2012

Hemp Lime Bio-composite as a Building Material in Irish Construction

Patrick Daly
Technological University Dublin, patrick.daly@tudublin.ie

Paolo Ronchetti

Tom Woolley Dr

Recommended Citation

Patrick Daly, Paolo Ronchetti, Tom Woolley. (2012) Hemp Lime Bio-composite as a Building Material in Irish Construction, Environmental Protection Agency STRIVE Report 2012 Ireland.

Funder: Irish Government

EPA STRIVE Programme 2007-2013

Hemp Lime Bio-composite as a Building Material in Irish Construction

2009-ET-DS-2-S2

STRIVE Report

Prepared for the Environmental Protection Agency

By

BESRaC
(Built Environment Sustainable Research and Consultancy)

Authors:

Patrick Daly (BESRaC)
Paolo Ronchetti (BESRaC)
Tom Woolley (Consultant)

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland
Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

ACKNOWLEDGEMENTS

This report is published as part of the Science, Technology, Research and Innovation for the Environment (STRIVE) Programme 2007-2013. The programme is financed by the Irish Government. It is administered on behalf of the Department of the Environment, Community and Local Government by the Environmental Protection Agency which has the statutory function of co-ordinating and promoting environmental research.

Special thanks to the steering committee for their advice and direction, notably John Finnan Teagasc, Sean Armstrong DECLG and Lisa Sheils EPA. Thanks also to all those who participated in the consultation process and workshops for their feedback and input.

DISCLAIMER

Although every effort has been made to ensure the accuracy of the material contained in this publication, complete accuracy cannot be guaranteed. Neither the Environmental Protection Agency nor the author(s) accept any responsibility whatsoever for loss or damage occasioned or claimed to have been occasioned, in part or in full, as a consequence of any person acting, or refraining from acting, as a result of a matter contained in this publication. All or part of this publication may be reproduced without further permission, provided the source is acknowledged.

The EPA STRIVE Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

The research in this report is a desktop study of existing research from various sources for the purpose of examining the performance of hemp lime as building material. The information in this report should not be interpreted as an assessment of the material in relation to Building Regulation Compliance or Certification of hemp lime as a building material.

EPA STRIVE PROGRAMME 2007-2013

Published by the Environmental Protection Agency, Ireland

PRINTED ON RECYCLED PAPER

Details of Project Partners

Patrick Daly	**Director / Lead Researcher**	**BESRaC**
Paolo Ronchetti	**Research Assistant**	**BESRaC**

BESRaC
Address: iLEEiD House, Clonkill, Mullingar, Co Westmeath, Ireland
Tel.: 00353(0)449372008 E-mail: info@besrac.net

Tom Woolley **Consultant**
Rachel Bevan Architects
Rachel Bevan Architects & Consultants
80 Church Road
Crossgar
Downpatrick
County Down
BT30 9HR
Northern Ireland
UK

Table of Contents

Executive Summary

Hemp lime is a bio-composite material formed by the mixture of the woody core of the hemp plant, also known as 'hurd', or 'shiv' and a lime based binder. After setting, the composite forms a rigid lightweight material and has applications to a range of construction solutions with claimed benefits of good thermal properties, vapour permeability, low environmental impact and carbon sequestration.

This report presents the finding of a scoping study carried out under the EPA 'STRIVE' research funding programme during 2010 to examine the potential application of hemp lime as a building material in Ireland. The study collated a growing body of international research on hemp lime and reviewed its increasing application in construction, including some significant demonstration projects, (mainly in the UK and France), and also involved industry consultation, a questionnaire, workshops and site visits to production facilities and construction / demonstration projects.

The study identified the principal use of hemp lime as an insulating non load bearing infill cast or sprayed into walls of timber frame construction and some application in roofs and floors. Hemp lime masonry infill blocks have also been used for non load-bearing situations. Hemp fibre itself is used for insulation in batt form and may have the potential to be used in cladding and board applications such as strand board, chip board, fibre board etc.

The study includes a review of hemp growing in Ireland, with various small scale trials and cultivation taking place, though this has been limited to some degree by complex licence procedures and more acutely by the absence of processing facilities, and also examined the production and supply of lime with most hydraulic limes used in the material being imported. An overview of the material application and demonstration in Ireland, identified the use of hemp lime mainly in small scale domestic projects with a significant increase in application of the material as a render / plaster. However a number of demonstration projects were identified including new build houses. Of particular note is a ten unit social housing development in Northern Ireland at Carnlough, Co. Antrim.

Environmental properties of the source materials and the composite are reviewed, including industry claims for 'carbon sequestration' properties of bio-composite material and a French LCA study which identifies an overall positive impact on the atmosphere in terms of Greenhouse Effect due to a negative CO_2 emission over a 100 year life span study.

A significant body of data was collated in the study to create the first significant collation of currently available literature and data on hemp lime bio-composite, with a number of summary and comparison tables, which should aid further investigation and research.

The core of the study involved a detailed review of publicly known available research / technical papers on hemp lime, including performance and testing data, which were compared to relevant standards and requirements to consider its performance as a building material in the Irish context. Knowledge or data gaps in the assessment of performance in structure, fire, moisture, acoustic, energy and material / workmanship were identified and examined.

While the study identified growing volume of research and data, it highlighted some limitations in application of data in terms of;

i) cross comparison of data due to differences in binders, mixes, application and testing,
ii) comparison of this data to known standards and requirements in particular in terms of comparable testing methods and quality
iii) challenges and limitations in comparing hemp lime performance to current construction standards are apparent as many of these standards were developed to assess the behaviour of materials that behave in very different ways to hemp lime. Thus some current testing methods may be considered inappropriate or limited in relation to testing hemp lime and its applications.

The use of Hemp Lime was considered under the following headings:

Structure: The available data gives some indication of hemp lime performances, with potential for structural application in masonry and other load bearing elements, with higher compressive strengths requiring higher cement additive. The literature study and industry consultation found that compressive tests / standards for concrete do not fully reflect the gradual deformation and 'failure' rate of more flexural materials such as hemp lime.

Fire: The availability of fire performance test data for comparison to standards is limited. There was no known independent test data available for hemp lime masonry blocks. Testing carried out by the BRE on an un-rendered load bearing stud test wall panel with hemp lime mix achieved a 73 minutes resistance in respect to integrity, insulation, and load bearing capacity.

Moisture: Available measured data and testing on the moisture resistance of hemp lime was limited, however its application in practice and testing carried out the BRE at Haverhill in 2002 indicated that appropriately rendered and detailed hemp lime constructions with certified materials should provide reasonable resistance to moisture.

Acoustics: There is limited measurable data on the acoustic performances of various hemp lime mixes, however the available data provides some indications of reasonable performance.

Energy: Research and data referred to in the collated literature indicates that hemp lime can have important thermal properties e.g. in the areas of thermal bridging and air permeability, but also in areas not fully accounted for within current thermal standards or testing methods, notably its potential thermal storage properties.

Material and Workmanship: The report identified that there is no known European or National Standards in relation to hemp lime as a bio-composite construction material, nor are there any known products with CE markings, or ETA's, however there are however some specific material suppliers who have secured national Agrément certificates for specific materials and specifications. The report also identified some key workmanship issues notably related to moisture content and drying time.

Recommendations and Further Research:

The report identifies specific areas of knowledge or data deficiency in the publicly available data and makes specific recommendations on further research. In order to encourage the use of hemp lime and further assess its use as a construction material, technical and material based research as well as research into economic, and market factors is needed. The study recommended that future research should be co-ordinated and include the involvement of a multi disciplinary team with third level co-operation.

Specific areas of research would include consideration of;

- i) hemp processing and economics studies into hemp industry,
- ii) detailed studies and coordinated testing of various hemp lime mixes,
- iii) hemp lime mechanical properties,
- iv) the dynamic thermal behaviour of hemp lime constructions
- v) testing of fire properties
- vi) testing of moisture resistance,
- vii) examination of alternative binders and mixes
- viii) examination of alternative or adapted applications.

The establishment of a hemp growing and processing industry in Ireland, as a prerequisite for a favourable context to develop hemp lime as construction material, was highlighted in the report. The many possible applications of hemp as an industrial crop, across a range of sectors as diverse as foods, plastics, construction etc., and the potential benefits to the agricultural sector, the economy and the environment were set out.

Third Party Certification e.g. Agrément or equivalent of particular hemp lime proprietary products or construction solutions, especially those based on Irish supplied hemp can demonstrate fitness for use of the material for the Irish construction industry. The possibility of developing a specific code or standard for hemp lime as a material in construction was explored at both industry consultation and technical workshops. Further testing of the material and experience in use are required in order to develop a standard.

Given the potential positive environmental benefits, including the potential for carbon sequestration, and the economic benefits to the manufacturing, rural and construction sectors further research and investigation into hemp lime as a construction material should be encouraged.

1. Introduction

This report presents the findings of a scoping study carried out during 2010, under the EPA 'STRIVE' research funding programme, to assess the potential application of hemp lime as a building material in Ireland.

1.1 Background to the Study

The original impetus for a study in this field grew out of the project promoter's interest in ecological building materials and more specifically following an initial exposure to hemp lime as a building material, gained while undertaking master's level research.

The proposal for the study, originally conceived in 2009, was developed from initial research carried out while drafting an article written by the promoter on the emergence and potential of hemp lime in construction, and its potential to reduce or abate negative environmental impacts arising from construction (Daly 2007).

It was envisaged that a scoping study into the emergence and potential of hemp lime in Ireland may assist in the development of the material and support its move from a craft / pioneering stage to a more mainstream application so that potential environmental benefits could be fully realised. In particular it was envisaged that a study could examine in detail the technical issues and challenges in assessing the performance of this material for use in the Irish construction industry.

Contextual changes in the industry and specifically important legislative developments in relation to energy and carbon reduction in the building sector were also seen as favourable factors, and while such legislation was primarily focused on reduction of operational energy in buildings, two key factors were identified as potential drivers toward material specification becoming more important from an environmental perspective. Namely that embodied energy of materials is becoming a more significant factor in the total (operational and embodied) energy use of a building over its lifetime and secondly that there is a drive toward more holistic environmental assessment and targets in the industry with broader environmental issues such as, ecology, toxicity and embodied energy being addressed, e.g. the UK Code for Sustainable Homes, (Dept for Com and Local Govt UK 2010).

1.2 Objective

The objective of the study was to assess the application of hemp lime as a bio-composite in construction in the Irish context, and to assess in detail its known technical performance in relation to the principal standards and requirements within the Irish building regulations. Aspects to be examined were;

a) Hemp and lime development and application in Ireland

b) Hemp and lime raw material and production in Ireland

c) Hemp lime - principal material construction properties

d). Hemp lime - main construction applications / methods

e) Hemp lime – collation and tabulation of known performance data

f) Hemp Lime – comparison of performance data to relevant Irish technical standards

It was envisaged that such a study could possibly provide a useful road map for further research and demonstration in Ireland and assist in promotion of the material and further mainstreaming.

1.3 Scope

The study was originally broken down into nine component work packages, literature and demonstration project review, material/construction properties, construction application, standards, workmanship, industry consultation and workshops, site visits, report compilation, and the development of booklet / guide. The core focus of the study was the collation of data on the materials construction properties and the comparative analysis of this data with key performance requirements and relevant standards in the Irish context.

As such the study required a comprehensive review of publicly available literature on hemp lime resulting in the collation of a growing body of international research on hemp lime and its increasing application in construction. This data was collated and summarised in a number of tables which are key to this report and are the first known detailed collation of current available literature and data on hemp lime bio-composite, which should aid further research and development. The following are the key supporting tables.

Table 2.1 '*Literature Review Research Summary Table'*, outlining the principal data collated, literature type and listing the key relevant content.

Table 4.1 '*Material Properties – Detailed Data Table'*, listing the key material properties, sources and test methods etc.

Table 4.2 *'Test Data and Comparison Table'*, listing the various relevant standard and their testing requirements with comparable test data on hemp lime.

Note: these tables present a summary of data gathered by BESRaC from a review of key technical literature on hemp lime as known and available at date of study (early 2010) and is not an exhaustive list of all data on the subject. Original documents should be referred to for detail and verification. While every reasonable effort has been made to ensure accuracy the authors, EPA & DECLG accept no responsibility for errors or liability arising from use of this data.

The study also included a review of key UK, French and Irish demonstration projects, and industry consultation was undertaken in Ireland throughout the study, via email survey and two workshops, which assisted in highlighting third level research in Ireland and the growing interest and application of the material.

2. Hemp and Lime – Current Developments

2.1 Literature and Data

A comprehensive review of publicly known available literature on hemp lime was undertaken with some forty four papers, reports and articles collected and reviewed. The majority of the literature was in the form of academic research and technical papers, with some manufacturer's data, mainly stemming from France and the UK where the material and technology has been pioneered. This review focussed on Hemp Lime rather than the growing of it.

This literature review indicated an emerging body of scientific and technical knowledge on hemp lime as a material and construction method, with research across a range of levels including scientific papers and PhD, MSc, and degree level thesis work, as well as manufacturers technical and product literature. However there is still scope for future research work notably on a coordinated basis with studies examining a range of performance assessments based on consistent mixes and standard testing methods.

While the principal research themes were found to be in the spheres of mechanical properties and thermal performance, research and investigations have also been undertaken in areas such as acoustic performance, moisture penetration and alternative binders. The literature is reviewed in a summary form, as detailed in Appendix 1 Table 2.1, '*Literature Review Research Summary Table'*, outlining the principal data collated, literature type and listing the key relevant content.

2.1.1 International Research

The study identified a number of key research centres / personnel active in this field notably:

Research at The University of Bath is focusing on the development of load bearing and non-load bearing hemp lime masonry blocks; the development of binders for use in hemp lime composite material; and the innovation and optimisation of hemp lime construction for mainstream uptake.

The University of Bristol (Interface Analysis Centre) is involved in hemp lime, as well as hemp-cement and also studying the mechanical and micro-structural properties of natural fibres based building materials.

Research at The Université Catholique de Louvaine in Belgium is currently studying the hygrothermal behaviour of sprayed hemp lime material through simulations.

The Université de Reims Champagne Ardenne in France in collaboration with the thermo-mechanical laboratory GRESPI (Groupe de Recherche en Sciences Pour l'Ingénieur) is currently looking at the hygrothermal performance of vegetable fibres based building materials in terms of modelling and actual behaviour.

The University of Nantes (Institut de Recherche en Génie Civil et Mécanique) in collaboration with the University of Rennes (LGCGM - EquipeMatériaux Thermo Rhéologie) and the Universitè de Bretagne Sud (Centre de Recherche de Saint-Maudé, LIMATB) are currently working in a research program called ‘Betonchanvre’, funded by the National Research Agency. The objective of this project is to focus on the optimisation of the manufacture of hemp concrete blocks by quantifying the impact of the elements and processes on the setting kinetics and the final performances of the material.

In addition to publicly available literature there is evidence of private commercially funded research being undertaken. Lime Technology in the UK, for example, has partnered with the University of Bath for the development of masonry blocks. The same company is currently involved together with Lhoist UK, Hemp Technology Ltd, and a number of other partners in a three year study at University of Bath aimed at further improving the mainstream uptake of hemp lime materials.

2.1.2 Some Key Papers

The work carried out by Dr. Arnaud Evrard between 2005 and 2008 at the Université Catholique de Louvain in Belgium produced a number of papers, which strongly contributed to a better understanding of the hygrothermal performance of hemp lime materials and their transient behaviour in dynamic context. He was the first to simulate the dynamic behaviour of hemp lime using “WUFI” software.

A BRE report (2002) resulted from a comparison between hemp lime and conventional construction systems in the Haverhill housing development in Sussex. The two systems were assessed in terms of their structural, thermal, acoustic, and durability qualities; reduction in waste generated on site; environmental impact and construction costs. It included a water spray test which has assisted in defining the moisture resistance of the material. The overall study concluded that hemp lime construction was equal to and in cases outperformed the conventional system.

2.1.3 Research in Ireland

Within Ireland a number of degree and masters level studies have also been undertaken, with a significant PhD study (funded under the EPA STRIVE research funding programme) currently underway by Rosanne Walker (Trinity College Dublin), which aims to examine some of the key properties of hemp lime materials including drying/setting times.

In the Dublin Institute of Technology a masters level thesis focused on the barriers to the mainstreaming of hemp lime in Ireland (Ronchetti, 2007), a degree level thesis in construction economics on the process of building with hemp lime (Flanagan, 2006), and a final year student of structural engineering is currently testing small-scale timber-frame panels with hemp lime infill for their resistance to in-plane lateral loading or racking resistance. In addition a thesis in engineering at University College Dublin focused on the combination of hemp and lime as a structural and insulating material for dwelling .(O'Dowd & Quinn, 2005).

2.2 Raw Materials and Processing in Ireland

2.2.1 Hemp Growing and Processing in Ireland

There are a small number of organisations and private companies that have grown or are currently growing hemp in Ireland. Currently there is no hemp processing facility in the country, which is one of the main barriers for the development of a domestic hemp industry / market.

In terms of growing hemp, Teagasc, conducted a number of projects on hemp during the past few decades. The first project was carried out in the '60s and looked at hemp as a source of fibre mainly for paper manufacture. Experiments were conducted on different soil types, at different seeding rates, with different levels of fertilization as well as with different varieties. It was concluded that hemp was not a viable source for paper making considering the then current market price (Finnan, 2010 pers. comm.).

More recently between 1997 and 1999, Teagasc looked at hemp as a crop for medium density fibreboard production. The aim was to establish the yield potential of the crop. Different varieties, sowing dates and seeding rates were tested. It was concluded that hemp can produce high yields of stem material, however harvesting and storage techniques had to be developed (Crowley, 2001). The most recent research project took place in 2008 with the aim of assessing hemp as an annual energy crop with experiments aimed at optimising the fertilisation rates (Finnan, 2010 pers. comm.).

Hemp plant growing at TEAGASC Research Centre, Ireland. Photo BESRaC

A number of private companies involved in the cultivation of hemp have also been identified. Hempire Building Materials (Co. Monaghan) was licensed and contracted farmers across Ireland (North & South) to grow hemp that would be used for construction purposes. Hemp was grown on 60 acres in 2006, 500 acres in 2007 (a total of 18 farmers) and 60 acres in 2008. This was likely to be the highest quantity of hemp grown in Ireland, however it is understood that resources were not all utilised locally due to delay in establishment of processing and some of the crop was eventually exported to the UK for processing. All the farmers involved provided positive feedback on the crop stating that hemp is extremely good as break crop with the main risk being the weather conditions both when seeding and harvesting (McCabe, 2010, pers. comm.).

Tokn Grain Products (Co. Offaly), a company supporting the introduction of hemp as a crop in Ireland, has successfully trialled hemp in small plots during the past five years (Tong, 2010, pers. comm.) with very positive results, including research on harvesting and cultivation.

Hemp Ireland Ltd is a R&D company established in 1998 which is focused on textile hemp fibres. They contracted farmers across Ireland (North & South) and developed new harvesting, decortification and degumming technologies. They are currently licensing their technology in China where hemp is forecasted to replace cotton over the next decades (Barman, 2010, pers. comm.).

Wexgen Ltd (Co. Wexford) is a farmers owned company which grows, processes and supplies bio-energy products from crops. They trialled hemp as a biomass crop over 140 acres during 2008.

Green Hemp Ltd is a company which aims to establish an indigenous hemp agri-business in the South-East of the country. They currently have licence applications for permits to grow hemp varieties on a trial basis.

In Northern Ireland there are two main examples of experience in hemp cultivation: the Agri-Food Bioscience Institute, which would have the same competence as Teagasc, grew from 5 to 10 acres of hemp between 1996 and 2007 for research purposes and focused on seeding rates, harvesting technologies and retting procedures. The only known private company involved in hemp cultivation in Northern Ireland is Harnetts Oil, a business which grows hemp for oil seed production. They also sell certified hemp seeds to farmers. Over the last 9 years they grew from 10 up to 100 acres each year.

There are a number of factors that limit the take up of the hemp industry in Ireland. In terms of hemp cultivation, only a limited number of varieties can be legally grown under license. According to EU regulations, farmers can only cultivate those varieties that contain less than 0.2% THC, which is the psychoactive ingredient of the plant. In addition the process for obtaining the growing license in Ireland is onerous with field inspection from officials of Garda Síochána required and multiple agencies involved. License requirements include the need for farmers to specify both a processor and a declared application for the yield. Such requirements on tillage farmers generally would be seen to distort markets, curtail farm production and limit economic opportunity (Caslin, 2009). Simplification of this complex procedure may make it more attractive to farmers.

There are currently no hemp processing facilities in the country, which is a necessary condition for the take up of the hemp cultivation. Hemp Company Dublin has drafted a business plan for a fully integrated fibre processing/production facility which would require a capital investment of €4-5 million and a crop area of 1000 hectares. It would employ about thirty staff and could be replicated regionally to generate up to 300 full-time jobs (Caslin, 2009). Product testing and certification to secure market access will require further investment .. Such high initial investments costs create a barrier to start-ups.

Hemp being harvested. Photo courtesy of Alec Tong

2.2.2 Lime Production and Supply in Ireland

The market for construction lime in Ireland is fairly limited. Clogrennane Lime is the only company manufacturing lime in Ireland and Kilwaughter lime in County Antrim also produce in Northern Ireland.
Clogrennane, part of CRH, an international group operating in the building material sector, own their limestone quarry and operate lime kilns in two different sites in Co. Carlow and Co. Clare. The great majority of their production goes into non-construction applications, namely chemical and pharmaceutical industry, agriculture, water treatment and soil stabilisation. The company manufactures three different products for the construction sector: quicklime, hydrated lime, and aqueous lime (Connolly, 2010, pers. comm.). Clogrennane have recently been involved in the Irish hemp lime market and despite the small size of hemp lime market they are interested to see it growing (Connolly, 2010, pers. comm.).

Natural hydraulic lime is not manufactured in Ireland because the mined raw material, i.e. limestone, does not contain the right amount of impurities like aluminates or silicates. However it is claimed that there are limestones suitable for production of hydraulic limes, for example Dublin ‘Calp Lime’ (McAfee P Limeworks) Hydraulic lime is a type of lime which sets in presence of water while hydrated lime, also called ‘air lime’ requires air to set. However it is not known how important this may be for Hemp Lime manufacture, or if there are significant transport costs/ carbon penalties for importing hydraulic lime.

Hydraulic types of limes are normally imported into the country, mainly from France. Traditional Lime Company is a business based in Co. Carlow which imports and distributes St. Astier Natural Hydraulic limes from France (Byrne, 2010, pers. comm.). Another company, Stoneware Studios from Cork, imports and distributes lime from the French group Socli under the name of 'Roundtower Natural Hydraulic Lime' (Dorrian, 2010, pers. comm.).
In Northern Ireland the company Heritage Ltd from Co. Antrim was identified. They recently took over another company called 'Narrow Water' which used to run a small scale hydrated lime manufacture operation. At the moment there is no production going on but is proposed to be re-started. Heritage also imports and distributes Roundtower Natural Hydraulic Lime from French group Socli (Patterson, 2010, pers. comm.).

Lime quarry and production plant Clogrennane, Ireland. Photo BESRaC

2.3 Material Application and Demonstration Projects

2.3.1 Material Application and Demonstration Ireland

An indicative survey of hemp lime projects in Ireland was carried out as part of the study, with the main sources of data coming from the three major pioneers of hemp building in the country: Steve Allin (Hempbuilding), Henry O'D Thompson (Oldbuilders Company), Marcus McCabe (Hempire Building Materials) and a number of self-build projects. See Table 2.2 and Fig 2.3 below.

Data collected shows that the majority of uses in Ireland consist of the application of hemp lime plaster (either internal or external). There are a small number of whole hemp buildings, all of them small-size one-off domestic building projects, and over 20 hemp lime wall applications identified. (see Table 2.2). Importantly the first applications of hemp lime in Ireland date back to 1997 with a clear exponential increase during the past 13 years., see Fig 2.3

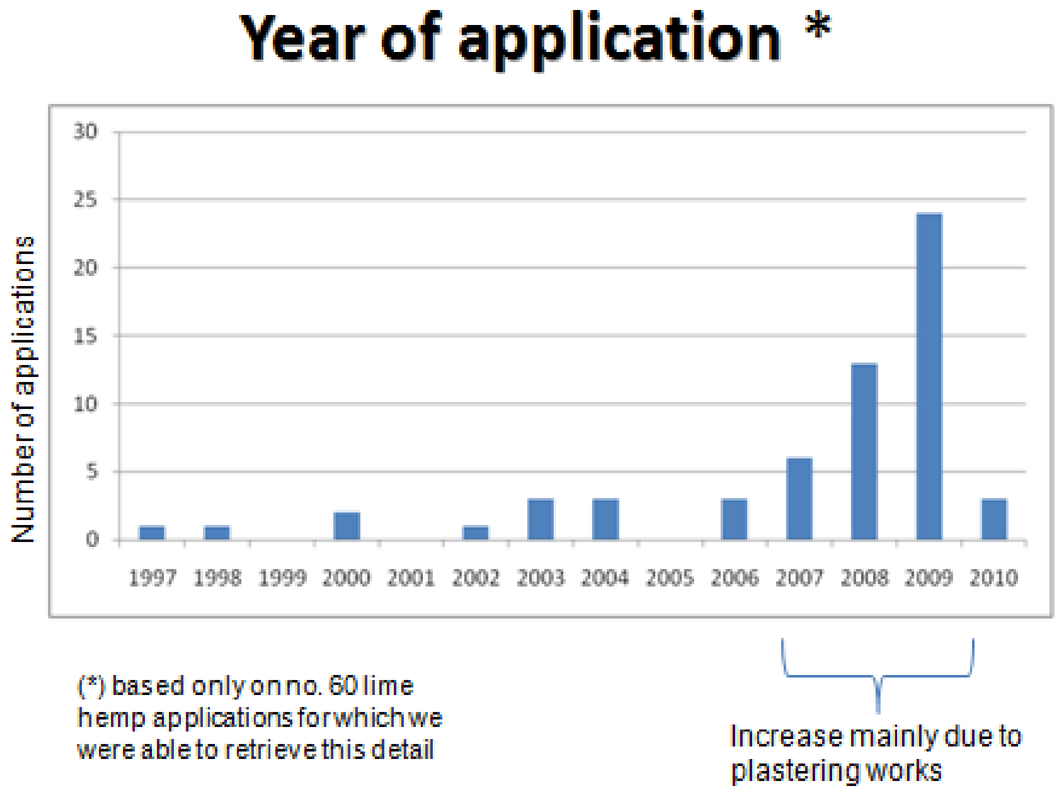
Table 2.2 – Type and location of hemp lime applications in Ireland

		Walls	Floors	Plaster
REP. OF IRELAND	Co. Kerry	3	1 (+2)	25 (+1)
	Co. Cork	2	1	22 (+2)
	Co. Clare	2	(+2)	14
	Co. Tipperary	2	1 (+1)	4 (+1)
	Co. Donegal	2		3
	Co. Wexford	1	(+1)	3
	Co. Dublin			4
	Co. Sligo	1	(+1)	3
	Co. Galway			4
	Co. Monaghan	1	(+1)	3
	Co. Wicklow	1	(+1)	2
	Co. Westmeath	1		2
	Co. Leitrim	1		1 (+1)
	Co. Carlow	1		1 (+1)
	Co. Kildare			2
	Co. Cavan			1
	Co. Mayo			1
	Co. Offaly			1
	Co. Waterford	1	(+1)	(+1)
NORTHERN IRELAND	Co. Down	1		3
	Co. Antrim	1		1
	Co. Fermanagh			1
	Co. Armagh			1
	Co. Tyrone	1	(+1)	(+1)
TOTAL		22	14	110

Source: produced by the BESRaC, derived from industry survey during desk base study

This table shows the distribution of the three main types of hemp lime application, i.e. wall, floor and plaster, derived from industry survey carried out by the authors. The number inside brackets means that those applications were part of another work already shown under a different category. For example two of the plastering jobs in county Cork were made in association with the wall construction.

Figure 2.3– Irish hemp lime applications per year



Source: Industry survey carried out by the authors BESRaC

The largest known hemp building project in Ireland was in progress during this study (commenced July, 2010) in Carnlough, Co. Antrim, Northern Ireland, on behalf of a housing association and consists of the construction of 10 number two bedroom houses (5 semidetached housing blocks) and one number three bedroom bungalow. All of which will have hemp lime external walls.

Hemp Lime infill to timber frame semi detached housing units at Carnlough, Co. Antrim, Northern Ireland. Early shuttering above and later pre rendering stage below. Photo BESRaC / Tom Woolley

2.3.2 Material Application and Demonstration in the UK

Hemp lime construction in the UK has been pioneered in the south of England with a number of significant demonstration projects and emerging commercial activity. For example, Lime Technology, a company operating in the development of lime based building products, in collaboration with Lhoist UK and Hemcore, (now Hemp Technology), the major processing company of industrial hemp in the UK, has been manufacturing and distributing hemp hurds and lime binder under the Tradical® Hemcrete® trademark for about ten years

(Lime Technology, 2007). Lime Technology has been identified as the major player responsible for the mainstream uptake of hemp construction in the UK. One of its key demonstration and dissemination projects was a social housing development for the Suffolk Housing Society in 2001, with important performance assessment data carried out by the BRE and being widely disseminated via the Internet.

Table 2.4 below presents a review of key UK demonstration projects, showing a diverse range of projects, from one off single residential houses and small size commercial buildings to medium size residential developments and large scale commercial type of construction.

Table 2.4 – UK demonstration projects

Project	Type	Method
Adnams brewery ware-house, Suffolk*	large commercial building	100,000 high density hemp lime blocks and 1,000m^3 of low density hemp lime mix
Reconstruction of old timber frame foundry, Suffolk*	community build-ing	hemp lime blocks in floor, cast wall infill into structure
Barn conversion, Hert-fordshire*	small scale	hemp lime infill into old oak frame
Self-build renovation of bungalow, London*	single family house	hemp lime external insulated render
Two-storey extension, Suffolk*	small scale resi-dential	hemp lime cast around timber frame
Haverill Social Housing, Suffolk*	medium scale res-idential (two houses)	hemp lime cast around timber frame and floors
Lime Technology offices, Oxfordshire*	office and com-mercial building	80m^3 sprayed hemp lime (walls); 30 m^3 hemp lime roof insulation
Clay Fields social housing, Suffolk*	large scale social housing scheme	26 homes - sprayed hemp lime onto timber frame
JenningsBusinessPark, Oxfordshire**	commercial build-ing	hemp lime walling infill
Temperature Controlled Warehousing, Hertford-shire**	large scale wine warehouse	prefabricated 3.6m by 2.4m panels of 400mm thick sprayed hemp lime
Private Housing Rose Vine, Cornwall**	private housing	hemp lime cast between tim-ber frame and stonework

*Source: *Bevan &Woolley (2008) – **Lime Technology (2010)*

The projects demonstrate a number of different methods for applying hemp lime the most common of which is hemp lime cast around a timber frame structure. Sprayed application to timber frame structures has also been developed and used on a large scale social housing project where speed of construction was key.
Some innovative ways of employing hemp lime must be highlighted like the use of large prefabricated 400 mm thick panels filled with a sprayed hemp lime mix. The panels are supported by a steel frame and were employed for the construction of a 50,000m3 warehouse housing more than 3.5 million bottles of wine. The monitoring of the internal environment of the warehouse has shown remarkable temperature stability despite daily external temperature variation and extended periods of sub-zero temperatures (Bevan & Woolley, 2008).

The two hemp lime houses built at Haverhill, Suffolk as part of a social housing scheme deserve particular attention because of the monitoring and evaluation carried out by the Building Research Establishment on the units with the aim to investigate structural, thermal, acoustic, permeability and durability qualities and also to report on reduction in waste generated on site; environmental impact; and construction costs (BRE, 2002).

2.3.3 Material Application and Demonstration in France

Hemp lime has been used in France since the early 1990s. It was initially discovered and successfully used as material for the restoration of historic timber buildings. It was later employed in new construction as wall infill in combination with structural timber frame, as well as insulation for floor and roof.

There are today several individual private houses and several social housing schemes that have been built with hemp lime in France. Around 4,000 tons of hemp hurds are used annually by the building industry, with an overall value of € 35 million (Woolley, 2006). This is well demonstrated by the fairly large number of companies identified that are involved in the production, distribution and application of hemp lime materials in France.

Hemp lime products have been used in commercial projects, amongst them, is a seven storey office building built for the Regional Government Office of Housing and Environment in Clermont Ferrand (Bevan &Woolley, 2008), where hemp lime blocks have been used as insulating wall infill in association with a wood and concrete structure.

3. Construction Approaches and Environmental Profile

3.1 Construction Methods and Solutions

Hemp lime is typically being used for in-situ applications, mainly in a hybrid wall construction comprising a timber frame structure with an in-situ hemp lime wall mixture applied via filling / tamping in temporary shuttering or via spray application. It is also being used as an in-situ floor slab mixture and a lightweight mix has been used in roof insulation. In addition to the above, developments in masonry blocks are also in progress and have been used in some applications usually non load bearing. However there are potential wider applications for hemp lime or hemp with other binders.

3.1.1 Masonry

Masonry construction is the most common form of construction in Ireland with cavity wall and hollow block being common for external walls and single leaf solid wall construction being generally used on older constructions externally and for internal walls in contemporary application.

Overseas developments in hemp lime masonry units to date include both load-bearing and non load-bearing blocks, with adaptations being hollow block with timber post infill and hemp magnesium oxide blocks.

Hemp Lime Masonry Examples:

Adnams Brewery Warehouse and Distribution Centre (Suffolk, UK) – The 4,400 m2 building is made of a supporting steel frame with 100,000 unfired lime and earth high-density blocks (containing hemp) forming a 15 m high diaphragm wall. In between the inner and outer blocks 1000 m3 of low-density hemp lime mix were applied as an infill to provide further insulation (Bevan & Woolley, 2008).

Regional Government Office of Housing and Environment (Clermont Ferrand, France) – Hemp lime thermal blocks have been employed as insulating wall infill in combination with a seven-storey wood and concrete structure (Bevan & Woolley, 2008).

3.1.2 Timber Frame

Timber frame has become a significant construction method in Ireland particularly in domestic buildings. It is commonly constructed in Ireland using an external block or brick leaf as weather protection for the timber frame. The timber frame would generally be insulated using a range of insulations e.g. mineral wool, cellulose, plastic insulations etc.

A hybrid wall construction comprising a timber frame structure with an in-situ hemp lime wall mixture applied via filling / tamping in temporary shuttering or via spray application is currently the most common form of hemp lime construction and is an alternative to the timber frame construction method described above. This method of hemp lime construction is probably the most developed in the UK with one hemp lime company having a BBA certified hemp lime product (British Board of Agrément, Agrément Certificate 10/4726).

Hemp Lime Timber Frame Examples:

Clay Fields social housing (Suffolk, UK) – Contemporary design and sustainable construction with low energy use and innovative local materials were the guiding principles for the construction during 2009 of 26 affordable homes on behalf of Orwell Housing Association in Suffolk, UK. Hemp lime was chosen, amongst other environmentally friendly materials, for the construction of external walls. The mix was sprayed against permanent internal shuttering panels onto a timber frame structure (Lime Technology, 2010).

WISE building at the Centre for Alternative Technologies (Wales) – Wise is a glue-laminated three-storey timber frame construction of offices and study bedrooms, conference hall and associated facilities. Hemp lime infill was mainly sprayed onto wood-wool boards attached to the inside of the timber frame, and in some cases pumped into temporary shutters. Walls are 500mm thick providing a high degree of insulation and air tightness whilst remaining breathable. Hemp lime has also been employed for the construction of ground bearing slabs.

3.1.3 Concrete Cast In-Situ (Structural)

Concrete cast in-situ work is a very common form of construction. Walls are commonly constructed using two methods: either a concrete wall cast using temporary shuttering and then insulated either internally or externally, or cast in permanent insulated shuttering usually made from EPS.

Cast hemp lime does not have load bearing structural properties. The hemp lime alternative to this method of construction requires the significant use of cement to improve strength requirements and as such application may be limited. Strengths of hemp lime cement mixtures have been recorded up to 13.58 N/mm^2, when tested to ASTM C109 and C39, however this increases the overall environmental impact of the construction in terms of embodied energy and embodied carbon, (Chew & MacDougall 2007).

Hemp Lime Cast In-Situ Examples:

There are no known examples of hemp lime cast in-situ structural applications. The infill timber frame method, however, is a form of hemp lime non-load bearing cast in situ work.

3.1.4 Pre-cast Construction

Pre cast panels are a possible application most likely in framed constructions where they are used in conjunction with a structural frame and as such require no direct load bearing function. Typical solutions are floor-to-floor panels with either insulation applied, e.g. a secondary insulated stud wall to the internal side of the pre-cast panels, or integral as a pre-cast sandwich panel with an insulation core.

Hemp lime has limited structural properties however non load bearing pre cast panels (on framed structures) have lower load requirements and hemp lime mix strengths can be improved with the addition of cement
Hemp lime has limited structural properties however non load bearing pre cast panels (on framed structures) have lower load requirements and hemp lime mix strengths can be improved with the addition of cement.

Pre-cast Hemp Lime Examples:

A panel which consists of a prefabricated timber frame with a hemp lime infill has been developed (Modcell, 2010) and may be an alternative to pre-cast concrete panels.

The wine society warehouse (Hertfordshire, UK) – Hemp lime has been employed for the production of pre-fabricated 3.6 by 2.4 m panels of 400mm thick-sprayed products within timber cassettes. Panels are supported by a structural steel frame and were employed for the construction of a 50,000 m3 warehouse housing more than 3.5 million bottles of wine (Lime Technology, 2010).

Hemp Lime Walls at the CAT Wise building in Wales. Photo BESRaC

3.2 Hemp Lime Environmental Profile Overview

3.2.1 Resource Availability and Reserves

Hemp is a renewable resource, it can be harvested with high yields on a yearly basis and has potential to be widely grown in Ireland. Lime is non-renewable, however Ireland is rich in limestone ore and the existing available global reserves of limestone globally are very large (Berge, 2000).

3.2.2 Limestone Extraction and Processing

Limestone is normally quarried in open pits with visual impacts on the landscape and some loss of wildlife habitat. Quarries usually cause an increase in local noise, pollution and erosion and dusts. Lime processing is an energy consuming operation. Limestone ore is burned in fossil fuels powered kilns at a temperature of 900-1100°C.

3.2.3 Hemp Cultivation and Processing

The cultivation of hemp generally requires low additional inputs; low levels of fertiliser and mechanised work resulting in s transport emissions (INRA, 2006). Processing of hemp is a low impact operation; it is based entirely on mechanical energy; it requires no chemicals, creates low waste products, and is claimed to emit no pollutants into the atmosphere (Hemp Technology, 2010). The only waste produced from hemp processing are dusts (INRA, 2006) which can be pressed into bricks and used as a bio-fuel, as it already happens in the UK (Bevan & Woolley, 2008).

3.2.4 Re-use and Recycling

A hemp lime mix can be reused at the end of its life by crushing it, mixing it with water and some additional lime binder and casting it anew. This applies to any form of hemp lime application, be it monolithic walls, bricks or blocks. The material also has potential for recycling in other applications such as composting, backfill or crushed up and spread on flower beds or fields in order to increase the ph of the soil and introduce a mulch (Lime Technology, 2007).

3.2.5 Final Waste

Being made primarily by hemp shiv, a biomass, and secondarily with carbonated lime, the hemp lime mix would have minimal environmental impact if sent to landfill. It may also be possible to break up and disperse onto land or agricultural fields, where the hemp shiv would biodegrade and lime (calcium carbonate) would blend with the soil.

3.2.6 Embodied Energy

The amount of primary energy employed for the production of hemp shiv equals to 2.1 MJ/kg when a rate of 60% shiv and 40% fibre is considered (INRA, 2006). A higher value of 3.8 MJ/kg was reported by Clark (2009). Calcinated lime (calcium oxide) requires 4.5 MJ/kg for its production (Berge, 2000). A value of 5.3 MJ/kg is reported for hydrated and hydraulic lime in Hammond & Jones (2008). It should be noted, however, that embodied energy analysis of materials in construction is based on the density and amount of the material per volume and not just on a weight basis.

3.2.7 Sequestered Carbon

Hemp absorbs carbon dioxide in the atmosphere during growth, and as such can store carbon within a construction element. According to Pervais (2003), 325 kg of CO2 are stored in one tonne of dried hemp.

A number of manufacturers claim benefits of overall carbon sequestration within a construction element using hemp lime mixes, arising from both the hemp and the carbonisation of the lime during setting. For example Lime Technology claims that 110 kg of CO_2 are sequestrated in each cubic metre of hemp lime construction when spray applied, and that shuttered and cast hemp lime sequestrates up to 165 kg of CO_2 per cubic metre, depending on the level of compaction during construction. This estimate is claimed to already take account of the CO_2 emitted when producing lime, therefore the overall mix is claimed to be carbon negative, Lime Technology (2007).

However there is no agreed method or standardised environmental assessment for the calculation of carbon sequestration, and as Bevan and Woolley point out methodological acceptance would need to be achieved in order for accurate and acceptable results, which can be used on comparison to a range of other materials. (Bevan & Woolley, 2008).

There is also some dispute about the emission levels and carbonisation in relation to lime binders. CO_2 is emitted when limestone is burned in the kiln both from the combustion of fossil fuels as well as from the chemical reaction occurring when calcium carbonate becomes calcium oxide. CO_2 is reabsorbed by the lime binder during the carbonation process, however it is difficult to say whether that amount fully compensates the amount that was emitted in the earlier phase of the lime cycle.

Bevan and Woolley highlighted the need for independent environmental assessment to be undertaken. One LCA study showed a net reduction in GHG emissions over a 100 year lifespan, due to storage of CO_2 equivalent in the materials used, mainly the hemp. (INRA, 2006).

3.2.8 Toxicity

The toxicity of hemp and lime processing and use in construction is limited to the production of dusts. They can irritate inhalation routes and form part of photochemical oxidants (Berge, 2000). Hemp lime bio-composite is a natural material with no or very little toxicity or off gassing, therefore its toxicity during demolition process is very limited.

3.2.9 Indoor Health

Hemp lime impact on indoor air quality is considered positive in much of the research in part due to its vapour permeability, hygroscopicity with reports of good humidity balancing and limitations on condensation which restrict mould growth (Bevan & Woolley, 2008).

3.2.10 French Life Cycle Assessment on Hemp Lime Construction

An LCA of hemp lime construction has been carried out in France in 2006 by the National Institute for Agricultural Research and funded by the Ministry of Agriculture and Fisheries (INRA, 2006). The study looked at both agricultural and building process. In terms of the agricultural process, the potential environmental impacts of hemp cultivation are due to nitrogenous fertiliser and transport. Transport is the main source of energy consumption and greenhouse gas emissions in the agricultural process.

The environmental performance of hemp straw could be improved by reducing the application of nitrogenous fertilizer and by growing hemp varieties that make the best possible use of the available nitrogen. The reduction of the travelled distance by the hemp straw would also improve its environmental performance.

In terms of the building process, the study highlights the positive impact on the greenhouse effect due to the ability of a hemp lime wall to act as an overall carbon sink over a period of at least 100 years. The production of lime based binder is what most contributes to the emission of greenhouse gases, consumption of non-renewable energy, formation of photochemical ozone and resource depletion. Transport is the main contributor to the destruction of the ozone layer and the second main contributor in terms of impacts on the consumption of non-renewable energy and the greenhouse effect.

Improvements in the emissions of greenhouse gases from the production of lime rely on its manufacturing industry. Shortening the transport between the factory producing the lime binder and distributors would also improve the overall potential impact of the building stage. The environmental performance could also be improved at the end-of-life with additional recycling options or recovery solutions.

.

Table 3.1 –Potential environmental impacts over 100 years for the construction of 1 m² of hemp lime wall cast around a timber frame

Impacts	Prod. of raw materials		Construction	Use	End of life	Transport (total)	Total
	Hemp shiv	Other materials					
Resource depletion (kg Sb eq)	$2.8*10^{-2}$	$7.7*10^{-2}$	$1.2*10^{-3}$	0	0	$2.6*10^{-2}$	$1.3*10^{-1}$
Atmospheric acidification (kg SO_2 eq)	$5.1*10^{-2}$	$4.8*10^{-2}$	$1.3*10^{-3}$	0	0	$5.1*10^{-3}$	$1.0*10^{-1}$
Greenhouse effect 100 years (kg CO_2 eq)	-45.9	23.1	0.2	-13.6	0	$6.7*10^{-1}$	-35.5
Destruction of the ozone layer (kg CF-11 eq)	$7.1*10^{-7}$	$3.3*10^{-6}$	$3.4*10^{-7}$	0	0	$5.7*10^{-6}$	$9.9*10^{-6}$
Formation of photochemical ozone (kg C_2H_4 eq)	$7.1*10^{-4}$	$4.2*10^{-3}$	$5.0*10^{-5}$	0	0	$3.8*10^{-4}$	$5.4*10^{-3}$
Non renewable energy (MJ)	52.3	265.8	19.9	0	0	56.3	394.2
Air pollution (m^3)	674	207.2	14.6	0	0	128.2	1024
Water pollution (m^3)	4.3	2.2	$6.1*10^{-2}$	0	0	$1.1*10^{-1}$	6.7
Generation of waste (kg)	6	n.a.	0.9	0	98	n.a.	104.9

Source: adaptation of the authors from French LCA (INRA, 2006)


LHS Internal Hemp Lime application to an old stone wall   Photo Steve Allin
RHS External Hemp Lime spray application to inner shuttered timber frame wall Photo Steve Allin

4. Material Properties and Data

This chapter provides a summary of the collated material properties and data, as detailed in Appendix 1 Table 4.1 *'Material Properties Detailed Data',* which provides a comprehensive schedule of the key relevant construction material properties and data collated in this study. .

However in interpreting and using this data it is imperative that the following factors are taken into consideration.

4.1 Data Basis and Limitation

a) The publicly available data on hemp lime has been drawn from a diverse range of sources and studies including academic research, product development and site testing. Manufacturers literature has not being drawn upon in this report, given that in many cases there were no substantiating reports or technical studies.

b) A range of test methods have been used in developing the data. Sometimes testing methods are not fully described and in some cases informal or hybrid tests have been used

c) Testing has been carried out at a range of centres, universities in various national contexts, and not necessarily from 'approved' test centres, or stated as 'approved test centre'

d) Importantly the data is based on a wide diversity of binders with variations in materials, proportions and additives etc. which complicates cross comparison of results from other research and development of 'generic' values.

e) Another variant is the density of the mixture, which is significantly influenced by the mode of application, compression etc. and further complicates cross comparison of results or development of 'generic' properties.

To aid interpretation and use of the data collated in table 4.1, key information on the type of mix, tests, sources etc. have been included where known. However reference should be made to the original sources for detailed information.

4.1.1 Cross Comparison of Reported Data

Given the above range of variations in the data and sources, compiling a generic overview of hemp lime material properties presents limitations in terms of cross comparison of data. As such the collated data in this report is only indicative of its potential performance. Again reference should be made to original sources.

4.1.2 Indicative Values

Value ranges given in this section and the Table 4.1 should not necessarily be considered ‘characteristic’ given the limited samples and diversity of testing they are based on, but rather indicative of the various reported performances of the material.

4.1.3 Use of Data in Performance Assessment

The diversity of data sources and testing collated form the available literature also presents challenges and limitations in relation to the comparison of the performance of hemp lime as a construction material against various standards, codes and guidance. This is especially critical in the area of testing, where the basis of testing is not always known or adequately described.

Appendix 1 Table 4.2 ‘Test Data Comparison Table’ includes a comparison of standards and testing requirements to known testing data from the collated literature, and is the key source of performance analysis used in the chapters 6 -11 on performance assessment.

4.2 Hemp Lime Generic Material Properties (Density, Porosity, Vapour Resistance)

The density of hemp lime depends on a range of factors, including mix proportions, application type and extent of compaction. Table 4.1 schedules the reported density value ranges drawn from the key literature and technical papers with reported values for manual tamped hemp lime infill applications in the region of 400 - 480 kg/m^3. Compaction, and especially mechanical methods, can significantly increase density with for example densities on hemp lime samples achieving up to 1200 kg/m^3 , (O’Dowd & Quinn, 2005). The addition of other additives notably cement can also impact on density with density value ranges of 523 to 1872 kg/m^3 being reported on hemp lime cement fibre block samples, (Chew & MacDougall, 2007).

Hemp lime is an inherently porous material because of the microscopic porosity of both hemp shives and binder mix and the macroscopic porosity resulting from the arrangement of particles. Measures of total porosity outlined in Table 4.1 ranged between 71.1%$_{vol}$ and 73%$_{vol}$ based on work by Evrard, (Evrard, 2006), (Evrard & De Herde, 2005).

Hemp lime materials can absorb moisture and allow water vapour to move through the building fabric. Properties are influenced by binder mix, application. Measures of reported dry vapour resistance in Table 4.1 range between 3.6 and 7.68 based on tests to EN ISO 12572 (Evrard, 2006), (Evrard & De Herde, 2005), and water absorption coefficient of hemp lime values in Table 4.1 range between 0.075 kg/(m^2√s) and 0.15 kg/(m^2√s) for different test samples and methods, (de Bruijn et al., 2009),), (Evrard & De Herde, 2005).

4.3 Hemp Lime Mechanical Properties

Compressive strengths of hemp lime mixes depend on mix content and proportions, compaction, application and intended use (load or non load bearing), the latter being the more common. Given the above compressive strength values listed in Table 4.1 vary significantly.

For hemp lime infill, compressive strength values reported by Cerezo range between 0.25 and 1.15 MPa (Cerezo 2005), compared with values from a test method for cellular plastics - BS ISO 844: 1998, of between 0.46 and 0.84 N/mm^2, (BRE 2002). Tests carried out by Bütschi et al on hemp lime cement block samples show compressive strengths ranging 1.3 and 3.4 MPa, (Bütschi et al., 2003 and 2004), with results from Chew & MacDougall reaching compressive strengths values up to 13.58 N/mm^2 based on significant cement addition, (Chew & MacDougall 2007).

Young's modulus describes the stiffness of an elastic material. A wide range of values, from 4 to 15,500 N/mm^2,has been reported for hemp lime in the reviewed literature, as listed in Table 4.1, with a typical value range of 20-160 N/mm^2 for a typical hemp lime mix. The huge variation is due to the different mix composition and proportions.

A number of studies report the high deformation capacity of hemp lime, which is effected by compaction and also presence of fibres. Flexural strength measures a material ability to resist deformation under load. Results from a tests on hemp lime mixtures range between 0.38 (infill mix) and 1.21 N/mm^2 (block mix), (BBA, 2010), (Elfordy et al., 2007). Higher values ranging between 6.8 and 9.5 N/mm^2 are reported for a mix of hemp fibre reinforced cement, (Sedan et al., 2007).

Tensile strength measures the maximum amount of tensile stress that a material can be subjected to before failure. Tensile strength values for a hemp lime sand mix ranged between 0.08 and 0.25 N/mm^2 and average at 0.16 N/mm^2, (O'Dowd & Quinn, 2005). An extreme value of 11.9 N/mm^2 has been reported for a mix containing hemp shives and cement. (Bydžovský & Khestl, 2007).

Other factors which impact on strength include various chemical treatments which can improve stiffness. Some studies experimented with additional agents such as metakaolin and waste paper pulp, which improved strength (Eires & Jalali, 2005). Impacts on setting also include the presence of pectin, which can delay setting (Sedan et al., 2007) and application moisture content, for example spray application can improve setting (Elfordy et al., 2007).

4.4 Hemp Lime Thermal Properties

The thermal conductivity of hemp lime construction varies by mix content and proportions as well as compaction, and is related to overall density. Thermal conductivity values across a range of studies on hemp lime wall infill listed in Table 4.1 vary between 0.06 and 0.13 W/(m·K) depending on the density and composition of the mix. Work by Cerezo reports values of 0.06 to 1.0 W/(m·K) for low density mixes of 200 kg/m^3 and 0.1 to 0.13 W/(m·K) for medium density mixes of 450 kg/m^3, (Cerezo, 2005).

Thermal conductivity values for hemp lime masonry are generally influenced by whether blocks have thermal or structural purposes, and their overall mix and compaction methods. For example results from studies on hemp lime cement block samples, that were machine vibrated and compacted, record a value of 0.34W/(m·K), (Bütschi et al., 2004) while hemp lime block samples from a different study that were spray applied reported values ranging from 0.179 to 0.543 W/(m·K), (Elfordy et al., 2007).

Example U Values of various constructions and mixes from the studies listed in Table 4.1 include 0.89 W/(m2•K) for a 300mm thick wall (Bütschi et al., 2004) compared to 0.37 W/(m2•K) for a 300mm thick wall and 0.23 W/(m2•K) for a 500mm thick wall (BBA, 2010), Calculated in accordance with BS EN ISO 6946 : 2007 and BRE report (BR 443 : 2006). *It should be noted that U Values assessment does not take into account thermal mass and dynamic heat transfer.*

A number of studies report on the thermal mass aspects of hemp lime construction and notably its good thermal storage capacity, which can aid in dampening of diurnal temperature variation and improve indoor temperature stability, (Bevan R & Woolley 2008),(Evrard et al., 2006). In addition to high thermal inertia, hemp lime wall components appear to have hygric inertia and moisture buffering capacity, which can dampen indoor relative humidity variation and reduce condensation risk, (Evrard et al., 2006).

4.5 Hemp Lime Acoustic Properties

According to testing carried out by the BRE at Haverhill Housing in the UK, on site acoustic testing resulted in sound reduction of 57-58 dB for separation walls of hemp lime infill mix, (BRE, 2002). Lab based measurements of hemp lime cement block samples that were mechanically vibrated and compacted achieved sound reduction values of 43-47 dB (Bütschi et al., 2004). Reported sound absorption values for hemp lime samples ranged between 0.3 and 0.9 (Cerezo, 2005).

4.6 Hemp Lime Fire Resistance Properties

Test reports on a loaded hemp lime wall infill report a 70 minutes resistance performance before failure of load bearing capacity (BRE, 2009)(BBA, 2010).

4.7 Hemp Lime Weathering / Durability Properties

Water spray tests on rendered hemp lime 200mm thick wall samples show that water gets absorbed only in the 50-70mm exterior layer after having gone through severe exposure to wind driven rain over a 96 hours period.(BRE, 2002).

Internal Photo of CAT Wise building in Wales. Photo BESRaC

5. Industry Consultation

Industry consultation was carried out at the commencement of and during the study via an industry email fact sheet and survey, an industry seminar and workshop event and a technical workshop reviewing the preliminary findings.

5.1 Industry Survey

Early stage consultation included an info fact sheet and email survey, on awareness, knowledge and perceptions of the material were widely circulated across a range of sectors. A small sample of surveys were completed (21), mainly from people attending the workshop, with more than half the respondents having no or limited awareness on hemp lime construction, while the awareness of the remaining was from fair to very good.

The survey attempted to gauge the industries perception of the material in terms of perceived strengths and weaknesses. In terms of perceived strengths the most recurring comments were on the environmental performance and the carbon sequestration potential of the material, with insulation properties, breathability and flexural properties also highlighted. Perceived weaknesses were strength limitations and questions over long term durability and drying time.

The major barriers and obstacles on hemp lime perceived by the respondents were in relation to the lack of knowledge and awareness by architects, the public and the building trade, with absence of certification and. availability of local materials also identified.

5.2 Industry Seminars / Technical Workshop - 1

The first industry consultation involved a morning seminar, afternoon workshop and feedback session, and gathered a range of disciplines, including architects, technologists, engineers, contractors, growers, academic/researchers etc. with 134 expressions of interest in the workshop and 43 registered.

The morning session was focused on information dissemination with presentations on lime hemp construction and developments in UK, lime hemp use in Ireland, growing hemp in Ireland and a review of a current PhD study in alternative binders and admixtures in the lime binder.

The afternoon session was divided into two activities, the first being a group activity where working groups of mixed disciplines were facilitated to examine a range of scenarios devised to explore key technical, market and legal issues, and secondly an open forum was conducted with feedback and question and answer sessions.

5.2.1 Group Scenario Sessions

Each working group was given one of four design scenarios and asked to act as a design team and advise on the application of hemp lime construction as appropriate and to identify issues with the principal themes being as follows:

i) Compliance / Certification

Design professionals (engineers, technologists, architects) in particular were cautious or even reluctant to specify a hemp lime application, mainly due to lack of knowledge, absence of Agrément certification for specific products resulting in what was seen as a significant burden of compliance resting with designers.

ii) Cost / Lack of local sources

The higher cost of the material compared to conventional solutions was raised within all groups. Due to the lack of domestic hemp processing facilities, raw material for hemp lime building has to be imported from abroad, mainly UK and France, thus increasing the final cost of this building technology.

iii) Information / Training / Research

Many feel that information is required publicly, in particular on comparative performance and cost of hemp lime versus conventional building methods. There is a need for builders to be trained in the use of hemp lime construction. Further research is also required to fill the knowledge gaps on the material properties, especially in relation to Passive Haus standards.

5.2.2 Open Forum Feedback

The open forum discussion provided positive debate and feedback with the following being the principal topics.

a) Training

There were requests that training be provided for designers, contractors etc.
This should include hands on experience with the material. A number of the lime and lime hemp specialists noted that they had workshop / training facilities to be used.

b) Material

Discussion and concern was raised around the content of proprietary binders versus the open source information on binder mixes and lime hemp mixes. Some advocated agreement on open source mixes and others noted the commercial investment in development of same and need to keep data sensitive.

It was noted that there is significant variation across lime types and care needs to be taken in relation to type of lime used.

c) Government Support

There was discussion and desire for support from Government. It was noted that given the materials nature such funding would require inter-departmental collaboration, e.g. trade, agriculture, environment etc.

d) Demonstration

The need for key demonstration projects in Ireland was highlighted to advance and promote the material.
The possibility of a special building regulation compliance or dispensation was discussed to facilitate some key research and demonstration projects.

e) Regulatory Context

There was discussion around impacts of regulatory context broadly as follows.
There are no commercially available Irish mixes or binders with Agrément certification
Energy and Carbon limitations in building regulations are exclusive to energy in use and do not account for embodied energy or carbon, where lime hemp may have an advantage.

There was discussion around widening focus of regulations in relation to healthy buildings.

f) Agrément Certification

It was noted that Lime Technology in the UK had recently received BBA Agrément certification.

Hempire Building Materials reported that they were in the process of developing an Agrément certification and noted the significant cost for a small firm at circa €60,000 per product

g) Alternative Products

Hemp as a product for use in OSB (Orientated Strand Board) was proposed.

h) Refurbishment

Given the current collapse in the construction sector, especially domestic, and the existence of an estimated 20,000 vacant homes there was discussion about focusing hemp and lime use in refurbishment contexts.

i) Representation

There was significant support for the establishment of a representative association to promote and support the emergence of lime and hemp in construction.

j) Hemp Lime Code or Standard

There was discussion in relation to devising an Irish Standard or Code in relation to lime hemp on similar grounds to the Timber Frame Standard and there was strong support for the development of such an Irish Standard. It should be noted that Timber Frame Construction itself is not an innovative product/construction method.

5.3 Industry Technical Workshop - 2

A second workshop was hosted toward the end of the study to review in detail the performance data and comparison to guidance and standards in the Irish Technical Guidance Documents and was attended by a selected range of professionals, builders, academics etc., who had knowledge and or experience in the material and who made valuable contributions to the performance comparisons.

In general the performance comparison technical reports were well received and would be very valuable to the industry including the collation of all the background data on hemp lime performance, which has not been done to date.

5.3.1 Structure

There was significant discussion on structural performance of hemp with engineering professions present and important contributions made. The difficulty of quantifying and testing a material such as hemp lime on the basis of tests and standards for rigid high strength materials was addressed given the fundamentally different material properties and behaviour of hemp lime, especially its flexural properties and deformation capacity.

The definition and identification of failure point in compressive cube testing was identified as problematic and the need for alternative testing methods or failure definitions was discussed.

It was also noted that the collated data was not giving characteristic structural values as the no of samples, and diversity of samples / sources etc. would not facilitate characteristic values which engineers need to design from.

It was identified that a new structural standard based around the specific behaviour of the material would be required with more appropriate testing methods. The need for consistency of structural properties was highlighted as important for engineering design.

5.3.2 Fire

Hempire building materials reported that they have tested a plaster product in terms of spread of flame and while it completed the test it did not achieve an A1 category (10 minutes in a furnace at 1000°C) but passed A2 (based on verbal report, test method is unknown), which is defined in EN 13501-1:2007 as satisfying the same criteria as class B and BL for the EN 13823. In addition, under conditions of a fully developed fire these products will not significantly contribute to the fire load and fire growth.

5.3.3 Moisture

The feedback focused on issues to do with drying time, moisture content and frost damage to renders, as opposed to moisture penetration, as these were considered more critical given that appropriate moisture content is required to allow setting and drying is very slow. There was consensus that rendering should be seasonal and application in frost risk periods should be avoided. It was noted that drying time also effects occupation and humidity levels internally can be very high during early months of drying. Detailing at openings was noted as critical and that hemp lime does not adhere well to plastic materials such as DPCs etc.

5.3.4 Acoustics

It was noted that hemp lime infill or screeds at intermediate floors should assist in improving sound insulation.

5.3.5 Thermal

The main discussion revolved around the thermal mass properties and claimed advantages of hemp lime, which are not adequately accounted for in current standards and need for more advanced methodology.

5.3.6 Materials and workmanship

There was significant discussion and feedback around the area of validation or third party certification of a material or product as meeting standards.

6. Performance – Structure

6.1 Principal Standards and Relevant Requirements

The principal Requirements in relation to structural properties and performance in Ireland is set out in Part A of the Building Regulations Technical Guidance Document A provides guidance on compliance with these Requirements and refers to a range of I.S. EN standards, Irish Standards and industry codes. The Requirements cover loading, ground movement and disproportionate collapse. The guidance is split into small domestic scale buildings and non-domestic buildings. *Note: At the time of writing Part A of the Building Regulations was in the process of revision, with references being updated to reflect the introduction of the Eurocodes, which are replacing IS and BS Structural Design Standards, and to incorporate harmonized product standards.*

For small domestic buildings the guidance is focused on masonry construction to I.S. EN and IS standards with guidance in the TGD on thickness, detailing, construction etc., and notably that 'other masonry units' have the same strength and min thickness as the conventional systems.

Requirements for buildings are based on Codes of Practice and Standards including use of masonry, the most relevant of which are standards for use of masonry, formerly IS 325 Part 1 & 2 and BS 5628 Part 1, now replaced with I.S. EN 1996 (Eurocode 6)Design of Masonry Structures, which establishes structural design requirements including construction methods. Guidance is also given in relation to disproportionate collapse. Buildings should be designed for disproportionate collapse in accordance with recommendations of I.S. EN 1991-1-7 (Eurocode 1) and any requirements set out in the relevant Eurocode for the structure type which, in the case of masonry structures, is I.S. EN 1996 (Eurocode 6) which supersedes IS 325 as above.

I.S. EN 1996-1-1 defines 4 groups of masonry units according to the material type, volume of holes and thickness of webs and shells. TGD A Table 2 Sets out the minimum compressive strength requirements for masonry units for houses and other small buildings. These range from 4.7 N/mm^2 to 9 N/mm^2 depending on material and group. 4.7 N/mm^2 is the lowest compressive strength requirement and is for aggregate concrete masonry units to I.S. EN 771-3 (replacing IS 20). This standard describes the principal requirements for concrete masonry units (Dense and lightweight aggregates)

For Timber Frame Construction sizes of key timber structural members are given and reference is made to timber framing codes

6.2 Relevant Tests – Requirements, Standards and Methods

6.2.1 Masonry and Mortars

I.S. EN 771-3 Specification for masonry units - Part 3: Aggregate concrete masonry units (Dense and light-weight aggregates) (replacing IS 20: Concrete Building Blocks), describes the principal requirements for masonry in Ireland and refers to I.S EN 772-1 which describes a test method for determination of compressive strength of concrete blocks.

EN 772-1 describes a method for testing individual masonry units. Tests are carried out on a set number of prescribed specimens which are placed between two platens (steel plates), one fixed and the other adjustable to allow alignment with specimen and fixed platen, the adjustable platen is restrained during loading to avoid tilting of platen. The specimens are subjected to a gradual application of load at a set rate and the average compressive strength is recorded.

EN 1052-1 describes a method for determining the compressive strength of a masonry wall section, rather than unit, with a partial section of wall built, including mortar joints, and subjected to the gradual application of load at a set rate.

BS 4551:2005+A1:2010 Specifies methods of sampling preparation, physical testing and, chemical analysis of mortars for bricklaying, plastering and, rendering.

I.S. EN 998-1 – Rendering or plastering mortar. Specifies properties, methods of sampling and physical testing for factory made rendering or plastering mortar with inorganic binders for use on walls ceiling columns and partitions.

I.S. EN 998-2 Masonry mortar. Specifies properties, methods of sampling and physical testing for factory made masonry mortar, for use in walls, columns and partitions. Different classes of mortars are defined by compressive strength. Compressive strength testing is to be in accordance with EN 1015-11.

EN 1015-11 describes a method for determining the compressive strength of masonry mortars using appropriately prepared and cured samples of size 40mm x 40mm x 80mm. Samples are subjected to loading at an increasing rate between 2 platens as specified in EN 1015-11.

<u>Other Related Tests:</u>

ASTM C109 is an American standard test method for compressive strength of hydraulic cement mortars using cube specimens. Method is similar to that of EN1015-11 with differences in curing procedures, sample sizes and preparation and fixing of platens. These differences may mean that results cannot be directly compared to EN 1015-11.

6.2.2 Concrete

I.S. EN 1992 (Eurocode 2): Design of concrete structures establishes structural design requirements for concrete structures and refers to I.S. EN 12390 for testing of hardened concrete.

I.S.EN 12390: Testing hardened concrete is made up of 8 parts, each dealing with a different aspect of tests for hardened concrete:

Part 1: Shape, dimensions and other requirements of specimens and molds
Part 2: Making and curing specimens for strength tests
Part 3: Compressive strength of test specimens
Part 4: Compressive strength - Specification for testing machines
Part 5: Flexural strength of test specimens
Part 6: Tensile splitting strength of test specimens
Part 7: Density of hardened concrete
Part 8: Depth of penetration of water under pressure

Compressive Strength tests are conducted on specimens sized in accordance with I.S.EN 12390 Part 1, prepared in accordance with I.S. EN 12390-Part 2 using an apparatus as specified in I.S.EN 12390 Part 4, following the procedure outlined in I.S.EN 12390 Part 3.

Tests are carried out on a set number of prescribed specimens which are placed between two platens (steel plates), one fixed and the other adjustable to allow alignment with specimen and fixed platen, the adjustable platen is locked during loading. The specimens are subjected to a gradual application of load at a set rate and the average compressive strength is recorded.

<u>Other Related Tests</u>

ASTM C39 is an American standard test method for compressive strength of cylindrical concrete specimens such as moulded cylinders and drilled cores and consists of applying a compressive axial load to moulded cylinders or cores at a rate which is within a prescribed range until failure occurs.

It is Unknown if ASTM C39 testing is comparable to testing in accordance with I.S. EN 12390.
The test procedure differs to that of EN 771-3, as the specimens are cylindrical and the platens used are circular and have to confirm to a different specification and is for a different scope as it is limited to concrete and is not applicable to masonry blocks

6.2.3 Timber Frame / Infill

Timber Codes and Standards:
For application of hemp lime infill the structural performance is carried by the timber structure with the hemp lime principally performing other functions.

6.2.4 Cellular Foams

ISO 844: 1998 (2004) is a standard for testing the compressive strength and corresponding relative deformation of cellular plastics and specifies a rate of deformation rather than a rate of load increase, and provides for a stated "test result" determined by the nature of the specimen's response. It can also provide the compressive stress at 10 % relative deformation and the compressive modulus of rigid cellular plastics. However it is unknown if there is an EN equivalent for this.

A wide variety of test standards and methods outlined in Table 4.1 have been utilised for testing a range of hemp lime mixes / samples, the results of which are not always comparable, however they do give a general indication of the behaviour of the material under load and assist in describing its general performance.

6.3 Hemp Lime Performance

The collated data on structural performance of hemp lime is quiet varied in the level of detail provided in relation to the basis of testing, with a diversity of testing methods and mixes used, partial descriptions, sub referenced and carried out at in a variety of locations, not always defined as 'accredited test centre's. Given such diversity, care should be taken in use of the data for comparative purposes or establishing generic values and for this reason a range of values and averages has been used in this section, drawn from Table 4.1 to give a general indication of performances, however reference should be made to the table to see the basis of the data and to the actual documents referenced for detail and verification. Table 4.2 outlines the principal testing requirements and the testing information from known hemp lime data.

6.3.1 Timber Frame – Wall Infill.

Structural properties of the hemp lime mix are less critical when employed as wall infill with a timber frame structure and this is the current predominant method of use.

The reviewed literature provided examples of a range of hemp lime wall infill compressive strength with for example between 0.25 and 1.15 MPa being reported by Cerezo, (Cerezo 2005), These are listed in Table 4.1

and are drawn from a range of studies and papers with some tests not described and often based on different mixes and densities, e.g. (Arnaud &Cerezo, 2002, samples and test undefined); (Cerezo, 2005, lab based with electro mechanic press); (de Bruijn et al., 2009 lab based hand compacted cubes and cylinders).Density of the wall mix from the reviewed literature ranged between 256and 990 kg/m3 and averaged around 500 kg/m3.

The compressive strength of the hemp lime wall infill mix was also assessed according to the standard ISO 844:2004 (BRE, 2002), which is a standard employed for rigid cellular plastic and it was chosen as a 'more appropriate' method for assessing a non-loadbearing flexural material. The BRE reported a value of 0.458 N/mm2 for the 'wall mix' and for a more densely compacted 'floor mix' they reported a value of 0.836 N/mm2. The BRE testing is perhaps the most applicable for the application of hemp lime wall infill, as the material in that application is non-loadbearing and the test was claimed to be more appropriate for a flexural material.

6.3.2 Hemp Lime Masonry

The type of test for assessing hemp lime masonry structural properties is not always reported in the literature, however some data is available, which shows a fairly wide range of values.

Studies by Bütschi et al., 2003 using a numerical control hydraulic press on hemp lime cement structural blocks indicate a range of 1.3 - 2.0 N/mm^2 (Bütschi et al., 2003) and in later tests based on EN 772-1 and EN 1052-1, with material density ranging between 510 and 730 kg/m^3 reported compressive strengths of 1.7 - 3.4 N/mm^2 (Bütschi et al., 2004).

Given the typical reported densities involved for hemp lime blocks, typically 500 – 730 kg/m^3, (Bütschi et al., 2003 and 2004), at less than 1500kg/m^{3,} and known strengths of current hemp lime mixtures and blocks its application is most likely suitable for non loadbearing infill walls and partitions, and indeed this is generally where such blocks are being used based on the review of demonstration projects. Applications in load bearing contexts would require evidence of appropriate 'characteristic' values from averaging of appropriate sample tests, which for general construction use above ground would require a definitive minimum compressive strength of 4.7 N/mm^{2}tested specifically under EN 771-3. This would most likely mean higher density blocks and possible use or increased use of strength additives, such as cement. *Note that EN 771-3. 2003 has been superseded with a new version in 2011, which includes as 2010 national annex for Ireland.*

For hemp lime blocks to achieve higher compressive strengths the quantity of hemp hurds is usually reduced in favour of higher quantities of lime, in most cases cement and sometimes sand. However, by doing so, the materials thermal properties are impacted because of the lower insulation properties of lime/cement binders. For higher compressive strengths compaction of the material is also very important and the highest reported compressive strength of 13.5 N/mm^2 has been achieved with a mix of very little hemp, high quantities of sand and cement (Chew & MacDougall, 2007, lab cube and cylinder samples to ASTM C109 and C39 and tested concrete testing machine) with an overall density of the mix in this case of 1837 kg/m^3,

Application in non-domestic complex buildings would be more restrictive, subject to specific applications and loading. However given that many non-domestic buildings would utilise a framed structure, hemp lime masonry may find application in such contexts, given the limited load bearing and non-load bearing situations.

Despite the differences in the method to EN 771-3 and differences in resulting values the study by Chew & MacDougall (2007), albeit on concrete samples as opposed to masonry, indicates that significantly higher compressive strengths are possible with strength additives and this should be an area of further research, which could facilitate wider application of hemp lime masonry.

6.3.3 Hemp Lime Cast In Situ

There is less data and no examples of structural cast in situ hemp lime, other than floor slabs, however with higher cement contents or alternative additives there may be applications where hemp lime cement could be used in cast in situ work.

The study by Chew & MacDougall (2007) using a concrete compression testing machine, with samples based on ASTM C109 for cement mortars using cubic samples and ASTM C39 for cylindrical concrete samples has indicated more significant strengths are achievable, up to 13.58 N/mm^2 based on hemp, cement and sand mixes.

6.3.4 Pre Cast

There are few examples of pre-cast work with hemp lime and load bearing pre cast hemp lime would most likely require additional cement or strength additives subject to load requirements. Non load bearing pre-cast hemp lime panels or cassettes were employed in the UK as wall infill in combination with a structural steel frame for the construction of a 4,000m^2 wine storage facility, by the off-site spray application of hemp lime into 3.6 by 2.4m timber cassettes which were then transported to site and applied to the building structure (Bevan & Woolley, 2008).. However monolithic pre cast units may be feasible given the strengths results reported by the Chew & MacDougall (2007) noted above, but the increased use of cement or other strength additives may impact on the claimed environmental benefits of hemp lime.

6.3.5 Cladding

Given that cladding systems are generally non load bearing, with dead and wind loads being primary issues, hemp lime cladding solutions or alternatives (e.g. hemp magnesium) may be applicable solutions for building cladding, subject to design loads, fixing testing and movement. The reported deformation capacity and flexural aspect of the fibre and composite may be of benefit here and should be an area of further research.

6.4 Knowledge / Data Gaps

A wide variety of testing standards and methods have been utilised in the testing of various hemp lime mixes, which give some indication of its structural performance, however the following knowledge and data gaps have been identified.

a) The current data is based on a wide diversity of binder mixes and density which complicates comparison. A comprehensive matrix of tests examining a range of properties against a range of mix, preparation, application / compaction and densities basis would be very valuable in examining the inter-relationship between these variables.

b) The question of appropriateness of test method, in relation to application is important and is an area that was raised in the technical workshops and by the BRE Haverhill study and needs further investigation. For example is conventional compressive strength testing appropriate for hemp lime mixes in all applications, e.g. wall infill, boarding, cladding etc. or should other test method be used. The interpretation, comparison, use and application of alternative strength tests needs to be examined in more detail.

c) The contribution and benefits of deformation and flexural strength properties of the material should be examined for certain applications notably cladding.

d) There are no known studies into the aging impacts on structural performance.

e) The application of the material in Cast in Situ, Pre Cast and Cladding should be explored.

6.5 Commentary

As noted previously the available data on hemp lime structural properties is principally drawn from experimental research, both academic and product development, and is based on a diversity of binders with variations in materials, mix proportions and with different test methods being used. As such the data is limited in terms of scope and in terms of cross comparison not only with other hemp lime data but also with other standards / tests. However the data does give some indication of its structural performances.

In terms of structural performance of masonry test data was available to EN 772-1 for masonry units and EN 1052-1 for masonry wall samples, (Bütschi et al., 2004) which used a cement additive. The results, ranging from 1.7 to 3.4 N/mm^2, and based on a hemp lime cement mix, indicate potential for structural hemp lime blocks and could form the basis of a further study.

The Chew & MacDougall (2007) study highlights the potential for hemp lime cement mixtures to be applied in structural masonry, cast in situ and pre cast solutions, although the densities would negate against the thermal advantages of lighter blocks and impact on its environmental properties

There was some debate amongst proponents of hemp lime at the workshops as to the best application and method to use the material, with some arguing that its application is best suited to non-load bearing applications, were its environmental properties and thermal function are best utilised, and others who argued for semi structural and structural applications, e.g. load bearing masonry, to facilitate its wider integration to mainstream construction.

A number of papers and discussions at the technical workshops themselves highlighted the principal difficulties and challenges in relation to comparing hemp lime as a material with existing standards and guidance in that hemp lime is an inherently different material and behaves in different ways to the materials that many of the standards were designed to test. This is especially so in the area of structural testing where testing methods designed to test high strength materials, such as concrete, that fail in a particular way, fracture for example, could be considered limited or inadequate in testing materials such as hemp lime which has a high deformation rate and the failure point is not as identifiable.

Material tests carried out by the BRE in the Haverhill hemp lime study were originally intended to be tested to BS 4551 for mortars, but it was reported that such tests were not considered ‘appropriate’ for the samples because ‘they were highly compressible and demonstrated a high degree of recovery’. As an alternative the BRE undertook compressive testing based on BS ISO 844: 1998 for cellular plastics, which specifies a rate of deformation rather than a rate of load increase, and provides for a stated "test result" not based on fracture. In the tests deformation continued beyond 10% with no maximum value of load as would be the case in a conventional compressive test followed by a clear failure.

This suggests the need for new, alternative or combined testing methods derived from an understanding of the materials properties and behaviour and appropriate to its various applications.

Further research and testing is required to examine the material in applications requiring higher strengths and loads and for load bearing cast in situ and precast construction, but based on the indicative data collated, actual solutions may be achievable with strength additives and appropriate design and detailing.

Hemp Lime walls with lime render at ‘The Village’ Cloughjordan, Co Tipperary. Photo BESRaC.

7. Performance – Fire

7.1 Principal Standards and Relevant Requirements

The principal Regulation in relation to performance of materials and construction elements in fire is set out in Part B of the Building Regulations. Technical Guidance Document B provides guidance on compliance with these Requirements and refers to a range of I.S. EN standards and industry codes.. As a construction material hemp lime requirements mostly relate to its fire resistance and spread of flame characteristics, which influence its application in terms of building type, element function, height etc.

Actual fire resistance requirements of building elements are subject to specific element function, room use, building purpose and height. Typical values required are for 30 and 60 minutes classification with some structures and elements requiring 90 and 120 minutes as set out in *Table A1 – Fire Resistances* of the TGD. Fire spread is restricted for internal linings, structure and external surfaces according to building / room purpose, building height, proximity etc.

7.2 Relevant Tests – Requirements, Standards and Methods

7.2.1 Resistance

TGD B outlines two different classifications of performance for materials in relation to resistance to fire, National Classifications and European Classifications the former of which is being phased out in preference to the European classification.

National:
BS 476: Parts 20-24:1987 describe the test methods for determination of the fire resistance of elements of construction on which the national classifications are based with the performance criteria to which each element is required to be tested being, i) resistance to collapse (load bearing capacity), ii) resistance to fire, smoke and hot gases penetration (integrity) and iii) resistance to the transfer of excessive heat (insulation). The results are expressed in the number of minutes that the element sustained resistance for each performance criteria.

European:
European classifications are described in I.S. EN 13501-2 : 2003, Fire classification of construction products and building elements, Part 2 - Classification using data from fire resistance tests (excluding products for use in ventilation systems). Performance criteria in relation to loadbearing capacity, integrity and insulation and

expression of test results are the same as those in BS 476. However they are defined as performance characteristics and are referenced as R – Load bearing capacity, E- Integrity and I - Insulation

The relevant European test methods referenced in I.S. EN 13501-2 : 2003 are

EN 1363-1, Fire resistance tests — Part 1: General requirements.
EN 1363-2, Fire resistance tests — Part 2: Alternative and additional procedures.
EN 1364-1, Fire resistance tests for non-loadbearing elements — Part 1: Walls.
EN 1364-2, Fire resistance tests for non-loadbearing elements — Part 2: Ceilings.
EN 1365-1, Fire resistance tests for loadbearing elements — Part 1: Walls.
EN 1365-4, Fire resistance tests for loadbearing elements — Part 4: Columns.

7.2.2 Reaction

TGD B outlines two different classifications of performance for materials in relation to reaction to fire, National Classifications and European Classifications, the former of which is being phased out in preference to the European classification.

National:
BS 476: parts 6 and 7 describe the tests on which the national classifications are based as follows:

Part 6: Method of test for fire propagation for products "*specifies a method of test, the result being expressed as a fire propagation index, that provides a comparative measure of the contribution to the growth of fire made by an essentially flat material, composite or assembly. It is primarily intended for the assessment of the performance of internal wall and ceiling linings."*

Part 7. Method of test to determine the classification of the surface spread of flame of products "*specifies a method of test for measuring the lateral spread of flame along the surface of a specimen of a product". "The test result is a function of the distance and rate of, the lateral spread of flame; and this is classified according to performance as classes 1 to 4."* Class 0 is not defined/identified by any standard test. Additional requirements to achieve Class 0 are defined in TGD B.

European:
The European classifications are described in I.S. EN 13501-1:2002, Fire classification of construction products and building elements, Part 1- Classification using data from reaction to fire tests. They are based on a combination of the following four European test methods;

I.S. EN ISO 1182: 2002, Reaction to fire tests for building products - Non combustibility test
I.S. EN ISO 1716: 2002, Reaction to fire tests for building products - Determination of the gross calorific value

I.S. EN 13823: 2002, Reaction to fire tests for building products - Building products excluding floorings exposed to the thermal attack by a single burning item and
BS EN ISO 11925-2: 2002, Reaction to fire tests for building products, Part 2 - Ignitability when subjected to direct impingement of flame.

Products are classified as either A1, A2, B, C, D, E or F and each classification requires different combinations of the above test methods to be carried out and criteria required by I.S. EN 13501-1:2002 to be met. For example, to achieve a class A1 both tests described in I.S. EN ISO 1182: 2002 and I.S. EN ISO 1716: 2002 must be undertaken.

7.3 Hemp Lime Performance

Literature on formal fire resistance testing of hemp lime bio-composite is limited to the following three reports, UK and French based, which cover both hemp lime masonry and hemp lime timber frame infill, only one of which was known to be carried out to a comparable standard.

7.3.1 Resistance - Masonry

Lime technology and Chanvribloc manufacturers literature report some results of fire performance of masonry units but no independent test data was available at time of study.

7.3.2 Resistance - Timber Frame Infill

BRE (2009) carried out a fire resistance test on a 3m x 3m Tradical® Hemcrete®, non-rendered or plastered, wall in accordance with BS EN 1365-1:1999. The wall was subject to a vertically imposed load of 135kN and was cast from layers of hemp lime mix, poured into a mould, and included eight vertical timber studs. The internal face of the wall was exposed to the fire and it resisted for 73 minutes in respect to integrity, insulation, and load bearing capacity. This test has formed part of their BBA certificate.

Notably some of the above tests, especially the BRE test, which was to EN 1365-1 were conducted on un-rendered or plastered walls and as such the performance is likely to be enhanced by the addition of a lime plaster or render.

7.3.3 Fire Spread / Reaction – General

There is limited data on spread of flame tests for hemp lime constructions, however some testing has been carried out for the French manufacturer Isochanvre, by the Centre Scientifique et Technique du Bâtiment, (verbal report no. 9233709 and no. RA01-397), which classifies the hemp lime wall mix as M1, improving to M0 with further carbonation of the binder (Isochanvre, 2001). A similar report at the same centre on Isochanvre loose hemp shiv classified this material as M2 which is 'low flammability' (test report no. 97/MPX-L/123/350).

French classification M0 and M1 both refers to 'non flammable materials'.

The Lime Technology BBA certificate notes that fire spread over the external rendered wall when assessed to BS EN 13501-1 in respect of the top coat component achieved a class A1 with less than 1% organic content. In relation to internal fire spread the cert refers to other regulations.

Given the above A1 classification is more likely achievable if rendered with material of limited organic content, whereas renders with organic content are more likely to achieve A2. In either case specific testing is required to assess spread of flame for specific render mixes.

.

7.4 Knowledge / Data Gaps / Further Research

The available data on performance in fire is limited .

The tests are limited to proprietary mixes, some of which may have additives or elements that contribute to fire resistance, including cement additive.

Testing a diversity of blends and proportions could assist in greater understanding of the mixes behaviour in fire in relation to mixes and binders.

In particular developing mixes and densities that achieve higher resistance to fire would be advantageous.

Testing of different construction applications in relation to fire performance would also be of interest, notably masonry testing carried out to EN 1365-1 would be informative.

The role of renders in fire resistance on hemp lime materials and constructions could be examined, in particular to examine how much additional resistance renders can provide.

7.5 Commentary

There is limited data on fire testing and the data tends to be based on proprietary mixes, tested in different jurisdictions and under different test methods. However the data gives some indication of how hemp lime is performing generally and that it has positive fire resistance properties.

Importantly the fire testing carried out to EN 1365-1 on a lightweight wall mix with timber frame infill indicates that 60 minutes fire resistance is possible,. Given that masonry blocks are stronger and denser these may achieve similar or better levels of performance, depending on the performance of the mortar in particular given the finding of the 2007 Lime Technology Study.

The tests and studies indicate that potential application in locations requiring fire resistance of one hour, (and possibly up to 90mins or more with adaptations in specification), which would cover most elemental and building fire rating requirements, however there would be some limitations as situations requiring fire resistance over 60 mins would be restricted in application notably certain structural load bearing elements and high buildings, as per requirements in TGD B table A1 (element of a building) and A2 (building purpose).
Further testing is required to show that hemp lime walls can achieve A1-A2 reaction. The spread of flame is dependent on organic content in renders especially in top coat as this can effect spread of flame test results.

8. Performance – Resistance to Moisture

8.1 Principal Standards and Relevant Requirements

Regulations in relation to moisture (vapour and liquid) from ground, and rain / snow is contained in Part C of the Building Regulations and guidance is given in TGD C. TGD C provides guidance on the application of damp poof membranes / courses and correct detailing at junctions etc on ground floors. In relation to wall elements the requirement is for resistance from ground and external moisture and for appropriate cladding resistance.

8.2 Relevant Tests – Requirements, Standards and Methods

Requirements:

There is no specific measure or test specified in relation to moisture penetration in the Irish TGD, with the stated requirement being for 'reasonable protection'.

Other Tests:

The following are a range of known test for testing moisture penetration through various elements and materials, which would be relevant.

ASTM C1601 - 10 Standard Test Method for Field Determination of Water Penetration of Masonry Wall Surfaces
ASTM E514/E514M - 09 Standard Test Method for Water Penetration and Leakage Through Masonry
BS EN 12390-8:2009 Testing hardened concrete. Depth of penetration of water under pressure
BS 4315-2:1970 Methods of test for resistance to air and water penetration. Permeable walling constructions (water penetration)
BS 1881-208:1996 Testing concrete. Recommendations for the determination of the initial surface absorption of concrete

8.3 Hemp Lime Performance

8.3.1 Ground Floor Slabs:

Appropriately detailed hemp lime ground floor slabs with suitable damp proof membranes or constructions could meet the requirements for moisture protection but strength requirements may require higher cement addition. Some proponents, such as. Ralph Carpenter, have claimed to have successfully detailed and constructed 'breathing floors' using hemp lime floors without use of DPMs.

8.3.2 Walls:

Hemp Lime walls of either masonry or infill are generally finished with a lime based external render and the literature review of hemp lime constructions has indicated no evidence of moisture penetration failures. Importantly historic experience in use of lime renders on stone, clay and earth walls has indicated good moisture resistance and durability.

Tests for water penetration were carried out by the BRE for the Haverhill project on plastered hemp lime 200mm thick test walls. A rotary spray apparatus was employed to apply water levels similar to one years of wind driven rain at a severely exposed location or five years elsewhere, over a 96 hours period, after which the absorption had reached an average 50-70mm depth. The water spray test was not part of any British Standard test method; it was originally tested to supplement results gained from testing water repellents by methods specified in BS 6477:1992 - Water repellents for masonry surfaces. However the test simulates a severe exposure and massive water application over a short period with positive results.

8.4 Knowledge / Data Gaps / Further Research

There is little measurable data on hemp lime moisture resistance, other than the BRE study, and further research in this area would be beneficial.

Assessment of moisture penetration for different mixes and the influence of renders would be valuable.
The range of moisture tests reported above or adaptations of same could form the basis for testing in this area.

8.5 Commentary

While there is little measurable data on the moisture resistance of hemp lime its application in practice, the BRE test and the historic evidence of lime renders indicates that appropriately rendered and detailed hemp lime constructions using certified materials should be able to provide reasonable resistance to moisture.

Feedback from practitioners at the workshop identified other key issues in the construction period that needs careful attention in order to ensure the successful application of the material and avoid moisture failures, notably the moisture level of the hemp lime mix itself and the weather context of application.

Hemp lime needs an appropriate level of moisture to be applied and set. Too much moisture can cause delay in drying out of the walls and as such delay occupancy, especially given that the drying process is slow in normal case. This has impacts on the application of plasters and renders which should also be avoided in frost seasons due to the risk of frost damage.

The development of a specific code / standard with detailing and construction / application guidance is important for the correct application of the material in construction.

Hemp Lime wall at cottage by Tom Woolley

9. Performance – Acoustics

9.2 Relevant Tests – Requirements, Standards and Methods

Requirements:

No test requirements or values are set out in the TGD, however the Irish TGD references the following tests for ‘similar’ constructions.
At the time of writing this report Part E of the Building Regulations was being revised.

IS EN ISO 140-4: 1998 Acoustics. Measurement of sound insulation in buildings and of building elements. Field measurements of airborne sound insulation between rooms supersedes BS 2750, Part 4: 1980 (1993) Field measurements of airborne sound insulation between rooms, and IS EN ISO 140-7:1998 Acoustics. Measurement of sound insulation in buildings and of building elements. Field measurements of impact sound insulation of floors supersedes BS 2750,Part 7: 1980 (1993) Field measurements of impact sound insulation of floors, from which can be determined the Standardised Level Differences (DnT) for airborne sound transmission and Standardised Impact Sound Pressure Levels (L'nT) for impact sound transmission.

I.S. EN ISO 717-1 Acoustics –Rating of sound insulation in buildings and of building elements – Part 1: Airborne sound insulation supersedes BS 5821: Part 1: 1984 (1993) Method for rating the airborne sound insulation in buildings and of building elements, and I.S. EN ISO 717-2 Acoustics –Rating of sound insulation in buildings and of building elements – Part 7: Impact sound insulation supersedes BS 5821: Part 2: 1984 (1993) Methods for rating the impact sound insulation also forms part of this test programme and defines how the Weighted Standardised Level Difference (DnT,w) for airborne sound and the Weighted Standardised Sound Pressure Level (L'nT,w) for impact sound are calculated.

Other Tests:

UK Building regulations approved document E requires testing to be carried for sound insulation with some exceptions and establishes performance standards. The testing required is outlined in Annex B: Procedures for sound insulating testing of the above mentioned document. It states that the sound insulating testing must be carried out in accordance with the following standards:

Tests Requires under UK Approved Doc E, BR 1991, 1992 edition,

Field Tests
BS 2750 Part 4 1980 for airborne sound insulation of a separating wall or floor

BS 2750 Part 7 1980 for impact sound transmission of a separating floor

Laboratory Tests
BS 2750 Part 3 1980 for airborne sound insulation of a separating wall and floors
BS 2750 Part 6 1980 for impact sound transmission of a separating floor

Note:
BS 2750 series was replaced by or renamed under the BS EN ISO 140 series. In Particular the BS 2750:Part 4:1980 was replaced by BS EN ISO 140-4:1998,and BS 2750:Part 7:1980 was replaced by BS EN ISO 140-7:1998,

Tests Requirements under UK Approved Doc E, BR 2000, 2003 edition, incorporating 2004 amendments
BS EN ISO140 Part 4 1998 Field measurements for airborne sound insulation of a separating wall or floor
BS EN ISO140 Part 7 1998 Field measurements for impact sound transmission of a separating floor
BS EN ISO 140-3:1995 Laboratory measurement of airborne sound insulation of building elements

9.3 Hemp Lime Performance

9.3.1 Densities / Mass

Hemp lime construction is less dense than masonry with typical densities of 300-450 kg/m^3 for hand tamped wall infill and even lower densities when the mix is spray applied (Bevan & Woolley, 2008). Typical densities of hemp lime masonry depends on whether blocks are for structural or thermal property functions. Thermal blocks densities range between 300 and 500 kg/m^3 (Chanvribloc, 2010; Lime Technology, 2009a) while structural blocks between 600 and 1200 kg/m^3 (Lime Technology, 2009b; Bütschi et al., 2003; Bütschi et al., 2004), as such hemp lime construction would generally not be of equivalent density as concrete.

9.3.2 Tested Values

There is limited data on tested acoustic values of hemp lime materials however the following results indicate possible performances.

In-situ acoustic performance tests were carried out at Haverhill (BRE, 2002) in a timber frame house with hemp lime infill walls and a traditional brick and block house. The hemp lime separating walls were two 150mm thick wall leaves with a 100mm stud and a 75mm cavity between. The other two rooms were separated by 100mm blocks either side with a 100mm cavity. Test were carried out in accordance with BS EN ISO 140: Part 4 (1998). Results showed a sound reduction of 57 and 58 dB on the tested hemp lime walls against a 63 and 64 dB sound reduction for the masonry walls, however the hemp lime walls still complied with the minimal requirements in the then current 1991 UK regulations, which was a 53 dB average for separating walls. Due to differences in adjustment factors it is not possible to directly compare these results to Irish requirements. Note: IS 140 replaced BS 2750 referenced in the Irish TGD.

Acoustic tests were also undertaken in a study that looked at the properties of structural hemp lime blocks (Bütschi et al., 2004). In this case sound reduction, which was tested in accordance with the standard ISO 140/III, ranged between 43 and 47 dB with a material density ranging from 630 to 730 kg/m3.

9.4 Knowledge / Data Gaps / Further Research

There is limited data in relation to testing of hemp lime constructions for acoustics properties. Further research in the area of both i) the materials acoustic properties in relation to binders, mixes, compaction, application etc and for ii) different construction solutions and detailing would be beneficial.

9.5 Commentary

Hemp lime construction is typically less dense than masonry or concrete and as such party walls may require further specification adaptation. The solution provided at Haverhill shows that hemp lime construction has the capability of achieving then current UK compliance values, however this is unlikely to be due to mass alone and issues such as material properties, continuity of material, detailing, junctions, cavity etc. would have influenced the result.

Equivalent Mass

In order for hemp lime to achieve equivalent mass values as those required for concrete block and clay brick party walls, both the thickness of walls and the density of the material will need to be considered.

For example a lime hemp infill solid wall with a density within the typical range of 300 - 450 kg/m^3 would require a thickness of more than 700mm to achieve an equivalent mass. A wall of 300mm thickness would require a density of 1200 kg/m^3 for an equivalent mass to clay brick walls and approx 1400 kg/m^3 for an equivalent mass to concrete block walls. Hemp lime block can have higher densities than hemp lime infill, up to 1200 kg/m^3 however the thickness of a wall has practical limitations. A wall with block density of 1200 kg/m^3 would require a thickness of 300mm for an equivalent mass to clay brick walls. This may require the manufacture of non typical blocks. Higher densities of blocks are also achievable, however this may require the introduction of cements or other additives into the mix.

Given the above, solutions are more likely to focus on performance and not equivalent mass, however improved mass would assist in achieving performance.

Equivalent Performance

As the mass of hemp lime is effected not only by the mix proportions and resulting material density but also the manufacture process or site application / compaction, the acoustic properties can be improved were required, including acoustic improvement from detailing and construction methods.

Optimal solutions are likely to lie in a combination of improved mass and construction approaches, (twin leaf etc). with appropriate mass being derived from a balance of denser mixes, greater compaction and thickness. For separating floors hemp lime infill or screeds are likely to improve acoustic properties.

To prove equivalence the use of hemp in a separating wall would need to be tested as part of a certified system.

Hemp Lime wall infill in timber frame / shuttering: Photo Tom Woolley

Hemp Lime wall infill in timber frame after striking of shuttering: Photo BESRaC

10. Performance – Energy

10.1 Principal Standards and Relevant Requirements

Part L of the Building Regulations deals with the Conservation of Fuel and Energy. Guidance and targets for the energy performance of buildings in terms of limiting fabric heat loss, heating and systems efficiency are set out in TGD L which include limits in relation to consumption of primary energy and resulting carbon emissions.

Principal relevant requirements are maximum allowable "U" Values for different construction elements, control of air permeability through construction elements, control of thermal leakage at construction junctions with guidance in relation to limitation of condensation / mould and limits on internal surface temperatures. In addition the mass of a material would also have some impacts on total energy and carbon use compliance within the DEAP calculation method and as such on overall requirements.

10.2 Relevant Tests – Requirements, Standards and Methods

Requirements:

Most of the requirements are not material based but are related to overall construction elements and assessment methods e.g. U Values, Linear Thermal Bridging, Thermal Mass in DEAP etc. However a key material property that would influence the thermal performance and its impact in the assessments methods is Thermal Conductivity.

TGD L refers to 2 standards in relation to the determination of thermal conductivity for homogeneous materials, 'IS EN ISO 10456:2007 Building materials and products -Hygrothermal properties -Tabulated design values and procedures for determining declared and design thermal values' and 'IS EN ISO 8990:1997 Thermal insulation. Determination of steady-state thermal transmission properties. Calibrated and guarded hot box'.

IS EN ISO 10456 refers to 3 test methods, IS EN ISO 8990, as mentioned above, 'ISO 8302:1991 Thermal insulation - Determination of steady-state thermal resistance and related properties - Guarded hot plate apparatus' and 'ISO 8301:1991 Thermal insulation -Determination of steady-state thermal resistance and related properties -Heat flow meter apparatus'.

Other Known Tests:
DIN 52616

10.3 Hemp Lime Performance

10.3.1 U Values / Thermal Conductivity

Thermal conductivity values found in literature display some differences, notably the different mix proportions, moisture content and type of compaction/application all of which have impact on density and conductivity. A further reason is the possible variation in methods used for measuring thermal conductivity, the most common method employed in the reviewed literature being the heat box and hot plate, however what standard these were carried out to was not always known.

A number of the referenced research papers (Evrard, 2006. Evrard, 2008. Cerezo, 2005. Bütschi et al., 2004. Elfordy et al., 2007.) describe/refer to hot box methods and heat plate methods used during research however none are referenced to the standards mentioned above and the descriptions provided are not directly comparable to the test methods described in IS EN ISO 8990, ISO 8302:1991 and ISO 8301:1991.

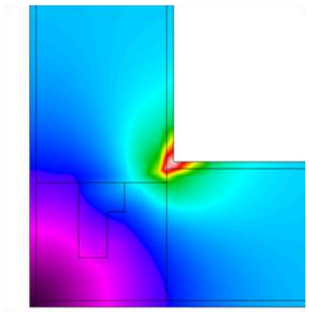
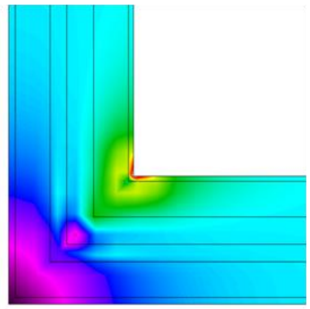
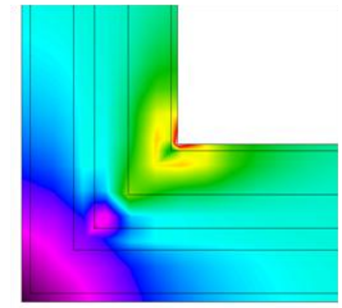
Thermal conductivity values across a range of studies on hemp lime wall infill listed in Table 4.1 vary between 0.06 and 0.13 W/(m•K) depending on the density and composition of the mix. Work by Cerezo reports values of 0.06 to 1.0 W/(m•K) for low density mixes of 200 kg/m3 and 0.1 to 0.13 W/(m•K) for medium density mixes of 450 kg/m3, (Cerezo, 2005). Thermal conductivity values for hemp lime masonry are generally influenced by whether blocks have thermal or structural purposes, and their overall mix and compaction methods. For example results from studies on hemp lime cement block samples, that were machine vibrated and compacted, record a value of 0.34W/(m•K), (Bütschi et al., 2004) while hemp lime block samples from a different study that were spray applied reported values ranging from 0.179 to 0.543 W/(m•K), (Elfordy et al., 2007).

Example U Values of various constructions and mixes from the studies listed in Table 4.1 include 0.89 W/(m2•K) for a 300mm thick wall (Bütschi et al., 2004) compared to 0.37 W/(m2•K) for a 300mm thick wall and 0.23 W/(m2•K) for a 500mm thick wall (BBA, 2010), Calculated in accordance with BS EN ISO 6946 : 2007 and BRE report (BR 443 : 2006).

10.3.2 Thermal Bridging

Hemp Lime thermal conductivity values are generally superior to concrete and subject to detailing can have additional benefits in terms of reduced thermal transmission at junctions, which reduces overall heat loss.

Figure 10.1 – Thermal bridging comparison: Hemp infill and block wall vs. Concrete block wall

		
Hemp Lime Infill Wall, Plan of Corner Junction. Ψ = 0.065 W/m	Hemp Lime Block Cavity Wall, Plan of Corner Junction. Ψ = 0.083 W/m	Concrete Block Cavity Wall, Plan of Corner Junction. Ψ = 0.088 W/m

Source: BESRaC, 2010 Linear Thermal Transmittance Modelling using Therm 5.2

Figure 10.1 above compares a typical external corner junction of a traditional concrete cavity wall construction with a hemp lime block cavity wall and a hemp lime infill wall with structural timber frame.

The exercise shows that the hemp lime infill junction has the lowest Psi value of 0.065 giving a 26% reduction in heat loss through the junction when compared to the concrete block junction. Using a hemp lime block in place of the concrete block will give a 5.7% reduction in heat loss through the junction.

10.3.3 Surface Temperatures

The minimum surface temperatures calculated for the three junctions in Figure 14.1 are all around 18.°C which would meet the criteria set out in Information Paper 1/06 (Ward, 2006) for min surface temperatures and avoidance of condensation or mould.

10.3.4 Air-permeability

In terms of wall infill hemp lime as a homogeneous material can assist in reduction of air leakage or infiltration. With the addition of wet renders and plasters this can make for a very airtight construction, which would also hold true for hemp lime masonry. An air tightness test was carried out on a timber frame construction with hemp lime wall infill as part of the Serve project (2010) at Cloughjordan eco-village in Co. Tipperary. Test results showed an excellent air tightness level of 1.12 $m^3(m^2.h)$@50PA..

Improved air-tightness may also have been a possible factor in the performance of the Haverhill hemp lime houses compared to the masonry built units, but this was not measured.

10.3.5 Thermal Mass – DEAP (Dwelling Energy Assessment Procedure)

A calculation under DEAP was undertaken by BESRaC to give an indication of the impact of thermal mass of hemp lime on compliance with overall energy or carbon emission levels for dwellings.

Based on DEAP the classification would define hemp lime as a thermally massive construction, or using EN ISO 13786: 1999, the internal area heat capacity of hemp lime based on typical conductivity of 0.11 W/mK would tend toward thermally light.

10.3.6 In-Situ Performance – U Values

Dr. Brian Pilkington BSc(hons) MCIOB MBEng Lecturer in Energy and Sustainability in the Built Environment at the University of Plymouth conducted field test measurements of the thermal conductivity of a 200mm thick hemp lime wall with a density of 463kg/m^3,using a thermal probe, (test method unknown). This study showed that the thermal conductivity of this wall was in the region of 0.072 W/mK to 0.099 W/mK (Pilkington, 2006).

This compares to a reported thermal conductivity of 0.1 W/mK for a hemp lime wall with density of 450kg/m^3, when tested using a hot box in lab conditions (Cerezo, 2005), which was based on the nearest similar density and mix.

10.3.7 Dynamic Thermal Properties

Importantly U values and associated steady state heat loss are limited in terms of accurately modelling actual heat flows in buildings which are dynamic, and studies have shown important thermal storage and release characteristics in hemp lime, which could provide additional thermal performance.

Simulation carried out using WUFI software shows that a 250mm thick hemp lime wall subject to sudden cooling of 20°C takes 72 hours to reach a steady state of heat transfer compared to 30 hours in cellular concrete and 12 hours in mineral wool of the same thickness. The energy lost from hemp lime in the first 24 hours is 187KJ/m^2, which equates to an average heat loss of 0.11 W/[m^2·K] despite the fact the theoretical U-value for this thickness of hemp lime is 0.29 W/[m^2·K] (Evrard& De Herde, 2005). This is evidence of how dynamic thermal performance can be different from predictions based on steady state figures / U values.

The same simulation provides evidence of the ability of hemp lime to almost completely (98.5%) dampen a sinusoidal change in external temperature of 20°C to 0°C over a 24 hour cycle with a time shift of 15 hours, the time delay of the peak temperature getting through the wall. This compares to a dampening of 77.5% for mineral wool with a time shift of only 6 hours and with a dampening of 95% for cellular concrete with a time delay of 10.5 hours (Evrard& De Herde, 2005).

Similar conclusions are reached in another study when hemp lime is compared to baked clay bricks and cellular concrete. Materials are submitted to various conditions of temperature and relative humidity. Hemp lime is characterised by lower temperature variation and it reaches a steady state after each modification as opposite to the other two materials where temperature continues to increase or decrease in the core of the wall. In terms of relative humidity, hemp lime shows important variations (around 15%) compared to other materials for which evolution of RH is rather constant (Arnaud, 2009).

In situ monitoring of Lime Technology offices built with 500mm hemp lime infill walls parallels simulations mentioned above by showing that variations of external temperature and relative humidity result in constant values inside the building (Lime Technology, 2008a). Hemp lime dynamic thermal properties have been exploited in the construction of a 4400m^2 wine and beer distribution centre in Suffolk, UK. The building has the ability to maintain an internal temperature at between 11 and 13°C without the need for mechanical cooling or heating systems (Lime Technology, 2008a).

10.4 Knowledge / Data Gaps / Further Research

There is a diversity of data and studies into the thermal properties of hemp lime and its impacts on energy use, which indicate important thermal performances not all of which are adequately reflected in steady state based analysis such as U Values.

Further research into the dynamic thermal transmittance of hemp lime and its implications in energy efficiency of buildings would be invaluable. These could be carried out by dynamic simulation, cell models and actual buildings.

The potential benefits and possible facilitation of achieving improved air permeability levels via a homogeneous material such as hemp lime should also be assessed.

10.5 Commentary

The collated literature indicates that hemp lime in construction can have important thermal properties and if appropriately specified and constructed can meet the principal standards in terms of fabric insulation, thermal bridging and air tightness with positive impacts on energy consumption and carbon emissions.

Importantly there is evidence that certain hemp lime material and thermal properties are providing additional energy and carbon improvements not adequately accounted for in steady state methods, notably its low embodied energy, embodied carbon, carbon sequestration and its thermal storage capacity, which are summarised as follows.

U Values / Thermal Conductivity

Low density mixes and applications can achieve better than concrete masonry lambda values and improved U Values, and reduce thermal bridging, which assist in achieving compliance.

Air Permeability

The monolithic nature of lime hemp construction with rendered finishes can promote air tightness and reported measurements indicate excellent possible results in excess of minimum requirements

Thermal Mass

Thermal mass properties of hemp lime may not be fully reflected in the DEAP methodology and importantly U value and steady state heat loss assessments do not reflect dynamic thermal mass behaviour and advantages. The studies collated indicated significant thermal impacts as a result of the materials thermal mass properties.

Hemp Walled House being rendered, Cloughjordan, Co Tipperary: Photo BESRaC.

11. Performance - Materials and Workmanship

11.1 Principal Standards and Relevant Requirements

Part D of the Building Regulations sets out requirements for materials and workmanship in construction with ‘proper materials’ meaning fit for intended use and conditions to be used in. Guidance is provided in TGD D on a number of alternative product standards, certifications and approvals, both at National and European level.

Materials are required to be of a suitable nature and quality, adequately prepared and applied or fixed so as to perform for intended purpose. Proper workmanship and appropriate use of materials is also required and may be specified in some certifications or standards.

11.2 Relevant Standards

The primary route for establishing the fitness of materials is through the following recognised standardisation procedures.

a) bear a CE Marking in accord with (Construction Products Directive); or
b) Comply with an appropriate standard, i) European Technical Approval or ii) National Technical Specification, as defined in (Construction Products Directive); or
c) Comply with Irish Standard, or Irish Agrément Board Certificate, or Alternative National Technical Specification of AEEA area. NSAI may be consulted in relation to ‘equivalence’ to Irish Standard.

In addition to the above the following methods may also be considered in establishing fitness.
a) Independent certification by an approved body e.g. NSAI (National Standards Authority of Ireland);
b) Tests / Calculations carried out by ‘Accredited Laboratory’, (NSAI – ensure tests carried out to recognised criteria);
c) Performance in use - experience

11.3 Hemp Lime Performance

There are no known European or National Standards in relation to hemp lime as a bio-composite construction material, nor are there any known products with CE markings, or ETA’s.

However recently Lime Technology in the UK has received a BBA certificate for its hemp lime wall system (hemp lime mix cast around a structural timber frame, water and a lime-based render finish), which is an important development as it means that a particular hemp lime product has had compliance with UK building regulations validated by an approved third party.

There is also the growing body of data and demonstrated application of hemp lime, as outlined in this study, which although limited and diverse gives some general indication of the potential performances of hemp lime as a material and in a range of applications.

11.4 Issues

A number of specific issues that relate to workmanship came to the fore during this study, most notably related to moisture content and its impacts on drying time / setting. There is an apparent competition for water between the hemp and the lime with behaviour effected by binder blend, timing of water application and method of construction application. Delays in setting have been reported and frost attacks on hemp based renders have also been reported. Given apparent risks here the behaviour of the particular material during mixing and in application needs to be understood more in terms of moisture and training in workmanship should be encouraged in order to reduce any risk due to prolonged setting times and possible surface frost damage. Seasonal application of the material was discussed and advised by promoters and experienced users of the material during technical consultation and application in frost risk periods was recommended to be avoided.

11.5 Knowledge / Data Gaps / Further Research

The available data on hemp lime as a building material is based on a diverse range of studies and reports with various objectives and methods and from various legislative contexts. The data presents supportive information on the performances of a range of hemp lime materials and construction methods but with limitations.

A comprehensive range of testing is required for the material, either generically or product based, for its various proposed construction applications to enhance the current data. Many of these areas of study have been outlined in the previous performances chapters.

Examination of its specific behaviour in the Irish climatic context would be beneficial.

Examination of Workmanship issues and risks would be important, including issues such as application impacts on thermal conductivity and other performances. The development of a workmanship guide would be beneficial.

11.6 Commentary

The absence of specific standards or codes in relation to the material or its specific construction applications, and the absence of certification of materials and products is limiting the use of hemp lime material i.e. materials must comply with Part D if it is to be used in buildings. Therefore product certification for the application of hemp lime in Irish construction is required to move from an 'early adopters' stage to mainstream deployment.

Certification

A particular manufacturer, or group of manufacturers, could obtain certification (certification may include a European Technical Approval, and Agrément Certificate or equivalent from a suitable 3rd party), demonstrating that the product is fit for purpose for which it is intended, the conditions in which it is to be used and meets the requirements of the Irish Building Regulations.

Irish Standard

This approach normally applies where there is extensive experience of a product in use over a long period of time, and would involve the development of a standard or range of standards by an Irish Technical Committee under NSAI Standards Section, for the specification and application of Hemp Lime solutions in Irish Construction. The establishment of some form of representative industry organisation, to initiate this process, would be an advantage and such a process could facilitate multiple manufacturers and contractors to emerge. Although not a directly comparable technology a case example is the development of an Irish standard for timber frame manufacturing in Ireland (I.S. 440, 2009), albeit this was a more established construction method and material. The diversity of material possibilities and construction applications currently being pioneered for hemp lime could complicate such a process and may mean that some simplification or limitation of scope is needed, for example either a single standard is developed for a limited product or range or that a suite of standards are developed for various mixes and construction solutions.

12. Conclusion and Recommendations

12.1 Conclusions

The use of hemp lime as a construction material is Ireland is increasing, albeit limited to small scale domestic projects. The recent application of hemp lime infill in timber frame walls in a social housing project in the North of the country is a welcome development and provides an important medium scale example of an application meeting building control standards in that jurisdiction.

This study has highlighted the important environmental benefits of hemp lime, and while there remains some variance in methods for calculating of carbon sequestration there are clearly CO_2 reduction benefits from use of the material in addition to other positive environmental benefits.

The thermal performance of the material has been one of the key focus areas of research to date, with important potential energy benefits that are not currently reflected in U Value or Steady State energy assessment methods.

A core focus of this study was the collation and comparison of key material properties and performance testing from the available literature with the performance requirements and testing within relevant standards and guidance in the Irish context. While this identified the growing volume of research and data, it also highlighted some limitations in the application of data in terms of i) cross comparison of data due to differences in purpose, binders, mixes, application and testing, ii) in terms of comparison of this data to known standards and requirements in particular in terms of comparison of testing methods and quality, and iii) challenges and limitations in comparing hemp lime performance to current construction standards were also found due to the fact that many of these standards were developed to assess the behaviour of materials that behave in very different ways to hemp lime. Thus current testing methods may be considered inappropriate or limited in relation to testing hemp lime and its applications.

Based on the general study into hemp lime and the core study of performances this report identifies the following areas of possible research activity.

12.2 Further Research

While there is a growing body of publicly available research on hemp lime bio-composite and emerging applications, there is still a need for knowledge and information to support both the development of a hemp industry in general and more specifically the application of hemp in construction, including hemp lime.

While research needs are broad and include technical, environmental, market and economic factors, this study has highlighted a number of gaps in the publicly available literature on hemp lime, and, most notably in the technical literature with limitations on cross comparison of data specifically, in the Irish context, together with, limitations in the comparison of the available data with certain standards and tests, principally due to the diversity of material mixes and binders and the variations in testing undertaken on same.

12.2.1 Hemp Industry

The development of a hemp industry in Ireland is a key factor in the development of hemp as a construction material and recommended areas of research to facilitate the hemp industry in general includes studies into the economic potential of a hemp industry in Ireland as well as the exploration of potential markets. The development of appropriate processing facilities is also an essential and to date missing component of a hemp industry and research into processing solutions, particularly in terms of scale, catchment, technical and economic viability etc. would be beneficial.

12.2.2 Hemp Lime Mixes and Binders

Current available data is based on a diverse range of hemp lime mixes and binders, which complicates cross comparison of data and test results. It would be helpful if research were undertaken which i) determined a limited or most applicable core range of standard mixes and binders that could form the basis of further testing on key material properties. This type of data could support the development of generic mixes or binders and assist in the development of cross comparable data and material properties.

It is also recommended that the limited availability of Irish hydraulic lime be examined in terms of carbon impacts to the material and the potential to manufacture and supply Irish hydraulic lime.

Investigating and understanding issues surrounding the competition for water in the bio-composite, principally during mixing and setting, and solutions to control and improve setting times are also recommended areas for further research.

12.2.3 Hemp Lime Mechanical properties

Noting the above, a key recommendation is for co-ordination of research so that cross comparable data is produced, which would require co-ordinated testing on a particular or more limited bio-composite mix range.

Specific recommended areas of study into mechanical properties are;

- Finding optimal strength mixes for various construction applications, while limiting cement based binders due to environmental impacts.
- Investigating alternative testing approaches and methods to establish mechanical properties of hemp lime based on its more flexural properties and gradual deformation, as opposed to failure patterns typical of material like cement and concrete testing.
- Exploring, examining and testing the material's key mechanical properties for potential application in other construction methods such as cast in situ, pre cast panels and in particular lightweight cladding systems. In addition to issues of strength, flexural properties may be advantageous in some circumstances and need to be understood and assessed as well as issues such as shear for anchoring etc.
- Establishing the aging impacts on structural performance

12.2.4 Hemp Lime Thermal properties

The thermal performance of hemp lime has been a key area of research focus to date and there are a range of detailed studies of its performance. This report suggests research areas in the field are

i) Variation of thermal conductivity values for in-situ infill methods, which needs to address the potential variation in density due to on site tamping or spray application

ii) The dynamic thermal performance of hemp lime should be further explored, in terms of its base properties and also in terms of specific behaviour and impacts in different building use types and contexts.

iii) Air permeability benefits or performance of the material and construction should also be further explored and defined.

12.2.5 Hemp Lime Acoustic properties

Acoustic properties and the performance of the material and various constructions needs to further explored and defined, including the testing of various hemp lime mixes for acoustic properties as well as developing optimal sound reduction performances through specification and construction detailing.

12.2.5 Hemp Lime Fire properties

There is limited publicly available data and testing in this area, perhaps due costs of tests, and what testing has been undertaken is based on various test methods and standards, not all directly comparable.

Based on a core generic range of mixes and binders being developed, it would be beneficial to have analysis of the core composites behaviour in fire, and to their performance in various construction applications and uses.

Solutions for improving fire resistance to 90 and 120 minutes threshold would be a welcome area of investigation and especially the role of renders in fire performance should be defined.

12.3 General Recommendations

The establishment of hemp lime as a construction material needs to happen in the context of an overall development of a hemp growing and processing industry in Ireland. Hemp as an industrial crop has a diverse range of applications and has important potential benefits as an alternative crop for the agricultural sector and as such should be given strategic support.

Promoter body or group

There is a need for an industry representative organisation to promote and support the development of hemp lime as a building material in Ireland. This could be a stand alone body or a sub-group of a wider body, for example a renewable materials or ecological construction organisation, or a sub group of an existing organisation. Such an organisation could initiate dialogue, provide education and training and promote good practice.

Product Certification

Certification of proprietary Irish supplied hemp lime bio-composites will demonstrate fitness for purpose of the systems and facilitate use of the material in the Irish construction industry. Note: certification may include a European Technical Approval and Agrément Certificate or equivalent from a suitable 3rd party and which would demonstrate that the product is fit for the purpose for which it is intended, the conditions in which it is to be used and meets the requirements of the Irish Building Regulation.

Development of a code or standard

The drafting of a guide or code for hemp lime material and or construction applications will provide useful information to industry on the appropriate use of hemp lime products. The work undertaken in this study, and indeed the professional network formed around the consultation process, could provide a core of data and specialists with experience and knowledge of the material to input into the drafting a guidance document. The development of a standard or code would require a more sophisticated multi disciplinary committee and would require significant supportive research and testing to be done in support of same This approach normally applies where there is extensive experience of a product in use over a long period of time.

Pilot and Demonstration Projects

The authors believe that it would be of significant impact if a flagship project or projects, which demonstrated significant application of hemp lime construction in Ireland, provided a context for research and analysis, raising the profile of the material via case study, industry visits etc.

Education and Training

It would be of assistance if training and educational initiatives across the industry, concerning hemp lime, which could include material properties and material behaviour, specification, construction application, workmanship, etc. were available

Acronyms and Annotations

BBA – British Board of Agrément

BRE – Building Research Establishment (UK)

BS – British Standard

CE – Communauté Européenne

CEN – Comité Européen de Normalisation

CENELEC – Comité Européen de Normalisation Électrotechnique

CITA– Construction Industry Training Association

CO_2– Carbon Dioxide

CPD – Construction Products Directive

CPD – Continuing Professional Development

dB – decibel

DEAP – Dwelling Energy Assessment Procedure

DoEHLG – Department of Environment, Heritage & Local Government

DPM – Damp Proof Membrane

DPC – Damp Proof Course

EN – EuropeanNorm

EPA – Environmental Protection Agency

EPS – Expanded Polystyrene

EOTA – European Organisation for Technical Approval

ETA – European Technical Approval

ETAGs – European Technical Approval Guidelines

EU – European Union

GRESPI – Groupe de Recherche en Sciences Pour l'Ingénieur (France)

IAC – Irish Agrément Certificate

INRA – Institut National de la Recherche Agronomique (France)

IS – Irish Standard

ISO – International Standards Organisation

$kg/(m^2\sqrt{s})$– Kilogram per square metre second square root

kg/m^2– Kilogram per square metre

kg/m^3– Kilogram per cubic metre

kJ/m^2– Kilo Joule per square metre

kN – Kilo Newton

LCA – Life Cycle Assessment

m – Metre

m^2– Square metre

m^3– Cubic metre

$m^3/(m^2.h)$ – Cubic metre per square metre hour

MJ/kg– Mega Joule per kilogram

N/mm^2– Newton per square millimetre

NSAI – National Standards Authority Ireland

NTS – National Technical Specification

OSB – Oriented Strand Board

RH – Relative Humidity

RIAI – Royal Institute of Architects of Ireland

SEAI – Sustainable Energy Authority of Ireland

TGD – Technical Guidance Document

THC – Delta 9-tetrahydrocannabinol

UK – United Kingdom

W/(m·K) – Watt per metre Kelvin

W/(m^2·K) – Watt per square metre Kelvin

WISE – Wales Institute for Sustainable Education

WUFI– Wärme und Feuchte instationär

References

ADAS, 2005, *UK Flax and Hemp production: The impact of changes in support measures on the competitiveness and future potential of UK fibre production and industrial use*, Report prepared by ADAS (Centre for Sustainable Crop Management) on behalf of the UK Department for Environment, Food and Rural Affairs, Boxworth, Cambridge, UK. Retrieved January 17, 2010 from http://www.defra.gov.uk/foodfarm/growing/crops/industrial/pdf/flaxhemp-report.pdf

Allin, S 2005, *Building with Hemp*, Seed Press, Rusheens, Kenmare, Co. Kerry, Ireland.

Arnaud L, Cerezo V, 2002, *Mechanical, thermal and acoustical properties of concrete containing vegetable particles*, Proceedings of the ACI 5th International Conference on Innovations in Design with Emphasis on Seismic, Wind and Environmental Loading: Quality Control and Innovations in Materials,Hot-weather Concreting, Cancun, Mexico.

Arnaud L, Samri D, 2005, *Hygrothermal behaviour of porous building materials*, Proceedings of the Third International Biot Conference, Oklahoma City, USA.

Arnaud L, 2009, *Comparative study of hygro thermal performances of building materials*, Proceedings of the 11th International Conference on Non-conventional Materials and Technologies (NOCMAT 2009), Bath, UK

Berge, B 2000, *The Ecology of Building Materials*, Architectural Press, Oxford

Bevan R & Woolley T, 2008, *Hemp lime construction. A guide to building with hemp lime composites*, IHS BRE Press, Bracknell, Berkshire, UK.

Bevan R & Woolley T, 2009, *Constructing a low energy house from hempcrete and other natural materials,* Proceedings of the 11th International Conference on Non-conventional Materials and Technologies (NOCMAT 2009), Bath, UK

Bocsa, I &Karus, M 1998, *The Cultivation of Hemp: Botany, Varieties, Cultivation and harvesting*, Hemptech, Sebastopol, CA, USA.

Building Research Establishment Ltd (BRE) 2009, Fire resistance test in accordance with BS EN 1365-1:1999 on a Lime Technology Ltd, 3m x 3m TradicalHemcrete loaded wall, Test Report Number 250990, England, UK.

British Board of Agrément, *Agrément Certificate 10/4726 – Lhoist Wall System, TradicalHemcrete Wall System*, Garston, Watford Herst, UK.

Building Research Establishment Ltd (BRE), 2000, *DETR Framework Project Report : Field investigations of the thermal performance of construction elements as built*, Glasgow: BRE

Building Research Establishment Ltd (BRE) 2002, *Final Report on the Construction of the Hemp Houses at Haverhill, Suffolk*, Client Report Number 209-717 Rev.1, England, UK. Retrieved January 17, 2009 from http://projects.bre.co.uk/hemphomes/HempHousesatHaverhillfinal.pdf

Building Research Establishment Ltd (BRE) 2003, *Thermographic Inspection of the Masonry and Hemp Houses at Haverhill, Soffolk,* Client Report Number 212020, England, UK. Retrieved January 17, 2010 from http://projects.bre.co.uk/hemphomes/HempThermographicReport.pdf

Busbridge, R 2009, *Hemp-Clay: an initial investigation into the thermal, structural and environmental credentials of monolithic clay and hemp walls*, MSc Dissertation, Architecture: Advanced Environment & Energy Studies, GraduateSchool of the Environment, Centre for Alternative Technology, Machynlleth, Powys, Wales, UK.

Bütschi P, Deschenaux C, Miao B, Srivastava, NK, 2003, *Utilisation du chanvre pour la préfabricationd'éléments de construction*, Proceedings of Annual Conference of the Canadian Society for Civil Engineering, Moncton, Nouveau-Brunswick, Canada.

Bütschi P, Deschenaux C, Miao B, Srivastava, NK, 2004, Caractérisation d'une maçonnerie composée d'éléments en aggloméré de chanvre, Canadian Journal of Civil Engineering, v. 31(3), pp. 526-539.

Bydžovský J Khestl F, 2007, *Utilization Of Hemp As A Filler Of Cement-bonded Particleboards*, Proceedings of the Central Europe towards Sustainable Building Conference (CESB 07), Prague, Czech Republic

Caslin, B, 2009, *Irelands Hemp Industry: Opportunities and Challenges*, Teagasc, Crops Research Centre, Oak Park, Carlow, Ireland

Cerezo V, 2005, *Propriétés mécaniques, thermiques et acoustiques d'un matériau à base de particules végétales: approche expérimentale et modélisation théorique*, PhDthesis, Ecole Nationale des Travaux Publics de l'Etat, France.

Chanvribloc, 2009, *Le Bloc de Chanvre*, Retrieved March 20th 2010 from http://www.chanvribloc.com/Documents/fiche%20technique%20generale.pdf

Chew P, MacDougall C, 2007, *Compressive Strength Testing of Hemp Mansory Mixtures*, Proceedings of the International Conference on Sustainability in the Cement and Concrete Industry, Lillehammer, Norway.

CIBSE, 2006, *Environmental design - Guide A*, Chartered Institution of Building Services Engineers, UK

Clark M, 2009, Selecting building materials to reduce environmental impact, MSc Dissertation, Architecture: Advanced Environment & Energy Studies, GraduateSchool of the Environment, Centre for Alternative Technology, Machynlleth, Powys, Wales, UK.

Collet F, Bart M, Serres L, Miriel J, 2007, *Porous structure and water vapour sorption of hemp-based materials*, Construction and Building Materials vol. 22, pp. 1271-1280

Crowley, JG & Rice, B 1998, *Hemp (Cannabis sativa L.) production and uses in Ireland*, Journal of the International Hemp Association, International Hemp Association, Amsterdam, The Netherlands. Retrieved January 17, 2010 from http://www.druglibrary.org/olsen/HEMP/IHA/jiha5114.html

Crowley, JG 2001, *The Performance of Cannabis Sativa (Hemp) as a fibre source for Medium Density Fibre Board (MDF)*, Teagasc, Crops Research Centre, Oak Park, Carlow, Ireland.

de Bruijn PB, Jeppssona KH, Sandin K, Nilssona C, 2009, *Mechanical properties of lime–hemp concrete containing shives and fibres*, Biosystems Engineering, vol. 103, pp. 474-479

EFOD, 2010, *Concrete Mix Design*, Retrieved April 9, 2010 from http://www.efod.org.uk/resource/C1%20Concrete%20Mix%20Design.pdf

Eires R, Jalali S, 2005, *Not Conventional Materials for a Sustainable Construction: A Bio-construction System Reinforced with Cellulose Fibres*, Department of Civil Engineering, University of Minho, Guimarães, Portugal

Elfordy S, Lucas F, Tancret F, Scudeller Y, Goudet L, 2007, *Mechanical and thermal properties of lime and hemp concrete (''hempcrete'') manufactured by a projection process*, Construction and Building Materials, vol. 22, pp. 2116–2123

Evrard, A. (ed.) (2003). *Bétons de Chanvre - Synthèse des propriétés physiques*. Construire en Chanvre, Saint Valérien.

Evrard A & De Herde A, 2005, *Bioclimaticenvelopes made of lime and hempconcrete*, Architecture et Climat – Université catholique de Louvain, Louvain-la-Neuve, Belgium.

Evrard A, De Herde A, Minet J, 2006, *Dynamical interactions between heat and mass flows in Lime-Hemp Concrete*, Proceeding of the third International Building Physics Conference, Concordia University, Canada and International Association of Building Physics.

Evrard A, 2006, *Sorption behaviour of Lime-Hemp Concrete and its relation to indoor comfort and energy demand*, Proceedings of the 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland.

Evrard A, 2008, *Transient hygrothermal behaviour of lime-hemp materials*, PhD in applied science. Universitécatholique de Louvain, Belgium.

Flanagan, D 2006, *Homes from Hemp: Building for the Future*, Thesis for the Degree in Construction Economics and Management, School of Real Estate and Construction Economics, Dublin Institute of Technology, Dublin, Ireland.

Gibson, K 2006, *Hemp for victory: history and qualities of the world's most useful plant*, Whitaker Publishing, London, UK.

Hammond G, Jones C, 2008, *Inventory of Carbon & Energy (ICE)Version 1.6a*, Sustainable energy Research Team (SERT), Dept. of Mechanical Engineering, University of Bath, UK.

Hemp Technology, 2010, *The environment*, Retrieved January 17, 2010 from http://www.hemcore.co.uk/environment.htm

Holmes, S & Wingate, M 2002, *Building with Lime*, Intermediate Technology Publications, London, UK.

IBO - Austrian Insitute for Healthy and Ecological Building, 2008, *Passivhaus-Bauteilkatalog - Details for passive Houses, A catalogue of ecologically related constructions*, Springer, Wien, New York

INRA, 2006, *Étude des caracteristiques environnementales du chanvre par l'analyse de son cycle de vie*, Ministère de l'Agriculture et de la Pêche, Retrieved January 19, 2010 from http://agriculture.gouv.fr/spip/IMG/pdf/chanvre_rapport_final_d235d.pdf

Isochanvre, 2001, *IsochanvreTechnical Document*, Isochanvre Sarl, Le Verger, René, France

Karus, M 2005, *European hemp industry 2001 till 2004: Cultivation, raw materials, markets and trends*, European Industrial Hemp Association, Germany. Retrieved January 17, 2010, from www.industrial-crops.com

Le Troëdec M, Peyratout CS, Smith A, Chotard T, 2009, *Influence of various chemical treatments on the interactions between hemp fibres and a lime matrix*, Journal of the European Ceramic Society, vol. 29, pp. 1861-1868.

Lime Technology, 2007, *Tradical® Hemcrete® Information Pack*. Retrieved January 17, 2010 from http://www.limetechnology.co.uk/upload/documents/Hemcrete/tradical_hemcrete_info_pack_updated.pdf

Lime Technology, 2008a, *The Thermal Performance of Tradical® Hemcrete®*. Retrieved January 17, 2010 from http://www.limetechnology.co.uk/upload/documents/Hemcrete/1201787723_the_thermal_performance_of_tradical_hemcrete.pdf

Lime Technology, 2008b, *Temperature Controlled Warehousing - The Wine Society*. Retrieved March 20, 2010 from http://www.limetechnology.co.uk/upload/documents/case%20studies/Limetech-Lhoist%20Case%20Study%20Wine%20society.pdf

Lime Technology, 2009a, *Hemcrete® Thermal Block Information Sheet*, Retrieved March 20, 2010 from http://www.limetechnology.co.uk/upload/documents/Hemcrete/HEMCRETE%20THERMAL%20BLOCK%20-%20Information%20Sheet_HTB0509.v2web.pdf

Lime Technology, 2009b, *Hemcrete® Structural Block Information Sheet*. Retrieved March 20, 2010 from http://www.limetechnology.co.uk/upload/documents/Hemcrete/HEMCRETE%20STRUCTURAL%20BLOCK%20-%20Information%20Sheet_HSB0509.v2web.pdf

Lime Technology, 2009c, *Tradical® Hemcrete® Product Datasheet,* Retrieved March 20, 2010 from http://www.limetechnology.co.uk/upload/documents/Hemcrete/HEMCRETE%20-DATA%20SHEET_H0509v2.pdf

Lime Technology, 2010, *Case Studies*, Retrieved January 17, 2010 from http://www.limetechnology.co.uk/pages/hcproj.php

Modcell, 2010, *Modcell Technical Sheet*, Retrieved March 20, 2010 from http://www.modcell.co.uk/cms_files/documents/pdf/modcell_technical_sheet.pdf

Neenan, M 1969, *The cultivation of hemp in Ireland*. *FIBRA* 14(1): 23.

Nguyen T, Picandet V, Amziane S, Baley C, 2009, *Influence of compactness and hemp hurd characteristics on the mechanical properties of lime and hemp concrete*, European Journal of Environmental and Civil Engineering, vol. 13/2009, pp. 1039-1050.

O'Dowd J & Quinn D, 2005, *An Investigation of Hemp and Lime as a Building Material*, Thesis Bachelor of Engineering, Department of Civil Engineering, University College Dublin, Ireland.

Office of the Deputy Prime Minister, 2000, *UK Building Regulations 2000, Approved Document E, Resistance to the passage of sound*

Pervais, M 2003, *Carbon storage potential in natural fiber composites*, Resources, conservation and Recycling, vol. 39, no. 4, pp. 325-340.

Pilkington, B 2006, *In-situ thermal conductivity measurements of lime and hemp based materials using a thermal probe at Hartest Suffolk*, University of Plymouth.

Pritchett, I 2003, *Lime versus cement: traditional methods for today s buildings*, Proceedings of the Institution of Civil Engineers, Engineering Sustainability, vol. 156, no. 2, pp. 83-85.

Rhydwen, GR 2006, *A model for UK hemp cultivation and processing to supply the building industry with hurds for hemp and lime concrete and fibres for insulation bats, with the ethos of environmental protection as a priority*, MSc Dissertation, University of East London, School of Computing and Technology, Dagenham, UK.

Roadstone, 2010, *High strength concrete blocks*, Retrieved March 20, 2010 from http://www.roadstone.ie/commercial/product_details.aspx?id=204

Ronchetti P, 2007, *The Barriers to the Mainstreaming of Lime-Hemp: a Systemic Approach*, MSc Dissertation, Dublin Institute of Technology, School of Spatial Planning, Dublin, Ireland.

Samir D, 2008, *Analyse physique et caractérisation hygrothermique des matériaux de construction : approche expérimentale et modélisation numérique*, Thèse de Doctorat, ENTPE, RetrievedFebruary 16, 2010 from http://docinsa.insa-lyon.fr/these/2008/samri/01_these.pdf

Sedan D, Pagnoux C, Smith A, Chotard T, 2007, *Mechanical properties of hemp fibre reinforced cement: Influence of the fibre/matrix interaction*, Journal of the European Ceramic Society, vol. 28, pp. 183–192

Simetric, 2010, Mass of materials, Retrieve March 20th 2010 from http://www.simetric.co.uk/si_materials.htm

Small, E & Marcus, D 2002, *Hemp: A New Crop with New Uses for North America*, in Janic, J &Whipkey, A (eds), *Trends in new crop and news uses*, ASHS Press, Alexandria, VA, USA, pp. 284-326. Retrieved January 17, 2009, from http://www.hort.purdue.edu/newcrop/ncnu02/pdf/small.pdf

St. Astier 2006, *Hemp mortars using St. Astier Natural Limes*, Retrieved March 20 2010 from http://www.stastier.co.uk/nhl/guides/hempconstruction.htm

Tran Le AD, Maalouf C, Mai, TH, Wurtz, E, 2009, *Study of the transient behaviour of a hemp concrete building envelope*, Proceedings of the Eleventh International IBPSA Conference, Glasgow, Scotland.

Woolley, T 2006, *NaturalBuilding: A Guide to Materials and Techniques*, The Crowood Press Ltd, Ramsbury, Marlborough, Wiltshire, UK.

Young, EM 2005, *Revival of Industrial Hemp: A systematic analysis of the current global industry to determine limitations and identify future potentials within the concept of sustainability*, Masters Degree of International Environmental Science Thesis, Environmental Science, Lund University, Sweden.

Regulatory documents and standards

Anderson B, Building Research Establishment Ltd (BRE), 2006, *BR 443: 2006 Conventions for U-Value Calculations 2006 Edition*, Watford:BRE Press

ASTM International, 2007, *ASTM C109 / C109M - 08 Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)*

ASTM International, 2009, *ASTM E514/E514M - 09 Standard Test Method for Water Penetration and Leakage Through Masonry*

ASTM International, 2010, *ASTM C39 / C39M - 10 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*

ASTM International, 2010, *ASTM C1601 - 10 Standard Test Method for Field Determination of Water Penetration of Masonry Wall Surfaces*

Anderson B, Building Research Establishment Ltd (BRE), 2006, *BR 443: 2006 Conventions for U-Value Calculations 2006 Edition*, Watford:BRE Press

British Standards Institute (BSI), 1970, *BS 4315-2:1970 Methods of test for resistance to air and water penetration. Permeable walling constructions (water penetration)*

British Standards Institute (BSI), 1980, *BS 2750:Part 4:1980, Measurement of sound insulation in buildings and of building elements. Field measurements of airborne sound insulation between rooms*

British Standards Institute (BSI), 1980, *BS 2750:Part 7:1980, Measurement of sound insulation in buildings and of building elements. Field measurements of impact sound insulation of floors*

British Standards Institute (BSI), 1987, *BS 476-20:1987 Fire tests on building materials and structures Part 20: Method for determination of the fire resistance of elements of construction (general principles)*

British Standards Institute (BSI), 1987, *BS 476-21:1987 Fire tests on building materials and structures Part 21: Methods for determination of the fire resistance of loadbearing elements of construction*

British Standards Institute (BSI), 1992, *BS 6477:1992 Water repellents for masonry surfaces*

British Standards Institute (BSI), 1996,*BS 1881-208:1996 Testing concrete. Recommendations for the determination of the initial surface absorption of concrete*

British Standards Institute (BSI), 1997, *BS 476-7:1997 Fire tests on building materials and structures Part 7: Method of test to determine the classification of the surface spread of flame of products*

British Standards Institute (BSI), 1998, *BS EN ISO 140 Part 4:1998 Acoustics. Measurement of sound insulation in buildings and of building elements. Field measurements of airborne sound insulation between rooms*.

British Standards Institute (BSI), 1998, BS EN ISO 140 Part 7:1998 *Acoustics. Measurement of sound insulation in buildings and of building elements. Field measurements of impact sound insulation of floors*

British Standards Institute (BSI), 1998, *PD 6520:1998 Guide to fire test methods for building materials and elements of construction*

British Standards Institute (BSI), 1999, *BS EN 1365-1:1999 Fire resistance tests for loadbearing elements Part 1: Walls*

British Standards Institute (BSI), 1999, *BS EN 1052-1:1999 Methods of test for masonry. Determination of compressive strength*

British Standards Institute (BSI), 2000, *BS EN 772-1:2000 Methods of test for masonry units Part 1: Determination of compressive strength*

British Standards Institute (BSI), 2002, *BS EN 1745:2002, Masonry and masonry products. Methods for determining design thermal values*

British Standards Institute (BSI), 2003, *BS EN 13501-2:2003 Fire classification of construction products and building elements Part 2: Classification using data from fire resistance tests, excluding ventilation services*

British Standards Institute (BSI), 2005, *BS 5628-1:2005 Code of practice for the use of masonry Part 1: Structural use of unreinforced masonry*

British Standards Institute (BSI), 2009, BS 476-6:1989+A1:2009Fire tests on buildingmaterialsandstructures — Part 6: Method of test for fire propagation for products

British Standards Institute (BSI), 2009, *BS EN 13501-1:2007 + A1: 2009 Fire classification of construction products and building elements Part 1: Classification using data from reaction to fire tests*

British Standards Institute (BSI), 2009, *BS EN ISO 13786: 2007, Incorporating Corrigendum February 2009, Thermal performance of building components — Dynamic thermal characteristics — Calculation methods*

British Standards Institute (BSI), 2009,*BS EN 12390-8:2009 Testing hardened concrete. Depth of penetration of water under pressure*

British Standards Institute (BSI), 2010, *BS 4551:2005+A1:2010 Mortar. Methods of test for mortar. Chemical analysis and physical testing*

Council Directive (EEC) 89-106 (1988, December 21st), *On the approximation of laws, regulations and administrative provisions of the Member States relating to construction products,* Official Journal, L. 40, p. 12

Department Of The Environment, Heritage And Local Government, 1992. *Statutory Instrument No. 198/1992, European Communities (Construction Products) Regulations 1992*. Dublin.

Department Of The Environment, Heritage And Local Government, 1994. *Statutory Instrument No. 210/1994, European Communities (Construction Products) (Amendment) Regulations, 1994*. Dublin.

Department Of The Environment, Heritage And Local Government, 1997. *Building Regulations 1997, Technical Guidance Document A, Structure.* Dublin: The Stationary Office.

Department Of The Environment, Heritage And Local Government, 1997. *Building Regulations 1997, Technical Guidance Document C, Site Preparation and Resistance to Moisture*. Dublin: The Stationary Office.

Department Of The Environment, Heritage And Local Government, 1997. *Building Regulations 1997, Technical Guidance Document E, Sound.* Dublin: The Stationary Office.

Department Of The Environment, Heritage And Local Government, 2002. *Marking of Construction Products under EU Directive 89/106/EEC*, Building Regulation Advisory Body. Dublin.

Department Of The Environment, Heritage And Local Government, 2004. *Statutory Instrument No. 128/2004, Housing (Floor Area Compliance Certificate Inspection) Regulations 2004*. Dublin.

Department Of The Environment, Heritage And Local Government, 2006. *Building Regulations 2006, Technical Guidance Document B, Fire.* Dublin: The Stationary Office.

Department Of The Environment, Heritage And Local Government, 2000. *Building Regulations 2000, Technical Guidance Document D, Materials and Workmanship.* Dublin: The Stationary Office.

Department Of The Environment, Heritage And Local Government, 2008. *Building Regulations 2007, Technical Guidance Document L, Conservation of fuel and energy - Dwellings.* Dublin: The Stationary Office.

Department Of The Environment, Heritage And Local Government, 2008. *Building Regulations 2008, Technical Guidance Document L, Conservation of fuel and energy – Buildings other than Dwellings.* Dublin: The Stationary Office.

Department for Communities and Local Government, Nov 2010, *Code for Sustainable Homes Technical guide*
UK Crown Copyright

International Standard Organisation, 1991, *ISO 8301:1991 Thermal insulation -Determination of steady-state thermal resistance and related properties -Heat flow meter apparatus*

International Standard Organisation, 1991, *ISO 8302:1991 Thermal insulation - Determination of steady-state thermal resistance and related properties - Guarded hot plate apparatus*

International Standard Organisation, 1995, *ISO 140-3:1995Acoustics -- Measurement of sound insulation in buildings and of building elements -- Part 3: Laboratory measurements of airborne sound insulation of building elements*

International Standard Organisation, 2000, *ISO 9001:2000 Quality management systems – Requirements*, ISO copyright office, Genève, Switzerland.

International Standard Organisation, 2004, *ISO 844: 1998 (2004) Cellular plastics. Compression test for rigid materials. Specification.*

International Standard Organisation, 2007, *ISO 10456:2007 Building materials and products -Hygrothermal properties -Tabulated design values and procedures for determining declared and design thermal values*

National Standards Authority of Ireland (NSAI), 1974, *I.S.20:1974 Concrete Building Blocks (Reinstated 1995)*, Dublin: NSAI

National Standards Authority of Ireland (NSAI), 1998, IS EN ISO 140-4: 1998 *Acoustics. Measurement of sound insulation in buildings and of building elements. Field measurements of airborne sound insulation between rooms*

National Standards Authority of Ireland (NSAI), 1998, IS EN ISO 140-7:1998 *Acoustics. Measurement of sound insulation in buildings and of building elements. Field measurements of impact sound insulation of floors*

National Standards Authority of Ireland (NSAI), 2011, I.S. EN 771-3: 2011 *Specification for masonry units - Part 3: Aggregate concrete masonry units (Dense and lightweight aggregates)*

National Standards Authority of Ireland (NSAI), 2011, I.S EN 772-1: 2011*Methods of test for masonry units - part 1: determination of compressive strength*

National Standards Authority of Ireland (NSAI), 2010, I.S. EN 998-1: 2010 *Specification for mortar for masonry - part 1: rendering and plastering mortar*

National Standards Authority of Ireland (NSAI), 2010, I.S. EN 998-2: 2010 *Specification for mortar for masonry - part 2: masonry mortar*

National Standards Authority of Ireland (NSAI), 2006, I.S. EN 1015-11: 2000 (2006)*Methods of test for mortar for masonry - part 11: determination of flexural and compressive strength of hardened mortar*

National Standards Authority of Ireland (NSAI), 2006, I.S. EN 1991-1-7: 2006 *Eurocode 1 - actions on structures - part 1-7: general actions - accidental actions (including Irish national annex)*

National Standards Authority of Ireland (NSAI), I.S. EN 1992*: Eurocode 2: design of concrete structures*

National Standards Authority of Ireland (NSAI), 2005, I.S. EN 1996-1-1: 2005 *Eurocode 6 - design of masonry structures - part 1-1: general rules for reinforced and unreinforced masonry structures (including irish national annex)*

National Standards Authority of Ireland (NSAI), 2000, I.S.EN 12390-1: 2000 *Testing hardened concrete - part 1: shape, dimensions and other requirements for specimens and moulds*

National Standards Authority of Ireland (NSAI), 2009, I.S.EN 12390-2: 2009 *Testing hardened concrete - part 2: making and curing specimens for strength tests*

National Standards Authority of Ireland (NSAI), 2009, I.S.EN 12390-3: 2009 *Testing hardened concrete - part 3: compressive strength of test specimens*

National Standards Authority of Ireland (NSAI), 2000, I.S.EN 12390-4: 2000 *Testing hardened concrete - part 4: compressive strength - specification for testing machines*

Sustainable Energy Ireland, 2008. *Dwelling Energy Assessment Procedure (DEAP) 2008 EDITION, VERSION 3.0 Irish official method for calculating and rating the energy performance of dwellings*.

Ward T, Building Research Establishment Ltd (BRE), 2006, *IP 1/06: 2006 Assessing the effects of thermal bridging at junctions and around openings*, Watford: BRE Press

Ward, T and Sanders, C, 2007. *Conventions for calculating linear thermal transmittance and temperature factors, BR497.*Watford: IHS BRE Press.

APPENDIX 1

Table 2.1

'BESRaC Hemp Lime   Literature Review Papers / Key Data Summary Table',
outlining the principal data collated, literature type and the key relevant content

Table 4.1

'Material Properties – Detailed Data Table',
listing the key material properties, sources and test methods, etc.

Table 4.2

'Test Data and Comparison Table',

listing the various relevant standard and their testing requirements with comparable test data on hemp lime.

Table 2.1 BESRaC Hemp Lime Literature Review Papers / Key Data Summary Table.

This table presents a summary of data gathered by BESRaC from a review of key technical literature on hemp lime as known and available at date of study (early 2010) and is not an exhaustive list of all data on the subject. This table presents a comparative summary of the some of the principal relevant data for this study and includes excerpts of the contents. Original documents should be referred to for detail and verification. While every reasonable effort has been made to ensure accuracy the authors accept no responsibility for errors or liability arising from use of this data. Trade Literature references are shown in italics with (trade Lit) noted after source. © BESRaC 2010. (Trade Literature references are shown in italics and (trade Lit) noted after Author name.)

Title	Topic	Author	Type of publication	Year	Country
Isochanvre technical document	*CONSTRUCTION – Technical and practical properties of Hemp Lime products manufactured by Isochanvre*	*Isochanvre (Trade Lit)*	*Report*	*2001*	*France*
Mechanical, thermal and acoustical properties of concrete containing vegetable particles - ABSTRACT ONLY	MATERIAL SCIENCE – Hemp Lime : Mechanical, Thermal, Acoustic properties	Arnaud L, Cerezo V	Conference Paper	2002	France
Final Report on the Construction of the Hemp Houses at Haverhill, Suffolk	CONSTRUCTION – Hemp Lime - Structure & durability, Thermal, Acoustic, Permeability, Waste, Costs	BRE	Report	2002	UK
Thermographic Inspection of the Masonry and Hemp Houses at Haverhill, Suffolk	CONSTRUCTION – Hemp Lime – Thermal properties	BRE	Report	2002	UK
Utilisation du chanvre pour la préfabrication d'éléments de construction	MATERIAL SCIENCE - PROCESSING - Hemp Lime blocks	Bütschi P, Deschenaux C, Miao B, Srivastava NK	Conference Paper	2003	Switzerland

Caractérisation d'une maçonnerie composée d'éléments en aggloméré de chanvre	MATERIAL SCIENCE – Hemp Lime blocks : structural, thermal, acoustic properties	Bütschi P, Deschenaux C, Miao B, Srivastava NK, 2004	Conference Paper	2004	Switzerland
Building with Hemp	CONSTRUCTION – Hemp Lime : overview of scientific properties and practical information on how to build with hemp	Allin, S	Book	2005	Ireland
Hygrothermal behaviour of porous building materials - ABSTRACT ONLY	MATERIAL SCIENCE – Hemp Lime : hygrothermal behaviour	Arnaud L, Samri D	Conference Paper	2005	France
Not Conventional Materials for a Sustainable Construction: A Bio-construction System Reinforced with Cellulose Fibres	MATERIAL SCIENCE - Biocomposite made of hemp, waste paper pulp, lime and metakaoline : Strength, Thermal	Eires R, Jalali S,	Conference Paper	2005	Portugal
An Investigation of Hemp and Lime as a Building Material	MATERIAL SCIENCE & CONSTRUCTION - Hemp Lime: Strength, Thermal	O'Dowd J & Quinn D	Undergrad. Thesis	2005	Ireland
Propriétés mécaniques, thermiques et acoustiques d'un matériau à base de particules végétales: approche expérimentale et modélisation théorique	MATERIAL SCIENCE – Hemp Lime: mechanical, thermal, acoustic properties	Cerezo V	PhD Thesis	2005	France
Bioclimatic envelopes made of lime and hemp concrete	MATERIAL SCIENCE -Hemp Lime: Hygrothermal	Evrard A, De Herde A	Conference Paper	2005	Belgium

Dynamical interactions between heat and mass flows in Lime-Hemp Concrete	MATERIAL SCIENCE - Hemp Lime: Hygrothermal + simulation	Evrard A, De Herde A, Minet J	Conference Paper	2006	Belgium
Sorption behaviour of Lime-Hemp Concrete and its relation to indoor comfort and energy demand	MATERIAL SCIENCE - Hemp Lime: Hygrothermal	Evrard A	Conference Paper	2006	Belgium
Porous structure and water vapour sorption of hemp-based materials	MATERIAL SCIENCE - Hemp Lime : Porosity, Water sorption	Collet F, Bart M, Serres L, Miriel J	Journal Paper	2007	France
Tradical® Hemcrete® Information Pack	*CONSTRUCTION – Technical and practical properties of Hemp Lime products manufactured by Lime Technology*	*Lime Technology (Trade Lit)*	*Report*	*2007*	*UK*
Mechanical properties of hemp fibre reinforced cement: Influence of the fibre/matrix interaction	MATERIAL SCIENCE - Hemp fibre reinforced cement: Mechanical properties	Sedan D, Pagnoux C, Smith A, Chotard T	Journal Paper	2007	France
Compressive Strength Testing of Hemp Masonry Mixtures	MATERIAL SCIENCE – Hemp, Cement, Lime, Sand : Structural properties	Chew P, MacDougall C	Conference Paper	2007	Canada

Utilization Of Hemp As A Filler Of Cement-bonded Particleboards	MATERIAL SCIENCE – Hemp and Cement particleboards	Bydžovský J Khestl F	Conference Paper	2007	Czech Republic
Mechanical and thermal properties of lime and hemp concrete (‘‘hempcrete’’) manufactured by a projection process	MATERIAL SCIENCE - Hemp Lime : Sprayed – Mechanical and Thermal properties	Elfordy S, Lucas F, Tancret F, Scudeller Y, Goudet L	Journal Paper	2007	France
Hemp lime construction. A guide to building with hemp lime composites	CONSTRUCTION – Hemp Lime : Strength, Structural, Thermal, Insulation, Acoustic, Deformation, Durability, Deterioration, Environmental, etc.	Bevan R, Woolley T	Book	2008	UK
The Thermal Performance of Tradical® Hemcrete®	*MATERIAL SCIENCE – Hemp Lime : Thermal performance*	*Lime Technology (Trade Lit)*	*Report*	*2008*	*UK*
Transient hygrothermal behaviour of lime-hemp materials	MATERIAL SCIENCE – Hemp Lime : Hygrothermal behaviour	Evrard A	PhD Thesis	2008	Belgium
Comparative study of hygro thermal performances of building materials	MATERIAL SCIENCE - Hemp Lime : Hygro thermal performance	Arnaud L	Conference Paper	2009	France

Mechanical properties of lime–hemp concrete containing shives and fibres	MATERIAL SCIENCE - Hemp Lime : Strength, Water sorption, Frost resistance	de Bruijn PB, Jeppssona KH, Sandin K, Nilssona C	Journal Paper	2009	Sweden
Influence of various chemical treatments on the interactions between hemp fibres and a lime matrix	MATERIAL SCIENCE – Hemp fibres : Chemical treatment and their interaction in a lime matrix	Le Troëdec M, Peyratout CS, Smith A, Chotard T	Journal Paper	2009	France
Study of the transient behaviour of a hemp concrete building envelope	MATERIAL SCIENCE - Hemp Lime : Simulation of heat and moisture transport through the building envelope	Tran Le AD, Maalouf C, Mai TH, Wurtz E	Conference Paper	2009	France
Influence of compactness and hemp hurd characteristics on the mechanical properties of lime and hemp concrete	MATERIAL SCIENCE – Hemp Lime – Compaction and Mechanical properties	Nguyen T, Picandet V, Amziane S, Baley C,	Journal Paper	2009	France
Hemp-Clay: an initial investigation into the thermal, structural and environmental credentials of monolithic clay and hemp walls	MATERIAL SCIENCE - Hemp & Clay : Thermal, Structural, Environmental	Busbridge, R	MSc Dissertation	2009	UK
Fire resistance test in accordance with BS EN 1365-1:1999 on a Lime Technology Ltd, 3m x 3m Tradical Hemcrete loaded wall	MATERIAL SCIENCE - Hemp Lime: resistance to fire	BRE	Report	2009	UK
Chanvribloc - Brochure complète	*CONSTRUCTION - Technical and practical properties of Hemp Lime blocks*	*Chanvribloc (Trade Lit)*	*Report*	*2009*	*France*
Agrément Certificate 10/4726 – Lhoist Wall System, Tradical Hemcrete Wall System	CONSTRUCTION - overall properties of Hemp Lime walling system	British Board of Agrément	Report	2010	UK

Table 2.1 *contd*

Title	Generic Material Properties		Chemical Properties	
	Type	Testing/Assessment method	Type	Testing/Assessment method
Isochanvre technical document	*density*	*Source not accurately defined, states: "various sources like the BRE, The CSTB, the CTBA, SOCOTEC, the FFB and the University of Rennes took part in studies, appraisals and the classification of isochanvr"*		
Mechanical, thermal and acoustical properties of concrete containing vegetable particles - ABSTRACT ONLY				
Final Report on the Construction of the Hemp Houses at Haverhill, Suffolk				
Thermographic Inspection of the Masonry and Hemp Houses at Haverhill, Suffolk				
Utilisation du chanvre pour la préfabrication d'éléments de construction	density	sample		
Caractérisation d'une maçonnerie composée d'éléments en aggloméré de chanvre	density	sample - stove - EN 772-13:2000		

Building with Hemp				
Hygrothermal behaviour of porous building materials - ABSTRACT ONLY				
Not Conventional Materials for a Sustainable Construction: A Bio-construction System Reinforced with Cellulose Fibres	density	sample		
An Investigation of Hemp and Lime as a Building Material	density	sample		
Propriétés mécaniques, thermiques et acoustiques d'un matériau à base de particules végétales: approche expérimentale et modélisation théorique	density	sample		
Bioclimatic envelopes made of lime and hemp concrete	density, total porosity - vapour permeability - water absorption coefficient	sample: helium pycnometer - DIN 52 617		
Dynamical interactions between heat and mass flows in Lime-Hemp Concrete	water content in capillary region - absorption & redistribution of liquid water -	sample: pressure plate apparatus - NMR apparatus		
Sorption behaviour of Lime-Hemp Concrete and its relation to indoor comfort and energy demand	drying time - mass variation due to carbonation - density - dry vapour resistance	sample: dry cup test (EN ISO 12572).		
Porous structure and water vapour sorption of hemp-based materials	mercury porosimetry - water vapour sorption	sample: BET, t & BJH methods		
Tradical® Hemcrete® Information Pack				

Mechanical properties of hemp fibre reinforced cement: Influence of the fibre/matrix interaction			analysis of chemical elements	induced coupled plasma spectroscopy (ICP) - scanning electron microscopy (SEM)
Compressive Strength Testing of Hemp Masonry Mixtures	density	sample		
Utilization Of Hemp As A Filler Of Cement-bonded Particleboards	density	sample		
Mechanical and thermal properties of lime and hemp concrete (''hempcrete'') manufactured by a projection process	density	sample	microstructural characterisation	sample: scanning electron microscope (SEM) equipped with an X-ray energy dispersive spectroscopy (EDS) analyser
Hemp lime construction. A guide to building with hemp lime composites				
The Thermal Performance of Tradical® Hemcrete®				
Transient hygrothermal behaviour of lime-hemp materials	density - porosity - water vapour permeability	sample: oven & electronic scale - helium pycnometer - dry/wet cup DIN 52 615 (EN ISO 12572)		
Comparative study of hygro thermal performances of building materials				

Mechanical properties of lime–hemp concrete containing shives and fibres	density - water sorption	sample		
Influence of various chemical treatments on the interactions between hemp fibres and a lime matrix				
Study of the transient behaviour of a hemp concrete building envelope				
Influence of compactness and hemp hurd characteristics on the mechanical properties of lime and hemp concrete	density	sample		
Hemp-Clay: an initial investigation into the thermal, structural and environmental credentials of monolithic clay and hemp walls	moisture - density	sample: moisture probe		
Fire resistance test in accordance with BS EN 1365-1:1999 on a Lime Technology Ltd, 3m x 3m Tradical Hemcrete loaded wall				
Chanvribloc - Brochure complète	*density - dry vapour resistance*	*Not stated*		
Agrément Certificate 10/4726 – Lhoist Wall System, Tradical Hemcrete Wall System	density	sample		

Table 2.1 *contd*

Title	Mechanical Properties		Thermal Properties	
	Type	Testing/Assessment method	Type	Testing/Assessment method
Isochanvre technical document			*thermal conductivity*	*refers to CSTB Report No GM 90-43*
Mechanical, thermal and acoustical properties of concrete containing vegetable particles - ABSTRACT ONLY	compressive strength - Young modulus	Not Stated	thermal conductivity	Not Stated
Final Report on the Construction of the Hemp Houses at Haverhill, Suffolk	compressive strength	sample: BS ISO 844: 1998	thermal comparison	in situ: heating fuel consumed
Thermographic Inspection of the Masonry and Hemp Houses at Haverhill, Suffolk			thermal comparison	in situ: thermography
Utilisation du chanvre pour la préfabrication d’éléments de construction	compressive strength	sample: numerical control hydraulic press		
Caractérisation d’une maçonnerie composée d’éléments en aggloméré de chanvre	compressive strength - Young modulus	sample: numerical control hydraulic press -prEN 772-1:1996 & prEN 1052-1:1995	thermal conductivity - overall heat transfer coefficient (U-value)	sample: heat box
Building with Hemp			thermal performance	Not Stated
Hygrothermal behaviour of porous building materials - ABSTRACT ONLY				
Not Conventional Materials for a Sustainable Construction: A Bio-construction System Reinforced with Cellulose Fibres	compressive strength	sample: numerical control hydraulic press		

An Investigation of Hemp and Lime as a Building Material	compressive strength - tensile strength	sample: cube compression tests - cylinder splitting tests		
Propriétés mécaniques, thermiques et acoustiques d'un matériau à base de particules végétales: approche expérimentale et modélisation théorique	compressive strength - Young's modulus - Poisson's ratio	sample: compression tests	thermal conductivity	heat box & model of dry and wet conductivity
Bioclimatic envelopes made of lime and hemp concrete			specific heat capacity	EN ISO 12572 (dry/wet cup method)
Dynamical interactions between heat and mass flows in Lime-Hemp Concrete			thermal conductivity	sample
Sorption behaviour of Lime-Hemp Concrete and its relation to indoor comfort and energy demand			thermal conductivity	sample: hot/cold plate (DIN 5216)
Porous structure and water vapour sorption of hemp-based materials				
Tradical® Hemcrete® Information Pack	*compressive strength*	*Not Stated*	*overall heat transfer coefficient (U-value) - air tightness*	*Refers to BRE Monitoring of Haverhill Houses*
Mechanical properties of hemp fibre reinforced cement: Influence of the fibre/matrix interaction	setting time -flexural strength - Young's modulus	sample: vicat test - three point bending test - non destructive ultrasonic method		
Compressive Strength Testing of Hemp Masonry Mixtures	compressive strength - moduli of elasticity - failure mode	Riehle or Unite-O-matic concrete compression testing machine		
Utilization Of Hemp As A Filler Of Cement-bonded Particleboards	tensile strength - modulus of elasticity	Not Stated		

Mechanical and thermal properties of lime and hemp concrete (''hempcrete'') manufactured by a projection process	flexural stress - compressive strength - hardness	sample: three point bending test - compression testing machine - spherical indentation	thermal conductivity	sample: hot/cold plate
Hemp lime construction. A guide to building with hemp lime composites	compressive strength - flexural strength	Refers to Lime Technology (Blocks), Refers to KIOY 2005: Lime Hemp Composites: Compressive strength and resistance to fungal attacks	thermal conductivity - overall heat transfer coefficient (U-value) - air tightness	Refers to Evrard 2006 Sorption behaviour of Lime-Hemp Concrete and its relation to indoor comfort and energy demand, Refers to Research by University of Plymouth, Refers to tests by National Physical Laboratory
The Thermal Performance of Tradical® Hemcrete®			*thermal performance*	*in situ: monitoring of internal/external temperature and relative humidity*
Transient hygrothermal behaviour of lime-hemp materials			thermal capacity - thermal conductivity - hygroscopic sorption - specific hygric capacity	sample: adiabatic can - hot/cold plate - climate chamber - glass desiccator
Comparative study of hygro thermal performances of building materials			hygrothermal behaviour (temperature & Relative humidity)	physical model: cell of exchange (climatic box
Mechanical properties of lime–hemp concrete containing shives and fibres	compressive strength - Young's modulus - splitting tensile strength - frost resistance	sample: compression test - freeze-thaw cycles		
Influence of various chemical treatments on the interactions between hemp fibres and a lime matrix	flexural strength	sample: three point bending test		
Study of the transient behaviour of a hemp concrete building envelope				

Influence of compactness and hemp hurd characteristics on the mechanical properties of lime and hemp concrete	compressive strength - elasticity modulus	sample: compression test		
Hemp-Clay: an initial investigation into the thermal, structural and environmental cre-dentials of monolithic clay and hemp walls	compressive strength	sample: rudimentary test by placing a board on top and loading with weights	thermal conductivity & thermal capacitance	sample: transient heat-transfer analyzer probe
Fire resistance test in accordance with BS EN 1365-1:1999 on a Lime Technology Ltd, 3m x 3m Tradical Hemcrete loaded wall				
Chanvribloc - Brochure complète	*compressive strength*	*Not Stated*	*thermal conductivity - specific heat capacity*	*Not Stated*
Agrément Certificate 10/4726 – Lhoist Wall System, Tradical Hemcrete Wall System	compressive strength - flexural strength	Not Stated. States "testing of samples supplied by the certifi-cate holder was carried out"	thermal conductivity & U-value	Not Stated

Table 2.1 *contd*

Title	Acoustic Properties		Weathering Properties	
	Type	Testing/Assessment method	Type	Testing/Assessment method
Isochanvre technical document	*sound reduction*	*Not Stated*		
Mechanical, thermal and acoustical properties of concrete containing vegetable particles - ABSTRACT ONLY	sound absorption	Not Stated		
Final Report on the Construction of the Hemp Houses at Haverhill, Suffolk	airborne sound insulation	in situ: BS EN ISO 140: Part 4 (1998) & BS EN ISO 717: Part 1 (1997)	water spray test	sample: rotary water spray apparatus
Thermographic Inspection of the Masonry and Hemp Houses at Haverhill, Suffolk				
Utilisation du chanvre pour la préfabrication d'éléments de construction				
Caractérisation d'une maçonnerie composée d'éléments en aggloméré de chanvre	sound reduction	sample: ISO 140/III & ISO 7117/1		
Building with Hemp			water spray test	Refers to tests Conducted by BRE
Hygrothermal behaviour of porous building materials - ABSTRACT ONLY				

Not Conventional Materials for a Sustainable Construction: A Bio-construction System Reinforced with Cellulose Fibres				
An Investigation of Hemp and Lime as a Building Material				
Propriétés mécaniques, thermiques et acoustiques d’un matériau à base de particules végétales: approche expérimentale et modélisation théorique	sound absorbtion	sample: Kundt's tube		
Bioclimatic envelopes made of lime and hemp concrete				
Dynamical interactions between heat and mass flows in Lime-Hemp Concrete				
Sorption behaviour of Lime-Hemp Concrete and its relation to indoor comfort and energy demand				
Porous structure and water vapour sorption of hemp-based materials				
Tradical® Hemcrete® Information Pack	*sound absorption*	*Refers to BRE Testing on Haverhill Houses*		
Mechanical properties of hemp fibre reinforced cement: Influence of the fibre/matrix interaction				
Compressive Strength Testing of Hemp Masonry Mixtures				
Utilization Of Hemp As A Filler Of Cement-bonded Particleboards				

Mechanical and thermal properties of lime and hemp concrete (‘‘hempcrete’’) manufactured by a projection process				
Hemp lime construction. A guide to building with hemp lime composites	sound absorption	Refers to BRE 2002 (Haverhill), Refers to research by ENTPE in France		
The Thermal Performance of Tradical® Hemcrete®				
Transient hygrothermal behaviour of lime-hemp materials				
Comparative study of hygro thermal performances of building materials				
Mechanical properties of lime–hemp concrete containing shives and fibres				
Influence of various chemical treatments on the interactions between hemp fibres and a lime matrix				
Study of the transient behaviour of a hemp concrete building envelope				
Influence of compactness and hemp hurd characteristics on the mechanical properties of lime and hemp concrete				

Hemp-Clay: an initial investigation into the thermal, structural and environmental credentials of monolithic clay and hemp walls				
Fire resistance test in accordance with BS EN 1365-1:1999 on a Lime Technology Ltd, 3m x 3m Tradical Hemcrete loaded wall				
Chanvribloc - Brochure complète	*sound reduction - sound absorption*	*Not Stated*		
Agrément Certificate 10/4726 – Lhoist Wall System, Tradical Hemcrete Wall System				

Table 2.1 *contd*

Title	Fire properties		Modelling		Construction application
	Type	Testing/Assessment method	Type	Software	
Isochanvre technical document	*reaction to fire*	*Refers to CSTB verbal reports No 9233709 and No RA01-397*			*General*
Mechanical, thermal and acoustical properties of concrete containing vegetable particles - ABSTRACT ONLY					General
Final Report on the Construction of the Hemp Houses at Haverhill, Suffolk					Infill
Thermographic Inspection of the Masonry and Hemp Houses at Haverhill, Suffolk					Infill
Utilisation du chanvre pour la préfabrication d'éléments de construction					Masonry
Caractérisation d'une maçonnerie composée d'éléments en aggloméré de chanvre					Masonry
Building with Hemp					General
Hygrothermal behaviour of porous building materials - ABSTRACT ONLY					General
Not Conventional Materials for a Sustainable Construction: A Bio-construction System Reinforced with Cellulose Fibres					General

An Investigation of Hemp and Lime as a Building Material					General
Propriétés mécaniques, thermiques et acoustiques d'un matériau à base de particules végétales: approche expérimentale et modélisation théorique			thermal - HAC (modélisation par homogénéisation autocohérente)		General
Bioclimatic envelopes made of lime and hemp concrete			hygro-thermal	WUFI	Infill
Dynamical interactions between heat and mass flows in Lime-Hemp Concrete			hygro-thermal	WUFI	General
Sorption behaviour of Lime-Hemp Concrete and its relation to indoor comfort and energy demand			hygro-thermal	WUFI	Infill
Porous structure and water vapour sorption of hemp-based materials					General
Tradical® Hemcrete® Information Pack	*resistance to fire - reaction to fire*	*Refers to fire testing carried out by CSTB*			*General*
Mechanical properties of hemp fibre reinforced cement: Influence of the fibre/matrix interaction					General
Compressive Strength Testing of Hemp Masonry Mixtures					Masonry
Utilization Of Hemp As A Filler Of Cement-bonded Particleboards					Masonry

Mechanical and thermal properties of lime and hemp concrete (''hempcrete'') manu-factured by a projection process					Masonry
Hemp lime construction. A guide to building with hemp lime composites	resistance to fire - reaction to fire	Refers to research by ENTPE and CSTB in France			General
The Thermal Performance of Tradical® Hem-crete®					*General*
Transient hygrothermal behaviour of lime-hemp materials			hygro-thermal	WUFI	Infill
Comparative study of hygro thermal per-formances of building materials					General
Mechanical properties of lime–hemp con-crete containing shives and fibres					General
Influence of various chemical treatments on the interactions between hemp fibres and a lime matrix					General
Study of the transient behaviour of a hemp concrete building envelope			thermal (th) & hygrothermal (HAM) models	Spark	General
Influence of compactness and hemp hurd characteristics on the mechanical properties of lime and hemp concrete					Infill

Hemp-Clay: an initial investigation into the thermal, structural and environmental cre-dentials of monolithic clay and hemp walls					Infill
Fire resistance test in accordance with BS EN 1365-1:1999 on a Lime Technology Ltd, 3m x 3m Tradical Hemcrete loaded wall	resistance to fire	BS EN 1365-1:1999			Infill
Chanvribloc - Brochure complète	*resistance to fire - reaction to fire*	*(based on other sources)*			*Masonry*
Agrément Certificate 10/4726 – Lhoist Wall System, Tradical Hemcrete Wall System	resistance to fire	BS EN 1365-1:1999			Infill

Table 4.1 Hemp Lime Material Properties Detailed Data Table

This table presents a summary of data gathered by BESRaC from a review of key technical literature on hemp lime as known and available at date of study (early 2010) and is not an exhaustive list of all data on the subject. This table presents a comparative summary of the some of the principal relevant data for this study and includes excerpts of the contents. Original documents should be referred to for detail and verification. Note - Reported values can be based on specific / particular mixes and test methods and as such are not always directly comparable to other data. While every reasonable effort has been made to ensure accuracy the authors accept no responsibility for errors or liability arising from use of this data.

BINDER MIX LEGEND

HH	Hemp Hurds
HF	Hemp Fibre
L	Lime
L (Tradical)	Proprietary Lime Mix (UK Manufacturer Lime Technology)
L (Isochanvre)	Proprietary Lime Mix (French manufacturer Isochanvre)
C	Cement
A	Additives
S	Sand

DENSITY							
Value Range [kg/m^3]		Mix/es	Sample/Application	Construction application	Source	Test	Notes
425	1196	HH - HF - L - S	lab samples - cubes & cylinders - compacted with procton hammer	general	O'Dowd & Quinn, 2005	not stated	3 mixes: HH+L; HH+HF+L; HH+L+S
587	733	HH - HF - L - C	lab samples - cubes & cylinders - hand compaction	general	de Bruijn et al., 2009	determined by calculating the mean value for five measurements of 1 l of uncompacted material	
256	782	HH - L (Tradical)	lab samples - compaction between 0.02 to 0.1 MPa	wall infill - roof insulation - slab - plaster	Cerezo, 2005	not stated	
480		HH - L (Tradical)	labs samples - hand compaction	wall infill	Evrard & De Herde, 2005	not stated	
480		HH - L (Tradical)	labs samples - hand compaction	wall infill	Evrard et al., 2006	not stated	
398		HH - L (Tradical)	lab samples - hand compaction	wall infill	Evrard, 2008	HL poured out in a 1 litre cylinder	
672	990	HH - HF - L	low compaction (hand) & heavy compaction (compression device)	wall infill	Nguyen et al., 2009	not stated	

453		HH - L (Tradical)	sample	wall infill	BBA, 2010	not stated	
507	603	HH - L - C - A	cement brick machinery - vibration and compaction	blocks	Bütschi et al., 2003	not stated	no details on additives & compaction
627	730	HH - L - C - A	cement brick machinery - vibration and compaction	blocks	Bütschi et al., 2004	EN 772-13	no details on additives & compaction
523	1872	HH - HF - L - C	lab samples - cubes & cylinders	blocks	Chew & MacDougall, 2007	by weighing the samples before and after placing them in a drying oven at 100 ºC for approximately 20 hours	no details on compaction
291	607	HH - L (Tradical)	spray into block moulds	blocks	Elfordy et al., 2007	estimated by measuring and weighing the 50 * 50 * 50 mm3 cubes that had been cut out from the fabricated blocks.	spray distance varying from 0.5 to 3 m
256		HH - L (Tradical)	lab samples - hand mix - hand compaction	roof insulation	Evrard, 2008	HL poured out in a 1 litre cylinder	

1285		HH - C - A	sample board	particleboard	Bydžovský & Khestl, 2007	not stated	no details on compaction
318	734	HH - L - Clay	lab samples - block	hemp clay	Busbridge, 2009	not stated	quicklime added only in some samples

DRY TOTAL POROSITY							
Value Range [% vol]		**Mix**	**Method/Application**	**Construction application**	**Source**	**Test**	**Notes**
71.1%		HH - L (Tradical)	labs samples - hand compaction	wall infill	Evrard & De Herde, 2005	helium pycnometer + calculation	
73%		HH - L (Tradical)	lab samples - hand compaction	wall infill	Evrard, 2008	helium pycnometer + calculation	

DRY VAPOUR RESISTANCE							
Value Range [μs]		**Mix**	**Method/Application**	**Construction application**	**Source**	**Test**	**Notes**
4.80		HH - L (Tradical)	labs samples - hand compaction	wall infill	Evrard & De Herde, 2005	EN ISO 12572 with dry cup and wet cup methods	
3.59	7.68	HH - L (Tradical)	lab samples cylinder - hand/electric mixing - hand/heavy compaction	wall infill	Evrard, 2006	EN ISO 12572 with dry cup method	

WATER ABSORPTION COEFFICIENT						
Value [kg/(m²√s)]	**Mix**	**Method/Application**	**Construction application**	**Source**	**Test**	**Notes**

0.15		HH - HF - L - C	lab samples - cubes & cylinders - hand compaction	general	de Bruijn et al., 2009	samples in water and weighted at different times --> formula	
0.075		HH - L (Tradical)	labs samples - hand compaction	wall infill	Evrard & De Herde, 2005	DIN 52 617	

COMPRESSIVE STRENGTH							
Value Range [MPa]		**Mix**	**Method/Application**	**Construction application**	**Source**	**Test**	**Notes**
0.40	1.20	HH - L	Not Stated. (abstract only)	general	Arnaud & Cerezo, 2002	Not Stated. (abstract only)	(abstract only)
0.30	1.10	HH - WP - L - MK - A	lab samples - cylinders	general	Eires & Jalali, 2005	numerical control hydraulic press	WP = waste paper; MK = metakaoline - no details on compaction
0.54	2.63	HH - HF - L - S	lab samples - cubes & cylinders - compacted with procton hammer	general	O'Dowd & Quinn, 2005	BS ISO 844:2004 (rigid cellular plastic)	3 mixes: HH+L; HH+HF+L; HH+L+S
0.25	1.15	HH - L (Tradical)	lab samples - compaction between 0.02 to 0.1 MPa	wall infill - roof insulation - floor slab - plaster	Cerezo, 2005	electromechanic press with lateral sensors	
0.15	0.83	HH - HF - L - C	lab samples - cubes & cylinders - hand compaction	general	de Bruijn et al., 2009	measure of forces and relative displacements - formula: F/A	

0.458		HH - L (Tradical)	lab samples	wall infill	BRE, 2002	BS ISO 844: 1998 for cellular plastics	no details on compaction
0.836		HH - L (Tradical)	lab samples	floor	BRE, 2002	BS ISO 844: 1998 for cellular plastics	no details on compaction
0.8		HH - L (Tradical)	sample	wall infill	BBA, 2010	Not Stated.	
1.3	2.0	HH - L - C - A	cement brick machinery - vibration and compaction	blocks	Bütschi et al., 2003	numerical control hydraulic press	no details on additives & compaction
1.7	3.4	HH - L - C - A	cement brick machinery - vibration and compaction	blocks	Bütschi et al., 2004	prEN 772-1:1996 & prEN 1052-1:1995	no details on additives & compaction
0.06	13.58	HH - HF - L - C	lab samples - cubes & cylinders	blocks	Chew & MacDougall, 2007	Riehle or Unite-O-matic concrete compression testing machine	no details on compaction
0.18	0.85	HH - L (Tradical)	spray into block moulds	blocks	Elfordy et al., 2007	Not Stated.	spray distance varying from 0.5 to 3 m

YOUNG MODULUS							
Value Range [N/mm2]		**Mix**	**Method/Application**	**Construction application**	**Source**	**Test**	**Notes**
20	90	HH - L	Not Stated. (abstract only)	general	Arnaud & Cerezo, 2002	Not Stated. (abstract only)	(abstract only)

12.65	49.40	HH - HF - L - C	lab samples - cubes & cylinders - hand compaction	general	de Bruijn et al., 2009	calculated with equation (Hooke's Law) on the slope of the stress-strain curve	
12,700	13,100	HF - C	lab samples	general	Sedan et al., 2007	non-destructive ultrasonic method	fibres subjected to different surface treatments
4	160	HH - L (Tradical)	lab samples - compaction between 0.02 to 0.1 MPa	wall infill - roof insulation - slab - plaster	Cerezo, 2005	electromechanic press with lateral sensors	
20	180	HH - L - C - A	cement brick machinery - vibration and compaction	blocks	Bütschi et al., 2004	equation on the stress-strain curve	no details on additives & compaction
4	35	HH - L (Tradical)	spray into block moulds	blocks	Elfordy et al., 2007	estimated by measuring the maximum slope of the stress–strain curve	spray distance varying from 0.5 to 3 m
113	15,489	HH - HF - L - C	lab samples - cubes & cylinders	blocks	Chew & MacDougall, 2007	Not Stated.	no details on compaction
7,330		HH - C - A	sample board	particleboard	Bydžovský & Khestl, 2007		no details on compaction

TENSILE STRENGTH						
Value [MPa]	**Mix**	**Method/Application**	**Construction application**	**Source**	**Test**	**Notes**

0.08	0.25	HH - HF - L - S	lab samples - cubes & cylinders - compacted with procton hammer	general	O'Dowd & Quinn, 2005	BS 8110	3 mixes: HH+L; HH+HF+L; HH+L+S
11.90		HH - C - A	sample board	particleboard	Bydžovský & Khestl, 2007		no details on compaction

FLEXURAL STRENGTH							
Value Range [MPa]		**Mix**	**Method/Application**	**Construction application**	**Source**	**Test**	**Notes**
6.80	9.50	HF - C	lab samples	general	Sedan et al., 2007	three point bending test	fibres subjected to different surface treatments
1.43	2.01	HF - L	lab samples	general	Le Troëdec et al., 2009	three point bending test	fibres subject to chemical treatments
0.38		HH - L (Tradical)	sample	wall infill	BBA, 2010	Not Stated.	
0.83	1.21	HH - L (Tradical)	spray into block moulds	blocks	Elfordy et al., 2007	three point bending test	spray distance varying from 0.5 to 3 m

THERMAL CONDUCTIVITY							
Value Range [W/(mK)]		**Mix**	**Method/Application**	**Construction application**	**Source**	**Test**	**Notes**
0.06	0.11	HH - L	Not Stated. (abstract only)	general	Arnaud & Cerezo, 2002	Not Stated. (abstract only)	(abstract only)

0.06	0.10	HH - L (Tradical)	lab samples - compaction between 0.02 to 0.1 MPa	wall infill - roof insulation - slab - plaster	Cerezo, 2005	heat box & model	low density [200kg/m3] dry - 50% RH - 75% RH
0.10	0.13	HH - L (Tradical)	lab samples - compaction between 0.02 to 0.1 MPa	wall infill - roof insulation - slab - plaster	Cerezo, 2005	heat box & model	medium density [450kg/m3] dry - 50% RH - 75% RH
0.12		HH - L (Tradical)	labs samples - hand compaction	wall infill	Evrard et al., 2006	Not Stated.	
0.115		HH - L (Tradical)	lab samples cylinder - hand/electric mixing - hand/heavy compaction	wall infill	Evrard, 2006	hot/cold plate (DIN 5216)	
0.115		HH - L (Tradical)	lab samples - hand compaction	wall infill	Evrard, 2008	hot/cold plate	
0.120		HH - L (Tradical)	sample	wall infill	BBA, 2010	Not Stated.	density of 489 kg/m3
0.34		HH - L - C - A	cement brick machinery - vibration and compaction	blocks	Bütschi et al., 2004	heat box	
0.179	0.543	HH - L (Tradical)	spray into block moulds	blocks	Elfordy et al., 2007	hot/cold plate	spray distance varying from 0.5 to 3 m
0.09	0.22	HH - L - Clay	lab samples - block	hemp clay	Busbridge, 2009	transient heat-transfer analyzer probe	quicklime added only in some samples

SPECIFIC HEAT CAPACITY						
Value [J/(kgK)]	**Mix**	**Method/Application**	**Construction application**	**Source**	**Test**	**Notes**

1550		HH - L (Tradical)	labs samples - hand compaction	wall infill	Evrard & De Herde, 2005	measured in adiabatic surrounding from the thermal capacity of water, mass of water and mass of sample - samples dried, heated to 100°C and put into water at 22°C	
1560		HH - L (Tradical)	lab samples - hand compaction	wall infill	Evrard, 2008	same as above	

U - VALUE							
Value Range [W/(m² K)]		**Mix**	**Method/Application**	**Construction application**	**Source**	**Test**	**Notes**
0.37		HH - L (Tradical)	Not Stated.	wall infill	BBA, 2010	Not Stated.	300mm thick wall
0.23		HH - L (Tradical)	Not Stated.	wall infill	BBA, 2010	Not Stated.	500mm thick wall
0.89		HH - L - C - A	cement brick machinery - vibration and compaction	blocks	Bütschi et al., 2004	resulting from thermal conductivity	310mm thick block wall

ACOUSTIC - SOUND REDUCTION							
Value Range [Db]		**Mix**	**Method/Application**	**Construction application**	**Source**	**Test**	**Notes**
57	58	HH - L (Tradical)	in situ	wall infill	BRE, 2002	BS EN ISO 140: Part 4 (1998) & BS EN ISO 717: Part 1 (1997)	sound reduction

43	47	HH - L - C - A	cement brick machinery - vibration and compaction	blocks	Bütschi et al., 2004	ISO 140/III & ISO 7117/1	sound reduction
ACOUSTIC - SOUND ABSORPTION COEFFICIENT							
Value Range [α]		**Mix**	**Method/Application**	**Construction application**	**Source**	**Test**	**Notes**
0.5	1	HH - L	Not Stated. (abstract only)	general	Arnaud & Cerezo, 2002	Not Stated. (abstract only)	sound absorption
0.3	0.9	HH - L (Tradical)	lab samples - compaction between 0.02 to 0.1 MPa	wall infill - roof insulation - slab - plaster	Cerezo, 2005	Kundt's tube	sound absorption

RESISTANCE TO FIRE							
Value Range [Min]		**Mix**	**Method/Application**	**Construction application**	**Source**	**Test**	**Notes**
73 min		HH - L (Tradical)	3m x 3m Tradical Hemcrete loaded wall	wall infill	BRE, 2009	BS EN 1365-1:1999	performance of 73mins on integrity, insulation, load bearing capacity
73 min		HH - L (Tradical)	3m x 3m Tradical Hemcrete loaded wall	wall infill	BBA, 2010	BS EN 1365-1:1999	performance of 73mins on integrity, insulation, load bearing capacity
REACTION TO FIRE							
Value Range [Classification]		**Mix**	**Method/Application**	**Construction application**	**Source**	**Test**	**Notes**

WEATHERING							
Value [mm]		Mix	Method/Application	Construction application	Source	Test	Notes
50	70	HH - L (Tradical)	sample	wall infill	BRE, 2002	rotary spray apparatus	

Table 4.2 Hemp Lime Material Properties Test Data and Comparison Table

This table presents a summary of data gathered by BESRaC from a review of key technical literature on hemp lime as known and available at date of study (early 2010) and is not an exhaustive list of all data on the subject. This table presents a comparative summary of the some of the principal relevant data for this study and includes excerpts of the contents. Original documents should be referred to for detail and verification. Note - Reported values can be based on specific / particular mixes and test methods and as such are not always directly comparable to other data. While every reasonable effort has been made to ensure accuracy the authors accept no responsibility for errors or liability arising from use of this data.

		SOURCE	TEST METHOD	VALUE	TEST CENTRE	NOTES
STRUCTURE	**STANDARD**	TGD A	IS 20 - gradual application of load at a set rate to a number of sample blocks and the average compressive strength is recorded	min 5 N/mm2 (Class A blocks) min 3 N/mm2 (Class B blocks) no strength requirements (Class C blocks)	Accredited	Replaced By IS EN 771-3
			I.S. EN 771-3 Specification for masonry units - Part 3: Aggregate concrete masonry units (Dense and lightweight aggregates)		Accredited	
			EN 772-1 Methods of test for masonry units. Determination of compressive strength	Compressive Strength (N/mm^2)	Accredited	
			I.S.EN 12390: Testing hardened concrete. made up of 8 parts each dealing with a different aspect of tests for hardened concrete		Accredited	

			I.S.EN 12390: Testing hardened concrete Part 3: Compressive strength of test specimens	Compressive Strength (N/mm^2)	Accredited	
			EN 1015-11 describes a method for determining the compressive strength of masonry mortars	Compressive strength result used to classifiy mortars in accordance with I.S. EN 998-2	Accredited	
		Other	EN 1052-1 Methods of test for masonry. Determination of compressive strength		Accredited	
			BS 4551:2005+A1:2010 Mortar. Methods of test for mortar. Chemical analysis and physical testing		Accredited	
			ASTM C39 standard test method for compressive strength of cylindrical concrete specimens		Accredited	
			ISO 844: 1998 (2004) Cellular plastics. Compression test for rigid materials. Specification		Accredited	
			ASTM C109 standard test method for compressive strength of hydraulic cement mortars using cube specimens		Accredited	
	RESEARCH DATA	Bütschi et al., 2003	Unknown	Between 1.3 and 2.0 N/mm2	Unknown whether accredited (University)	Masonry
		Bütschi et al., 2004	EN 772-1 (similar to IS20 with differences in fixing of platens during loading) & EN 1052-1 (compressive strength of masonry wall built in partial section	Between 1.7 and 3.4 N/mm2	Unknown whether accredited (University)	Masonry

			including mortar joints and load applied at a set rate)			
		Chew & MacDougall, 2007	ASTM C109 (standard test method for compressive strength of hydraulic cement mortars using cube specimens) & ASTM C39 (standard test method for compressive strength of cylindrical concrete specimens)	Between 0.06 and 13.5 N/mm2 [Equivalent Value to Class A, B and C blocks]	Unknown whether accredited (University)	Masonry
		Elfordy et al., 2007	Unknown	Between 0.18 and 0.85 N/mm2	Unknown whether accredited (University)	Masonry
		SOURCE	**TEST METHOD**	**VALUE**	**TEST CENTRE**	**NOTES**
FIRE	**STANDARD**	TGD B	Fire resistance: National Classification BS 476: Parts 20-24:1987 (Fire Tests on Building Materials and Structure, describe the tests on which the national classifications are based) European Classification I.S. EN 13501-2 : 2003 (classification of construction products and building elements using data from fire resistance tests EN 1363-1, EN 1363-2, EN 1364-1, EN 1364-2, EN 1365-1, EN 1365-4)	Typical values required are for 30 and 60 minutes classification with some structures and elements requiring 90 and 120 minutes as set out in Table A1 - Fire Resistances	Accredited	

			Fire resistance: National Classification BS 476: parts 6 and 7 (Fire Tests on Building Materials and Structure, describe the tests on which the national classifications are based) European Classification I.S. EN 13501-1 : 2002 (classification of construction products and building elements using data from reaction to fire tests I.S. EN ISO 1182: 2002, I.S. EN ISO 1716: 2002, I.S. EN 13823: 2002, BS EN ISO 11925-2: 2002)	Based on classifications as outlined in Table 2, class 1, 2, 3 and 4	Accredited	
	RESEARCH DATA	BRE, 2009	Fire resistance - BS EN 1365-1:1999 (Fire Resistance of Load Bearing Elements)	3m x 3m non rendered/plastered HL wall subject to vertical load of 135kN resisted for 73 minutes in respect to integrity, insulation, and load bearing capacity	Accredited test centre	Timber frame infill
		BRE, 2009	Fire spread (reaction) - BS EN 13501-1 (Fire classification of construction products and building elements)	HL external rendered HL wall assessed in respect of the top coat component achieved a Class A1 (limited combustibility or non combustibility) with less than 1% organic content	Accredited test centre	Wall infill
		SOURCE	**TEST METHOD**	**VALUE**	**TEST CENTRE**	**NOTES**

		TGD C	No specific measure or test is specified in relation to moisture penetration with the stated requirement being for ‘reasonable protection’	No values are stated. Good practice construction for masonry walls is provided insofar as it relates to non-complex buildings of normal design and construction	n.a.	
		Other	ASTM C1601 - 10 Standard Test Method for Field Determination of Water Penetration of Masonry Wall Surfaces	Unknown	Accredited test centre	
			ASTM E514/E514M - 09 Standard Test Method for Water Penetration and Leakage Through Masonry	Unknown	Accredited test centre	
			BS EN 12390-8:2009 Testing hardened concrete. Depth of penetration of water under pressure	Unknown	Accredited test centre	
			BS 4315-2:1970 Methods of test for resistance to air and water penetration. Permeable walling constructions (water penetration)	Unknown	Accredited test centre	
	STANDARD		BS 1881-208:1996 Testing concrete. Recommendations for the determination of the initial surface absorption of concrete	Unknown	Accredited test centre	
MOISTURE	**RESEARCH DATA**	BRE, 2002	Water spray penetration tests on plastered HL 200mm thick test walls with water levels similar to one year of wind driven rain at a severly exposed location were carried out over 96 hours period.	Absorption reached an average 50-70mm depth	Accredited test centre	Wall infill

		SOURCE	TEST METHOD	VALUE	TEST CENTRE	NOTES
SOUND	**STANDARD**	TGD E	Requirement is for 'reasonable resistance'. Various construction solutions are given	Illustrations of typical constructions are shown in the TGD E that, when built correctly show prima facie compliance with Part E. Section 4 describes a test method to be employed in order to establish whether a particular construction, present in one development, will be suitable for use in another develop-ment. A table sets out guideline sound transmission values that should be achieved under test if the acoustical performance is to be deemed acceptable for these purpos-es. In the absence of any other form of objective guidance, these values are often employed as a basis for as-sessing sound insulation perfor-mance. The current target mean airborne sound insulation values in Section 4, Table 1 are 53dB DnT,w (walls) and 52 dB D nT,w (floors) allowing individual values, within a group of tests, to be 4dB (e.g. 49dB and 48dB) lower than the target mean value. For impact sound transmission, the tar-get mean is 61dB L’nT,w but in-		

				dividual tests can be 4dB above (e.g. 65 dB L’nT,w)		
			Walls - (Solid masonry or cavity masonry) The principal deter-mining limiting factor is construc-tion mass	No actual sound transmission values are specified. Construction mass 415 kg/m2 (concrete or concrete blocks with plaster) and 375 kg/m2 (clay bricks with plaster		Illustrations of typical constructions are shown in the TGD E that, when built correct-ly show pri-ma facie com-pliance with Part E
			Timber frame construction or proprietary solutions forms of construction should be under-written by 'recognised testing houses' and suitable for achiev-ing 'reasonable resistance'.	The 'Homebond' construction manual provides details in relation to timber frame solutions. The resistance to airborne sound of a timber framed wall depends on the mass per unit area of the leaves, the isolation of the frames, and the ab-sorption in the cavity between the frames.		
			Floors - Construction and details for separating first floors are setout.	Type 1 (concrete base with a soft covering): mass 365 kg/m2 - Type 2 (concrete base with a floating floor): mass 220 kg/m2 - Type 3 (timber base with floating layer): min 25mm thick layer of mineral fibre and 100mm thick layer of mineral fibre between joists		Illustrations of typical constructions are shown in the TGD E that, when built correct-ly show pri-ma facie compliance

						with Part E.
			Similar Constructions: BS 2750 Part 4 1980 (for airborne sound insulation of a separating wall or floor)	Weighted Standardised Level Difference (D_nT,w)	Accredited test centre	Superseded by BS EN ISO 140-4: 1998, Refer to other below
			Similar Constructions: BS 2750 Part 7 1980 (for impact sound transmission of a separating floor)	Weighted Standardised Impact Sound Pressure Levels (L_nT,w)	Accredited test centre	Superseded by BS EN ISO 140-7: 1998, Refer to other below
		Other	UK Build. Reg. 2000 approved document E 2003 edition incorporating 2004 amendments. 'Resistance to the passage of sound' gives sound insulation values for separating walls, floors and stairs that provide a separating function between dwellings/rooms for residential purposes.	Typical values from table 0.1a and b for airborne sound insulation range between 43 to 45 D nT,w +C tr dB. Impact sound insulation values for separating floors and stairs range from 62 to 64 L'nT,w dB.	Accredited test centre	Note further amendments have taken place in 2010.
			UK Build. Reg. 2000 approved document E, 2003 Edition incorporating 2004 amendments re-	TEST METHOD Weighted Standardised Level Difference (D_nT,w)	Accredited test centre	

			fers to test method BS EN ISO140 Part 4 1998 (for airborne sound insulation of a separating wall or floor)			
			UK Build. Reg. 2000 approved document E, 2003 Edition incorporating 2004 amendments refers to test method BS EN ISO140 Part 7 1998 (for impact sound transmission of a separating floor)	TEST METHOD Weighted Standardised Impact Sound Pressure Levels (L_nT,w)	Accredited test centre	
	RESEARCH DATA	BRE, 2002	BS EN ISO 140-4:1998 (Measurement of sound insulation in buildings and of building elements. Field measurements of airborne sound insulation between rooms) - BS EN ISO 717-1:1997 (Rating of sound insulation in buildings and of building elements. Airborne sound insulation)	In situ test with HL infill walls (two 150mm thick wall leaves with 100mm stud and 75mm cavity). Sound reduction of 57-58 dB	Accredited test centre	Wall infill
		Bütschi et al., 2004	ISO 140-3 (Measurement of sound insulation in buildings and of building elements. Laboratory measurement of airborne sound insulation of building elements)	Sound reduction of 43-47 dB for structural HL blocks	Unknown whether accredited (University)	Masonry
		SOURCE	**TEST METHOD**	**VALUE**	**TEST CENTRE**	**NOTES**

ENERGY	STANDARD	TGD L	IS EN ISO 10456:2007 Building materials and products - Hygrothermal properties - Tabulated design values and procedures for determining declared and design thermal values			
			EN 1745:2020 Masonry and masonry products - Method for determining design thermal values	Thermal transmittance U [W/m^{2}K] & Thermal resistance R [m^{2}K/W]	Accredited test centre	
			EN 8990:1997 Thermal insulation - Determination of steady-state thermal transmission properties - Calibrated and guarded hot box	Thermal transmittance U [W/m^{2}K] & Thermal resistance R [m^{2}K/W]	Accredited test centre	
		Other	ISO 8301:1991 Thermal insulation -Determination of steady-state thermal resistance and related properties -Heat flow meter apparatus	Thermal transmittance U [W/m^{2}K] & Thermal resistance R [m^{2}K/W]	Accredited test centre	
			ISO 8302:1991 Thermal insulation - Determination of steady-state thermal resistance and related properties - Guarded hot plate apparatus	Thermal transmittance U [W/m^{2}K] & Thermal resistance R [m^{2}K/W]	Accredited test centre	
			DIN 52616	Unknown		
	RESEARCH DATA	Cerezo, 2005	heat box (built for the purpose) & model of dry and wet conductivity	Between 0.06 and 0.10 W/(mk) [low density - 200kg/m3 - dry. 50%RH, 75%RH] Between 0.10 and 0.13 W/(mk) [medium density - 450kg/m3 - dry, 50%RH, 75%RH]	Unknown whether accredited (University)	wall infill - roof insulation - slab - plaster (lab samples, compaction between 0.02

						and 0.1 Mpa)
		Evrard, 2006	hot/cold plate (DIN 5216)	0.115 W/(mk) - mean value	Unknown whether accredited (University)	wall infill
		Evrard, 2008	hot/cold plate - DIN 52 615 (Testing of thermal insulating materials; determination of water vapour (moisture) permeability of construction and insulating materials)	0.115 W/(mK)	Unknown whether accredited (University)	wall infill
		Elfordy et al., 2007	hot/cold plate - unknown standard	Between 0.179 and 0.543 W/(mK)	Unknown whether accredited (University)	blocks