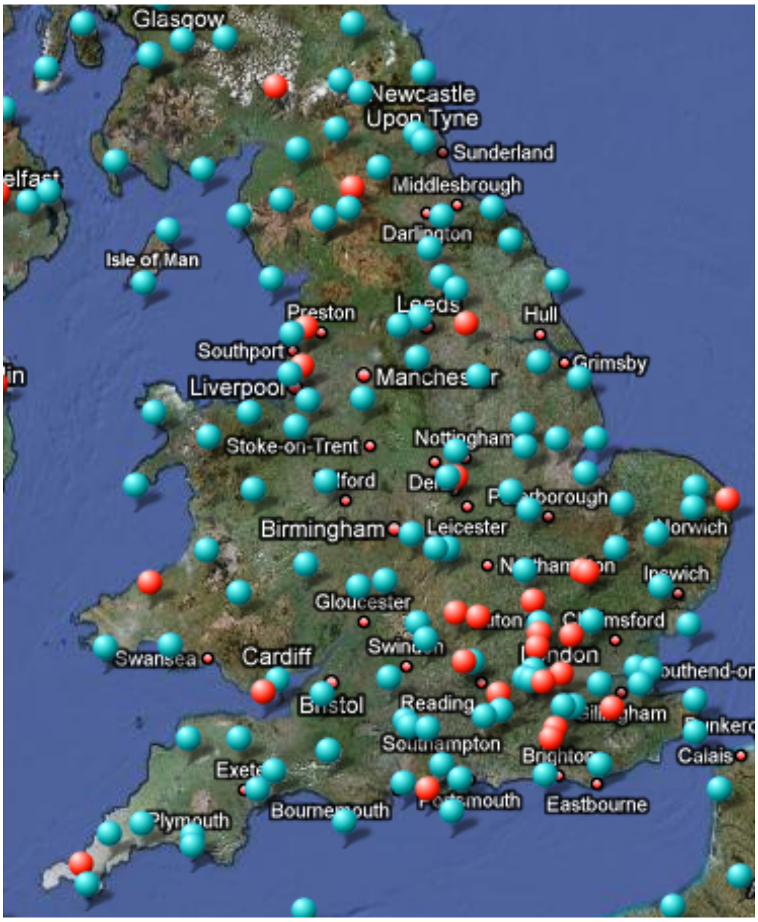


Figure B.2. *Distribution of weather stations used by Meteonorm (TerraMetrics 2009).*

Appendix C

C.1 ASCII

Below in *fig. C.1* is a sample of an ASCII output from WUFI. The first column is a hourly time reference, the second, is external air temperature, the third is temperature at the monitor position 5mm in from the bricks external surface and the fourth is the water content of the external 10mm layer of brick.

```
1.000000E+0000    1.090000E+0001    1.516722E+0001    3.921155E+0000
2.000000E+0000    1.020000E+0001    1.352723E+0001    3.826545E+0000
3.000000E+0000    9.400000E+0000    1.240507E+0001    3.785946E+0000
4.000000E+0000    9.000000E+0000    1.165897E+0001    3.775750E+0000
5.000000E+0000    8.600000E+0000    1.103028E+0001    3.772996E+0000
6.000000E+0000    8.300000E+0000    1.047058E+0001    3.710426E+0000
7.000000E+0000    8.600000E+0000    1.091427E+0001    3.697382E+0000
8.000000E+0000    9.300000E+0000    1.176023E+0001    3.586078E+0000
9.000000E+0000    1.010000E+0001    1.289006E+0001    3.456682E+0000
1.000000E+0001    1.090000E+0001    1.398622E+0001    3.303000E+0000
1.100000E+0001    1.150000E+0001    1.494989E+0001    3.201042E+0000
1.200000E+0001    1.190000E+0001    1.567089E+0001    3.148240E+0000
1.300000E+0001    1.210000E+0001    1.595307E+0001    3.102468E+0000
1.400000E+0001    1.220000E+0001    1.580967E+0001    3.096912E+0000
1.500000E+0001    1.200000E+0001    1.528482E+0001    3.106675E+0000
1.600000E+0001    1.170000E+0001    1.461370E+0001    3.108155E+0000
1.700000E+0001    1.100000E+0001    1.361169E+0001    3.306198E+0000
1.800000E+0001    1.060000E+0001    1.271530E+0001    3.531868E+0000
1.900000E+0001    1.020000E+0001    1.178520E+0001    3.681611E+0000
2.000000E+0001    9.800000E+0000    1.126612E+0001    3.858343E+0000
2.100000E+0001    9.400000E+0000    1.078571E+0001    3.956559E+0000
```

Figure C.1. *Sample of the 39,409 in an ASCII output file from WUFI.*

C.2 AWK

Below in *fig. C.2* is one of the AWK programmes used for analysis of the WUFI results. The four columns in the ASCII files are scanned by the AWK, when the AWK detects column 3 drop below 0°C it prints the reference column 1, the temp column 3 and the water content column 4 into a new output file.

```
{
gsub(/E\+000/,"e"); gsub(/E\-000/,"e-")            # gets rid of excess
zeros, note \ is to define "+" as a charcater not an action

#print $0

if (TOld>=0 && $3<0 && $4>100) print int($1/24),$3/1,$4/1       # checks
if temperature drops below zero and prints ref, temp and water

TOld=$3                                                           #
resets temperature

}
```

Figure C.2. *AWK programme used in the analysis of ASCII files.*

C.3 Terminal Commands

Fig. C.3 shows the command lines that instruct the computer to use the AWK programme to scan a specific ASCII file and then output the results to a new location. This is done through the Apple Macintosh 'Terminal' application. A line had to be individually input for each of the 200 walls simulated.

```
Last login: Mon Sep  7 11:10:31 on ttyp1
Welcome to Darwin!
dan-brownes-computer:~ danbrowne$  tr -d '\r' < /exp/wufi_results/1.2.4.asc |   awk -f /exp/awks/frost28.awk > /exp/
awk_results28/1.2.4.out
dan-brownes-computer:~ danbrowne$  tr -d '\r' < /exp/wufi_results/1.3.4.asc |   awk -f /exp/awks/frost28.awk > /exp/
awk_results28/1.3.4.out
dan-brownes-computer:~ danbrowne$  tr -d '\r' < /exp/wufi_results/1.4.4.asc |   awk -f /exp/awks/frost28.awk > /exp/
awk_results28/1.4.4.out
dan-brownes-computer:~ danbrowne$  tr -d '\r' < /exp/wufi_results/2.1.4.asc |   awk -f /exp/awks/frost28.awk > /exp/
awk_results28/2.1.4.out
dan-brownes-computer:~ danbrowne$  tr -d '\r' < /exp/wufi_results/2.2.4.asc |   awk -f /exp/awks/frost28.awk > /exp/
awk_results28/2.2.4.out
dan-brownes-computer:~ danbrowne$  tr -d '\r' < /exp/wufi_results/2.3.4.asc |   awk -f /exp/awks/frost28.awk > /exp/
awk_results28/2.3.4.out
dan-brownes-computer:~ danbrowne$  tr -d '\r' < /exp/wufi_results/2.4.4.asc |   awk -f /exp/awks/frost28.awk > /exp/
awk_results28/2.4.4.out
dan-brownes-computer:~ danbrowne$  tr -d '\r' < /exp/wufi_results/3.1.4.asc |   awk -f /exp/awks/frost28.awk > /exp/
awk_results28/3.1.4.out
dan-brownes-computer:~ danbrowne$  tr -d '\r' < /exp/wufi_results/3.2.4.asc |   awk -f /exp/awks/frost28.awk > /exp/
awk_results28/3.2.4.out
dan-brownes-computer:~ danbrowne$  tr -d '\r' < /exp/wufi_results/3.3.4.asc |   awk -f /exp/awks/frost28.awk > /exp/
awk_results28/3.3.4.out
dan-brownes-computer:~ danbrowne$  tr -d '\r' < /exp/wufi_results/3.4.4.asc |   awk -f /exp/awks/frost28.awk > /exp/
awk_results28/3.4.4.out
dan-brownes-computer:~ danbrowne$  tr -d '\r' < /exp/wufi_results/4.1.4.asc |   awk -f /exp/awks/frost28.awk > /exp/
awk_results28/4.1.4.out
dan-brownes-computer:~ danbrowne$  tr -d '\r' < /exp/wufi_results/4.2.4.asc |   awk -f /exp/awks/frost28.awk > /exp/
awk_results28/4.2.4.out
```

Figure C.3. *Command lines for instructing the computer to use the AWK programme to scan the ASCII outputs.*

Appendix D

D.1 External Air to External Brick Temperatures

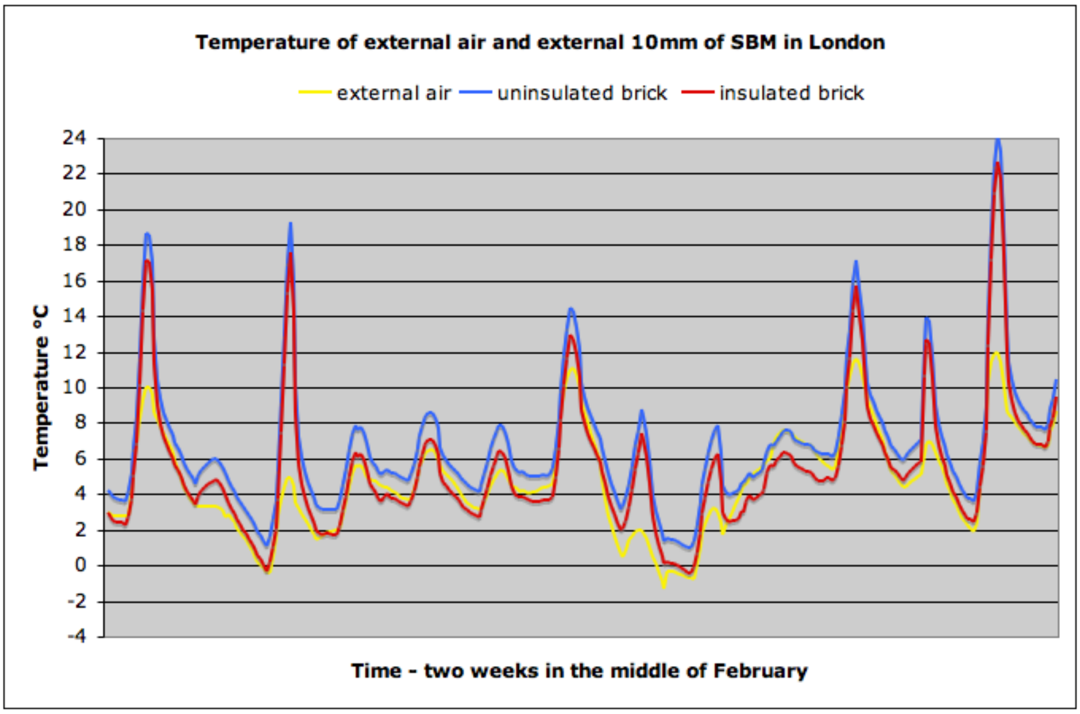


Figure D.1. *Graph showing the temperature of external air and the external 10mm of insulated and uninsulated SBM in London*

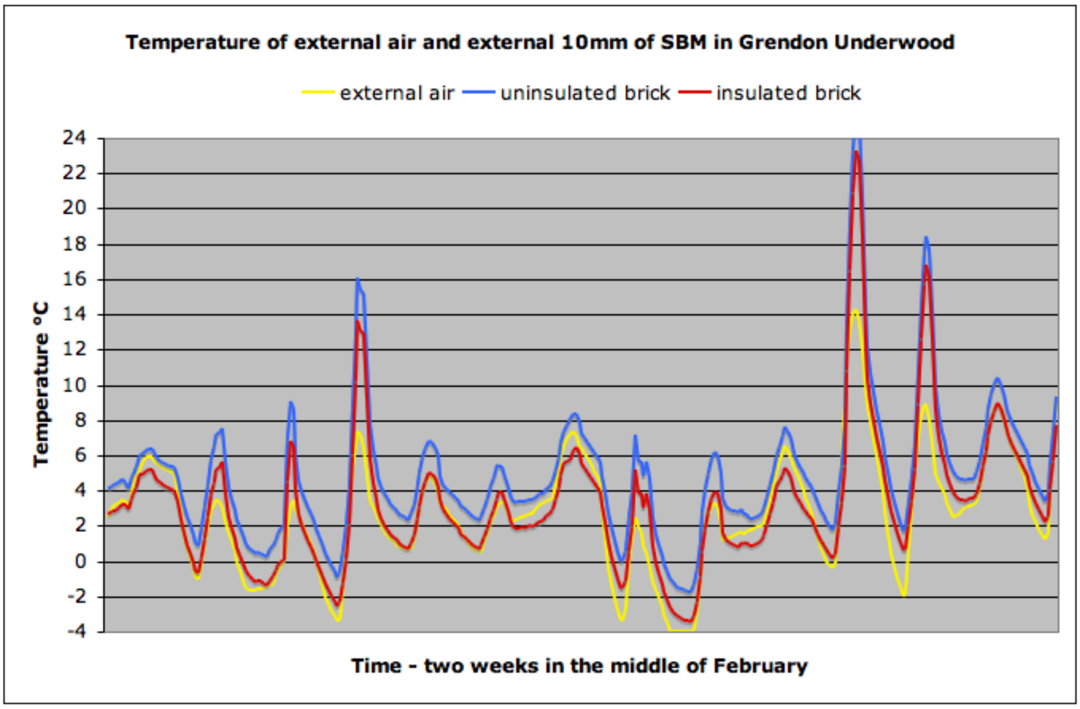


Figure D.2. *Graph showing the temperature of external air and the external 10mm of insulated and uninsulated SBM in Grendon Underwood.*

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