Ruth Busbridge
MSC Architecture: Advanced
Environment & Energy Studies
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Graduate School of the Environment
Centre for Alternative Technology,
Machynlleth
Powys
SY20 9AZ
Tel: 01654 705981

School of Computing and Technology
University of East London
Docklands Campus
4-6 University Way
London
E16 2RD
Tel: 0208 223 3000

Hemp-Clay: an initial investigation into the thermal, structural and environmental credentials of monolithic clay and hemp walls.

Abstract

The benefits of hemp-lime construction are discussed. Its monolithic walls enclose and protect a structural timber frame and provide a breathable construction that meets UK building regulations through largely passive means. The absence of toxic or synthetic materials ensures a healthy living environment.

The eco-credentials of hemp and its ability to sequester carbon are reviewed and are found to be convincing. However the high embodied energy and carbon dioxide emissions associated with lime limit the potential of the method for carbon sequestration. The literature on light-earth construction is reviewed drawing particularly on German experience, and the parallels between the two methods are highlighted.

The main experimental research focuses on the thermal properties of stabilised and un-stabilised hemp-clay blocks which are tested using a transient heat-transfer probe to measure thermal conductivity, volumetric heat capacity and derive thermal diffusivity and effusivity. Rudimentary compressive strength tests are also conducted. Results are compared with published values for hemp-lime and found to be similar.

A discussion of the results assesses the use of clay as an alternative binder in the hemp-binder method, and concludes that it has potential to reduce the environmental impact of the method and facilitate the move towards zero-carbon housing.

Acknowledgements

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Finally, I am indebted to my partner Brett, for his proofreading, patience, support , and his tolerance of hemp-clay chaos.

Contents

Abbreviations

λ   Thermal conductivity
AECB   Association of Environmentally Conscious Builders
BRE   Building Research Establishment
CEC   Cation exchange capacity
DTI   Department of Trade and Industry
EE   Embodied energy
EC   Embodied carbon
EMC   Equilibrium moisture content
LEC   Light-earth construction
MC   Moisture content
MMC   Modern methods of construction
OPC   Ordinary Portland cement
RH   Relative humidity
WME   Wood moisture equivalent

Glossary of Terms

%WME (Wood moisture equivalent) – a unit for measuring the moisture content of
materials other than timber. This is the amount of moisture that would be
contained by timber if it were in moisture equilibrium with the material being
measured. Timber is used as the standard because, unlike other materials, its
moisture content is predictable when it is exposed to any given relative
humidity; eg if the relative humidity is 60% any timber will contain roughly 11%
moisture (see also sections 3.7 and Appendix 3.7)

Absorption - a liquid or gas permeates into or is dissolved by another liquid or solid forming
a solution, ie molecules of one substance are taken up by the volume of
another.

Adsorption - a liquid or gas accumulates on the surface of a solid forming a thin film, often
only a molecule thick; ie molecules of one substance are taken up by the
surface of another substance

Air lime - lime produced from high purity limestone. It sets by carbonation alone, slowly
absorbing CO_2 from the atmosphere and turning back into limestone.

Breathable wall/construction – a method of building that uses vapour permeable materials, allowing water vapour to naturally diffuse through the walls. Breathability is a bit of a misnomer, it is about the passage of water vapour not air. It focuses on the ability of materials to absorb and release water vapour and liquid water. Breathable buildings can be airtight, and indeed should be.

Bulk density - defined as the mass of the many particles of a material divided by the total volume they occupy. This volume includes the volume of the material of the particles plus the voids between the particles and the pores within the particles. The bulk density can change as the material is handled, and is always less than the solid density.

Carbon sequestration – The process of removing carbon from the atmosphere (generally in the form of CO_2) and storing it in a stable form in a carbon sink of some type thereby preventing it from being re-released into the atmosphere. Natural carbon sinks are forests, soils, oceans, but carbon can be sequestered artificially eg in underground reservoirs, depleted oil and gas fields. With judicious choice of materials, carbon can also be sequestered in buildings.

Cation exchange capacity (CEC) – a term to describe the capacity of soils to exchange positively charged ions (cations) between the soil and the soil solution. It is a measure of fertility and nutrient retention capacity, but also (importantly for building) binding ability.

Capillary absorption – liquid water drawn into capillaries in a material through the action of surface tension.

Clay slip - a mixture of plastic clay in water, blended to a smooth consistency. For the purposes of this study the following terms are used: '1:1 slip' = 1kg water to 1kg plastic clay, '1:1.5 slip' = 1kg water to 1.5kg plastic clay, and '1:2 slip' = 1kg water to 2kg plastic clay

Dewpoint – when a sample of air is cooled the relative humidity (RH) rises. The dewpoint is the temperature at which the water in the air starts to condense out because RH has reached 100%, ie the air has become saturated.

Embodied carbon – similar to embodied energy but referring to the carbon dioxide released into the environment as a result of all processes relating to the provision of a material, product or service. Sometimes quoted in tonnes of carbon, and sometimes in tonnes of CO_2.

Embodied energy – the amount of energy used in all processes associated with the manufacture and supply of a material, product or service during its entire life cycle; including mining, processing, manufacturing, packaging, distribution, recycling, disposal, etc. Start and end points for the calculation should be

specified for it to be meaningful. Sometimes it is calculated as cradle to (factory) gate, or cradle to site, rather than cradle to grave.

Equilibrium moisture content – the amount of water contained in a material when it is in moisture equilibrium with air at a specified temperature and relative humidity. It depends on the hygroscopicity of the material. Moisture content is measured as a percentage of the dry weight (the material must be oven dried to 105°C for > 2hrs [Oxley & Gobert, 2006, 12]).

$$moisture\ content = \frac{wet\ weight - dry\ weight}{dry\ weight} * 100$$

Free water – water in a material that is not bound by electrostatic forces but is instead free to move (eg under the influence of gravity, capillary action, electricity); the free water content is measurable by a conducting moisture probe.

Heat capacity – "heat required to raise the temperature of a substance by unit temperature interval under specified conditions, usually measured in joules per Kelvin" [Collins English Dictionary]. See specific and volumetric heat capacity.

Hemp hurds (aka hemp shivs) – the chopped woody core of the stem of the hemp plant

Hydraulic lime - lime produced from limestone with high levels of clay minerals and other impurities which provide a hydraulic set, ie a chemical reaction in the presence of water. Natural Hydraulic Limes are graded according to their hydraulicity: NHL 1 to 5. They also harden slowly by carbonation, but the much faster hydraulic reaction provides early strength.

Hygroscopic - adj: of a substance, tending to absorb vapour water from the air; attracts and absorbs water vapour molecules.

Hygric – pertaining to water vapour

Interstitial condensation – condensation that occurs within the fabric of the external walls of a building due to the changes in temperature and relative humidity between inside and outside.

Light-earth construction (LEC) - a mix of earth containing a high clay content with a fibre such as straw, hemp, or woodchips that is pushed into a formwork between or around a timber frame to form an insulative infill material.

Lime – see Hydraulic lime and Air lime.

Monolithic construction – buildings whose walls consist of a single skin of material (like an igloo) as opposed to a series of different materials layered on top of one another.

Mycotoxins - secondary metabolites of moulds. Moulds produce mycotoxins in response to environmental stress, such as other competing fungi and bacteria or changes in pH.

Perlite – an expanded form of granular volcanic glass

Pozzolan – any of various natural or artificial additives such as volcanic ash, fly ash, rice hull
ash, that are added to lime based binders to give a chemical set. They are
generally very fine particles that have been subjected to very high
temperatures.

R-value. See Thermal resistance.

Relative humidity - Water can exist at normal temperatures in either liquid or vapour
states. Water vapour in the air exerts pressure on the surfaces containing it.
This vapour pressure increases as the amount of vapour in the air increases. Air
at a given temperature can only support a certain amount of water vapour and
no more. Any more and the vapour starts to condense into liquid water. This is
the saturation humidity for the air at that temperature. The relative humidity
(RH) of the air at a given temperature and pressure can be defined as

$$\frac{\text{vapour pressure of water in air}}{\text{vapour pressure of water in air at saturation humidity}} * 100$$

When air at a given temperature is warmed or cooled its RH changes. If air at
0^oC and 100% RH is warmed to 20^oC the RH drops to around 25%; the RH inside
is often lower than outside, particularly in the winter.

Retting - to ret is "to moisten or soak (flax, hemp, jute, etc) to promote bacterial action in
order to facilitate separation of the fibres from the woody tissue by beating"
[Collins English Dictionary].

Sequestered carbon. Carbon removed from the atmosphere and stored permanently in a
stable form. Carbon is stored in the sea, the soil and fossil reserves. Fossil fuel
use has resulted in stored carbon being released into the atmosphere largely in
the form of carbon dioxide (CO_2) and methane (CH4), two of the most
significant greenhouse gases. Carbon sequestration is an attempt to reverse
this process. It can take various forms, including pumping liquefied CO_2 into old
oil and gas fields, storing charcoal in the soil (biochar), and locking up quantities
of quick growing plants such as hemp or coppiced timber in buildings.

Slip – see clay slip.

Sorption – encompasses absorption and adsorption (see above).

Specific heat capacity (c_p) – amount of energy required to raise the temperature of 1kg of a
substance by 1 kelvin (units: J/kg.K).

Thermal conductivity (λ) – when a material is exposed to a temperature gradient
perpendicular to its surface (ie there is a temperature difference between its
two sides) the thermal conductivity is a measure of the rate of transfer of heat
energy in that direction. It is an inherent property of the material, a constant
(rather than a property of the building component). It assumes a steady state

situation; in practice, heat flow is affected by other factors in addition to temperature difference, such as thermal mass (units: W/m.K).

Thermal diffusivity (α) – diffusivity is a measure of the rate at which a temperature disturbance at one point in a body travels to another point, ie the speed that heat flows from one side to the other of a material that is not in a steady state. Thermal diffusivity = $\lambda/\rho.c_p$ where λ is thermal conductivity, ρ is density, and c_p is specific heat capacity. Materials with high thermal diffusivity will quickly propagate a change in temperature. (units: m^2/s).

Thermal effusivity (e) – effusivity is a measure of a material's ability to exchange heat energy with its surroundings. Thermal effusivity = $\sqrt{(\lambda\rho c_p)}$ where λ = thermal conductivity, ρ = density and c_p = specific heat capacity.   It is a heat transfer property that dictates the interfacial temperature when two objects at different temperatures touch. Compare touching wood with touching metal; metal has a higher thermal effusivity so heat flows away faster giving the impression that it is colder even when it is at the same temperature (units: $J/K.m^2.s^{1/2}$).

Thermal mass – any material that has the capacity to store heat, such as concrete, earth or water. It is the mass of the material * the specific heat capacity of the material. Thermal mass inside a building acts like a thermal battery, absorbing heat when the temperature is high and releasing it when the temperature drops, thereby acting as a buffer against temperature variations and flattening out the extremes. This thermal inertia provided to the building is sometimes known as the thermal flywheel effect. Materials used to provide thermal mass in buildings ideally have high density and high specific heat capacity.

Thermal resistance (R-value) - the capacity of a building element to resist heat flow when a temperature gradient exists across it, aka thermal insulance. Directly proportional to the thickness of the material (l) and inversely proportional to the thermal conductivity(λ); $R=l/\lambda$. It can also be described as the temperature difference across a unit area of a material of unit thickness when a unit of heat energy flows through it in unit time. To get the heat flow in Watts through an element, multiply its area by the temperature difference across it and divide by the R-value (units: $K.m^2$/W).

Thermal resistivity – a measure of a material's ability to resist heat flow.   Property of the material, unrelated to the thickness of the material. Inverse of thermal conductivity. (Units: K.m/W).

Thermal transmittance (U-value) - the overall rate of heat flow through a unit area of a building component given a unit temperature difference across the component. Inverse of total thermal resistance (R_t). $U = 1/ R_t$. (Units: $W/m^2.K$).

Total thermal resistance (R_t) - For a building element this includes the resistances of all its components plus the internal and external air film resistances. $R_o + \sum R + R_i$ Components may be added in series (eg a multi-layered wall) or in parallel (a window in a wall).

U-value. See Thermal transmittance.

Vapour permeable – (adj) of a material, allows water vapour to diffuse through it.

Volumetric heat capacity (c_v) – product of specific heat capacity and density. The amount of energy required to raise the temperature of $1m^3$ of a substance by 1 Kelvin (units: $J/ m^3.K$).

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... or build with straw, clay, and rain

the fragrant love nest ...

Pablo Neruda

The Poet Says Goodbye to the Birds

1 Introduction

1.1 Overview

Public awareness is higher than ever before of climate change and the importance of reducing greenhouse gas[1] emissions as quickly as possible. In the UK, buildings account for about 50% of the CO_2 emissions, 30% from residential and 20% from commercial buildings [Harrabin, 2006]. The production of construction *materials* is believed to be responsible for between 10 and 20% of total global CO_2 emissions [Der-Petrossian, 2000, 9]. In this context there is a groundswell of opinion amongst those interested in 'green' building methods that conventional methods using cement, concrete, steel, and brick are too damaging and should be avoided if possible. There is a need for research into alternatives that reduce the impact of construction on the environment. One such alternative is hemp-lime which is being promoted as a new environmentally responsive eco-material with potential for widespread use.

Hemp-lime is a composite material made from the chopped woody core of the hemp plant bound together with a lime-based binder into a form of organic concrete. Monolithic hemp-lime walls are constructed around a structural timber frame. They are insulating and relatively lightweight. As will be discussed, hemp-lime has heat and moisture handling properties which make it appealing to those designing low energy buildings. It is being promoted as a material which can actually remove carbon from the atmosphere.

This thesis argues that while hemp-lime does indeed have properties that make it appealing, its lime-rich composition is a major detractor. Much of the benefit incurred by sequestering hemp (and therefore carbon) in the fabric of buildings is undone by the carbon emissions associated with the production of the energy-intense binder; this is particularly true of the commercially produced binders which contain a high proportion of cement.

Clay and earth have been used for building for millennia. If the lime binder in hemp-lime could be replaced with clay, the environmental benefits of the method would be significantly increased. It could play a significant role in the move towards zero carbon buildings by sequestering large amounts of carbon in their construction and, through improved building performance, reducing the carbon emissions of the buildings in use.

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[1] The main greenhouse gases (GHG) are water vapour, carbon dioxide, methane, nitrous oxide, and ozone; due to its abundance, the most important GHG of anthropogenic origin is carbon dioxide.

1.1.1 The Carbon cycle

For half a million years CO_2 levels in the atmosphere fluctuated slowly between 200 and 300 ppmv [2]. Carbon moves between the atmosphere and the biosphere through the processes of photosynthesis, respiration, decomposition.   Plants and microorganisms fix carbon in the soil and in the oceans. After thousands of years some of these carbon sinks eventually become part of the fossil reserves.   By releasing carbon from the fossil reserves into the atmosphere we have upset the balance of the natural carbon cycle (Figure 1).
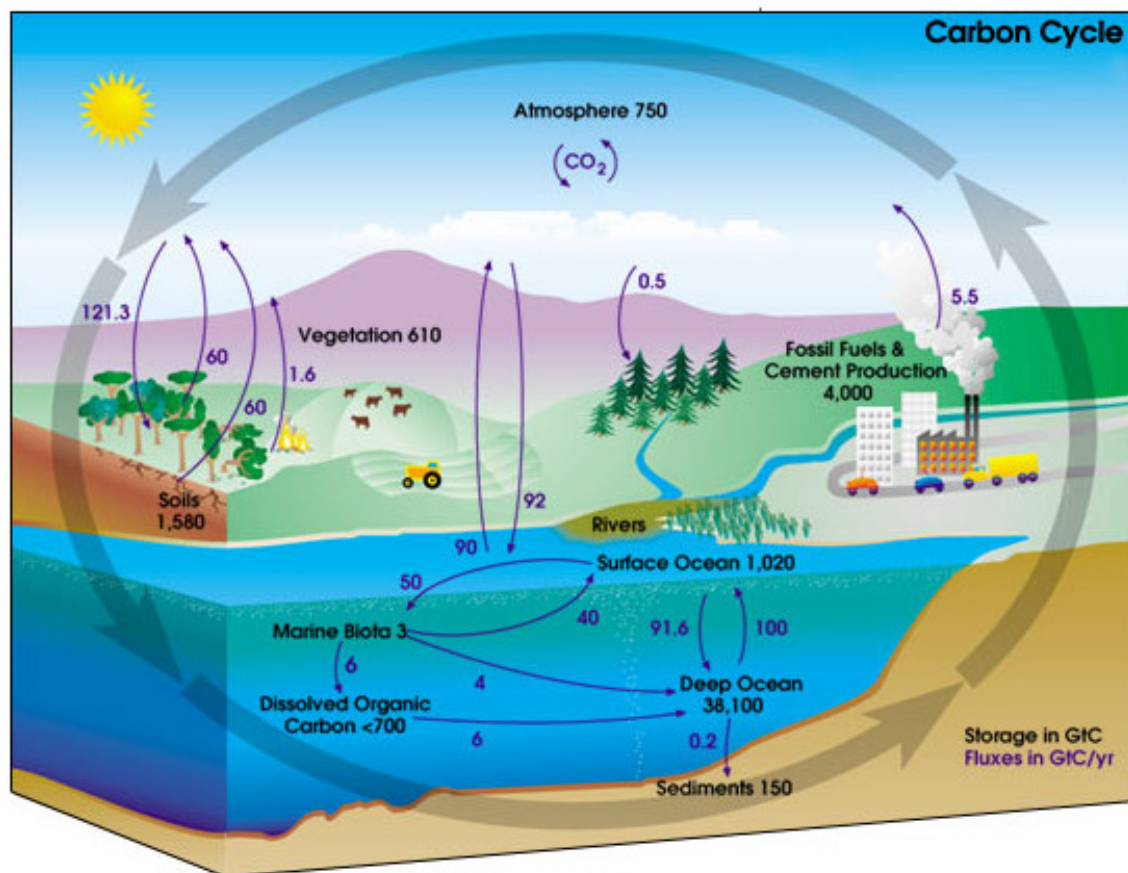
Figure 1: The Carbon Cycle [NASA Earth Observatory, 2009] showing the total amount of carbon stored in the various carbon sinks (in gigatonnes) and the annual fluxes between them (in gigatonnes per annum).

Anthropogenic increases in greenhouse gases from fossil fuels over the last few hundred years are a major contributor to climate change[3]. CO_2 levels in the atmosphere have risen

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[2] Parts per million by volume, often abbreviated to ppm (parts per million)

[3] This statement has been disputed especially in the mass media, but almost all scientists now accept that it is happening [IPCC, 2007]

from pre-industrial levels of around 270ppmv to 370ppmv in 2000, and are predicted to rise to between 540 and 970ppmv by 2100 [Hansen, 2008; Boyle et al, 2004, 16]. The effects of the greenhouse gases (GHG) already in the atmosphere will not be fully realised for several decades, and we are still extracting coal, oil and gas which will result in yet more GHGs in the atmosphere. Scientific consensus is that the tipping point after which climate change will be irreversible will arrive at around 450ppm sometime between 2015 and 2020 [Smith, 2008]. To reverse this process, Hansen [2008] (director of the NASA Goddard Institute for Space Studies) argues that CO_2 levels must be reduced to 350ppm. Latest figures for CO_2 levels today are around 385ppm, increasing by approx 2ppm per annum [ESRL, 2008].

We need to stop pumping out CO_2 and we need to remove it from the atmosphere, and with the utmost urgency.

1.2   Buildings and climate change

Cement is the most widely consumed material after water [BCA, 2007; Harris & Borer, 2005]. The UK produces about 12 million tonnes of cement each year and global cement production was 2.1 billion tonnes in 2004 [Index Mundi, 2007], increasing by 5% annually. For each tonne of cement, along with other environment-contaminating by-products, a tonne of CO_2 is released into the atmosphere and 4GJ of energy is consumed [EcoSmart Concrete, 2007].

Cement production is responsible for 3.8% [Marland et al, 2007] to 10% [Greenspec, 2007] of global CO_2 emissions, around three times as much as aviation[4] [IPCC, 1999]. CO_2 emissions from cement are expected to reach nearly 6 billion tonnes per annum by 2020. Although the larger portion of the CO_2 emissions currently comes from the fossil fuel used in the firing process, almost half is liberated during "calcination" (heating) of the limestone (see section 2.3.1). This proportion cannot be avoided even if a source of completely renewable energy were harnessed for the firing, though some of it may subsequently be reabsorbed by the material (see section 2.3.4).

Lime is also a fired material with associated CO_2 emissions from firing and calcination in similar proportions to cement. At current rates of production emissions from lime are

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[4] Global emissions from aviation were around 2% of the total anthropogenic CO2 emissions in 1992 predicted to rise to 4% by 2050. [IPCC, 1999, 6; Webb, 2007]

insignificant compared to those from cement which is far more widely used, but this would change if there was a widespread move towards lime from cement.

Annual global production of concrete, the main use for cement, is about 4 billion cubic metres and demand is predicted to double in the next 30 years; twice as much concrete is used in construction as all other building materials combined [Greenspec, 2007, and EcoSmart Concrete, 2007].

Compounding the impact of this growth in construction, ironically, is the drive towards energy efficient buildings. Higher volumes of materials are being used (eg thicker walls, more insulation) and many of these have higher embodied energy and carbon[5] (eg high spec windows, polyurethane foam, heat recovery systems). The embodied energy of modern buildings is approaching half the lifetime energy consumption [CSIRO, 2008].

The UK government plans to build 3 million new homes by 2020 and are trying to improve the energy standard of buildings through new regulations such as part L of the Building Regulations, and the Code for Sustainable Homes. These and other buildings standards, such as PassivHaus and AECB Silver and Gold standards, emphasise the need for airtightness and significantly increased levels of insulation.

 Given that the construction industry has such an impact on the environment any method of building that can reduce this is worth investigating; the hemp-*binder* method appears to have potential.

1.3   Outline of this thesis

This thesis aims to assess the potential for clay to substitute for lime in the hemp-*binder* method. Chapter 2 therefore reviews the literature on the raw materials in an effort to evaluate the comparative environmental impacts of hemp-lime and hemp-clay. Also reviewed are 'alternative' building methods using natural materials, followed by a detailed look at the properties of clay and earth.

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[5] Embodied energy and embodied carbon (see glossary for definitions and appendix 1.1) correlate closely but cannot be directly converted, since the carbon emissions associated with a unit of energy obviously depend on how it is generated. However, CSIRO [2008] estimate that, on average, 1 gigajoule of embodied energy represents 0.098 tonnes of CO_2)

A description of how sample hemp-clay blocks were made, the techniques for measuring their thermal conductivity, thermal capacitance, moisture content, and compressive strength follows in the Methodology, chapter 3.

Details of the material proportions in the blocks, and observations about mould and clay slip from the process of making and drying them, are presented in chapter 4, along with the results from testing.

The discussion in chapter 5 examines the wider implications of the results and the potential for hemp-clay as a building material. In order to assess the impact of a material, we need a set of criteria by which to judge it. The environmental impact of hemp-lime and hemp-clay will be assessed using criteria recommended by Harris [1998, 159], these include.

- Embodied energy (closely related to CO_2 emissions, see section Appendix 1.1)
- Raw materials consumption: how much raw material is consumed?
- Scarcity factor: how limited is the resource and is this a valid use?
- Recycling potential: can we avoid materials going to landfill?
- Effects on occupants of building or handlers: indoor air quality, toxic hazards.
- Potential for using recycled materials.
- Influence on energy consumption.

These criteria should be assessed over a full life cycle: in construction, in use, and at end of life. This will include transportation, methods of building, production of materials, carbon sequestration.

1.3.1   The scope of this study

While hemp-lime is a newcomer to the mainstream construction scene, hemp-clay is virtually unheard of, and is unlikely to be considered unless its credentials can be proven.

Qualitative conclusions drawn from the literature review are presented. These are compared with the primary research in this study which focuses on the thermal performance of a 'concrete' made from hemp and clay. A heat transfer analyzer probe is used to determine the thermal conductivity, thermal capacitance, thermal diffusivity and thermal effusivity of hemp-clay. Rudimentary compressive strength tests are also conducted for a rough assessment of the structural robustness of the material.

Despite an extensive search, no evidence could be found that this topic has been reported previously in quantitative experimental research.

2 Literature Review

2.1 Overview

After a brief history of hemp production this section will look at the environmental benefits and drawbacks of lime, hemp, and the combination of the two as a building material. It then reviews traditional and 'alternative' building methods, with particular attention to the recent resurgence of interest in other countries in light-earth construction. This is followed by a discussion of the properties and types of clay and its feasibility as an alternative to lime in the hemp-*binder* method.

2.2 Hemp

2.2.1 A brief history

Ignoring a short sighted and politically dubious prohibition on the production of hemp in the twentieth century (possibly to protect the vested interests of a powerful few)[6] the cultivation of hemp has underpinned the development of human culture and trade. Its versatility, as a food crop, fuel crop, and source of fibre for paper, cordage and cloth has given it a prominent role in the history of civilisation.

The US Marihuana Tax Act in 1937 effectively stopped the production of all forms of cannabis. Led by the US, the plant has been demonized in much of the developed world because of the presence of the narcotic tetrahydrocannabinol (THC) in some strains of the plant. The pharmacological variety of hemp, marijuana, contains up to 20% THC. In contrast, to meet European legislation today industrial hemp must contain less than 0.2% [Eur-Lex, 1998]. Since the 1990s most nations have overturned legislation banning the cultivation of hemp, though in the US prohibition remains in force.

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[6] William Randolph Hearst (newspaper magnate with investments in timber and paper industries) and the DuPont Company are popularly accused of a conspiracy to get hemp outlawed and thereby eliminate the threat to their investments. Other than the circumstantial evidence that Du Pont's Nylon was patented in April 1937, the same year the US Marihuana Tax Act was passed, no peer-reviewed sources could be found to validate this claim. The prime source for the conspiracy-theory is a book called "The Emperor Wears No Clothes: Hemp and the Marijuana Conspiracy" by Herer, which partly kindled the rehabilitation of hemp since the mid 1980s.

2.2.2   Uses of hemp

Hemp is grown mainly for its energy rich seeds and long, strong fibres. Modern applications include insulation, paper[7], cloth[8], biofuel[9], cosmetics, food, bio-remediation of contaminated soils, and bio-composite materials which already have multiple mainstream uses (ironically even in the US) [Smith-Heisters, 2008]. The woody core of the stem (the hurds or shives) is sometimes considered a waste product and is used mainly for animal bedding; it is the hurds that are used in hemp-lime construction.

Figure 2: hemp stem showing fibre and core (hurds) [http://en.wikipedia.org/wiki/File:Hanfstengel.jpg#file]

2.2.3   Cultivation and processing

Hemp has very sound environmental credentials if grown organically, though these are greatly reduced if it is grown as a monoculture [Rhydwen , 2006]. It is a quick growing, low-input, low-impact and multi-purpose crop. It is naturally resistant to pests and diseases, requiring little in the way of irrigation, herbicides or pesticides. It is highly adaptable to a wide range of climates and environmental conditions, and different cultivars are grown successfully across the world, the major producers being China, Russia, Hungary and France. [ibid; Smith-Heisters, 2008]. In comparison to most of the world's major crops,

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[7] wood paper production requires far more energy than hemp paper

[8] compared with cotton, hemp has higher fibre yield per hectare, is more durable and demands less water and agrochemicals; polyester fibre requires six times the energy required to produce hemp fibre

[9] compared with corn ethanol hemp is less damaging to the environment and has higher potential yields

hemp is far more ecologically friendly and actually increases biodiversity [Rhydwen , 2006, 38; Small & Marcus, 2002, 315].
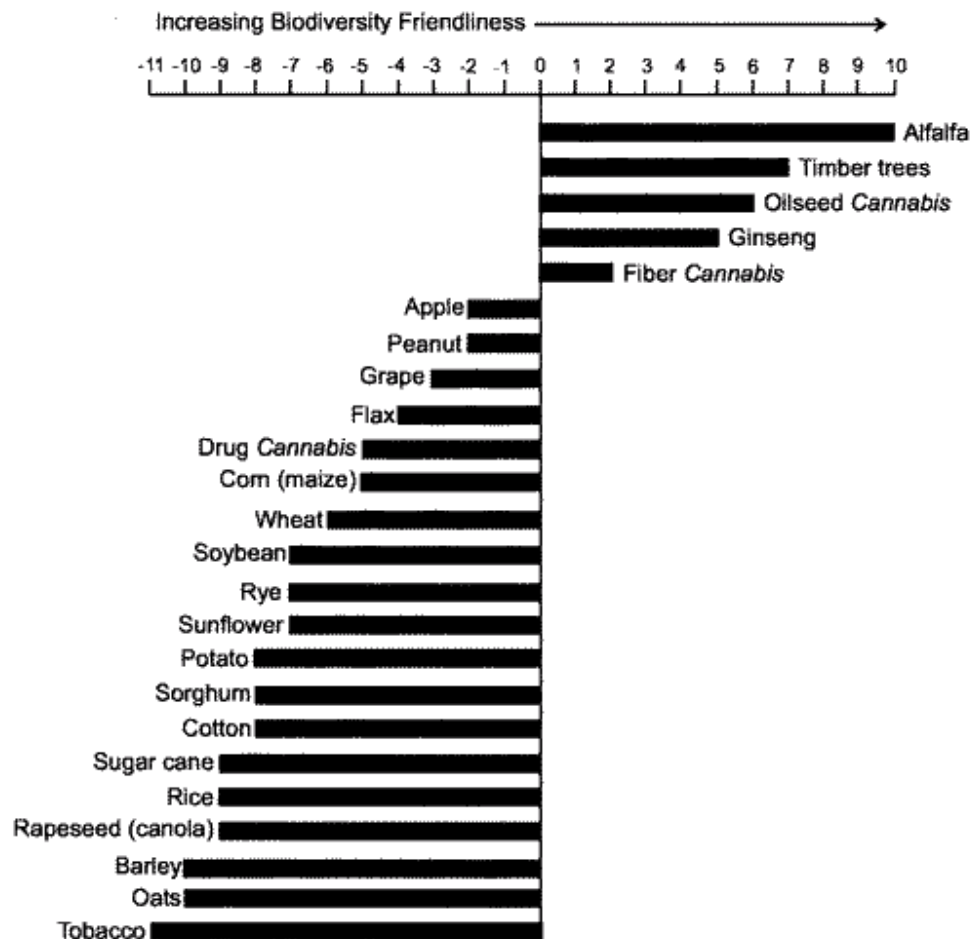
Figure 3: The ecological friendliness of Fiber Cannabis and Oilseed Cannabis compared with other major crops [Small & Marcus, 2002]

The intended crop determines the manner in which is it grown, harvested and processed [Rhydwen , 2006]. Because it grows so densely hemp intercepts 99% of the sunlight making it an effective break crop which can clear the land of unwanted plants below it. It sheds its leaves as it grows creating a leaf-litter mulch, protecting the soil and returning to it between 40% and 70% of the nutrients [Rhydwen , 2006, 35 & 81-3]. It grows very quickly typically reaching a height of 2-3m in a 4 month growing season, though it can reach 5m, and has the potential to produce 3 harvests a year [Daly, 2008].

While there are other methods of processing hemp fibre, the main process in use in the UK today is the process of dew retting whereby the hemp stems are left lying in the fields for

3-6 weeks allowing bacteria and fungi to break them down releasing the fibres from the woody core [Rhydwen , 2006, 35]. This process has drawbacks, not least weather dependency, but other methods including water retting and mechanical retting are more labour or energy intensive, financially inhibitive or environmentally damaging [Rhydwen , 2006].

2.2.4   Hemp and Carbon sequestration

Like all green plants growing by the process of photosynthesis, hemp absorbs CO_2 from the atmosphere and incorporates the carbon into the structure of the plant, releasing the oxygen.   Carbon is thus removed from the atmosphere, and stored in the hemp plant where it remains until the plant is eaten, burned or it decomposes at which point the carbon is once more released into the atmosphere, most probably as CO_2.

If this CO_2 can be 'locked up' in the fabric of a building then it is removed from the atmosphere for the lifetime of the building. The amount of carbon in the hurds is about 50% of the total weight [Pervaiz & Sain, 2003], which is equivalent to removing from the atmosphere 1.83 tonnes CO_2 per tonne of hemp hurds[10].

Average annual yields in the UK in 2005 were 5.5 tonnes per hectare though they are improving. Many farmers were achieving between 7 and 11 t/ha and there are estimates that with selective breeding 26 t/ha are achievable (Rhydwen , 2006, 44). The hurds account for 60% of the yield by weight [LHoist, 2009]. Therefore, assuming a yield of 6 t/ha, each hectare will produce 3.6 tonnes of hurds containing the carbon from 6.6 tonnes of CO_2.

2.2.5   What is its embodied energy?

Hemp has a low bulk density, which means that storage costs, transport costs and associated CO_2 emissions per tonne are high. Local production reduces the cost and embodied energy of the hurds and is essential if hemp is to become competitive. Per tonne, haulage releases between 7.5 and 18 kgCO_2 per kilometre [Rhydwen , 2006, 36-7].

This said, the embodied energy of hemp has been calculated to be around 1.4MJ/tonne [BRE, 2001 in Rhydwen , 2006, 49], which is equivalent to 0.14 kgCO_2 per tonne using

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[10] Atomic weight of carbon is 12, and CO_2 is 44, a ratio of 1 to 3.7, therefore 1kg of hurds containing 0.5kg of carbon is equivalent to 1.83kg CO_2. (0.5kg * 3.7)

conversion factors quoted by CSIRO[11] [2008].   This is negligible compared with the 1.83 tonnes of CO_2 sequestered per tonne of hemp hurds.

2.2.6   What are the properties that make it suitable as a building material?

Hemp is a very good natural insulation material (its thermal conductivity λ is very low, from 0.047 to 0.058W/m²K []); the fibres can be used to make insulation batts, usually in combination with some form of synthetic polymer binder, or the hurds can be combined with lime to make a type of concrete known as hempcrete, the topic of this thesis.

Hemp hurds are very similar to some hardwoods in their cellular structure and composition, comprising 50% cellulose, 28% lignin and 20% hemicelluloses [Evrard, De Herde & Minet, 2006, 70]

cross section of hemp stem
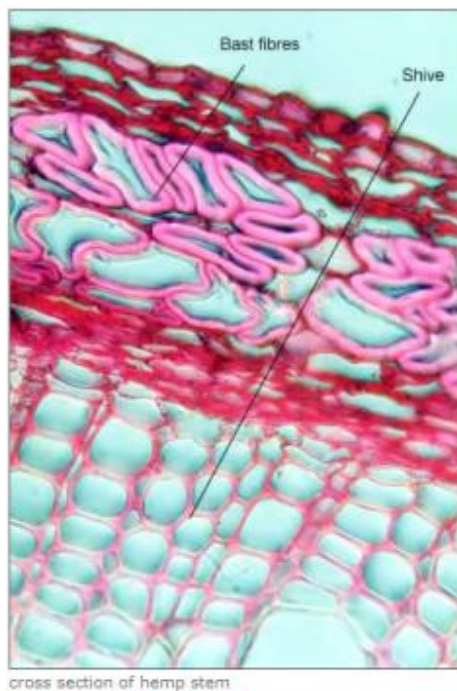
Figure 4: cross section of hemp stem [source, http://www.flaxandhemp.bangor.ac.uk/english/growth_develop.htm]

The hurds are very absorbent, hence their use as animal bedding. Compared to synthetic insulation materials hemp has a lower R-value but it is permeable and ideally suited to breathable[12] construction methods. The hurds are micro-porous with a very fine capillary

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[11] 1 gigajoule of embodied energy represents 0.098 tonnes of CO_2

[12] See glossary.

structure and are highly hygroscopic. These properties make them an excellent natural insulator and moisture buffer (see section 5.2.3).

2.2.7   Hurdles?

Hemp is not currently widely grown in the UK and there is only one major processor, Hemcore, and unfortunately only one organic grower [Rhydwen , personal communication Jan 09]. Hemcore currently exports most of the fibres to France and Germany [Rhydwen , 2006, 39]. The hurds can easily be bought as animal bedding, however, and if the local demand increases there is no reason why a local supply chain could not be established.

There are those who regard hemp as a wonder-plant, the solution to all our problems. It is unlikely, however, that hemp would remain without negative environmental impacts if it were adopted by the mainstream construction industry. If it became commercially viable to grow it on a wide scale with multiple sowings each year then it would require agrochemicals like any other monoculture. There is however no reason to go down this route since it is an effective break crop and organically grown hemp has higher yields [Rhydwen , 2006, 32].

2.3   Lime

Lime is a material that is not generally well understood. It is created by firing limestone, one of the most abundant rocks on the planet. 'Lime' embraces a range of materials with different properties.

2.3.1   The production of lime

Pure non-hydraulic lime[13] is produced from pure limestone[14] through a process known as calcination in which it is heated in a lime kiln to about $900^{\circ}C$ and carbon dioxide is driven off. The resulting quicklime[15] can be used directly from the kiln or slaked before storage to produce hydrated lime or lime putty depending on the volume of water added. In use, it sets by reacting with the atmosphere as it dries, losing water and reabsorbing the CO_2 that was driven off, turning back into limestone; this is known as carbonation. In theory we end up with the same material we started with but in a different location. This is the lime-cycle in its purest sense (Figure 5).

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[13] non-hydraulic lime (or air-lime) = calcium hydroxide, $Ca(OH)2$.
[14] pure limestone = calcium carbonate, $CaCO3$.
[15] quicklime = calcium oxide, CaO.
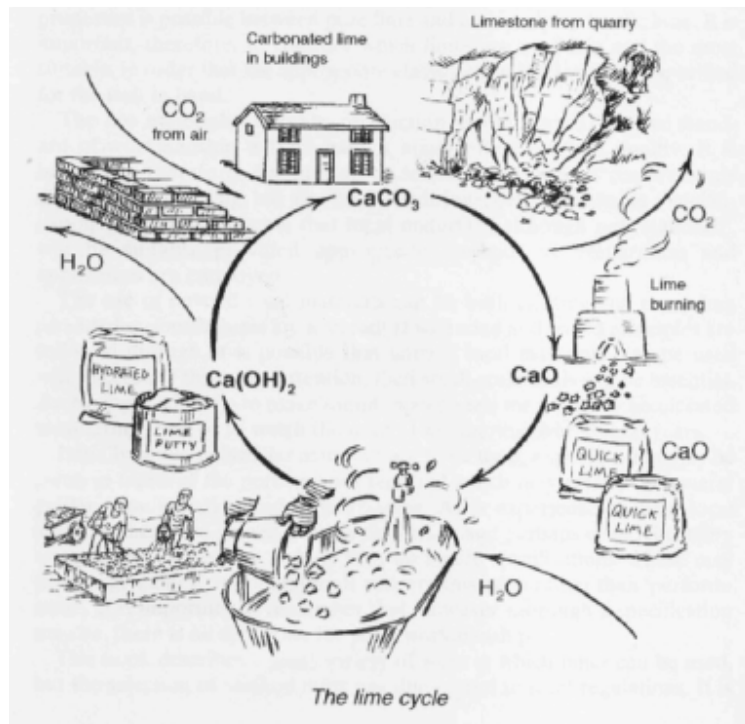
Figure 5 The Lime Cycle [Holmes & Wingate, 2002, p8]

2.3.2   The lime spectrum

Non-hydraulic lime (aka air-lime) is situated at one end of a spectrum of fired lime-based binders (see Figure 6) which also includes hydraulic limes, natural cements, ordinary Portland cement (OPC) and other artificial cements; the physical properties vary predictably from one end to the other.

Naturally Hydraulic Limes (NHL) are produced from limestone containing clay impurities. They set initially by chemical reaction between the lime and reactive clay, and more fully later by carbonation. It is this chemical reaction (hydraulic set), in the presence of water, between the lime and the (mainly) silicon-based compounds in the clay that produces the cementitious properties which distinguish pure lime from cement. NHLs are rated according to their hydraulicity[16] which is dependent on the proportion of reactive impurities[17] in the limestone.

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[16] Non-hydraulic (<6% clay), Feebly hydraulic (6-12% clay) NHL 2, Moderately hydraulic (12-18% clay) NHL 3.5, Eminently hydraulic (12-25% clay) NHL 5, Natural cement (25-55% clay) (Ratcliff & Orton, 1998)(Greenspec, 2007).

[17] Mainly clay; clay is largely Aluminium Silicate (see later).

Ordinary Portland Cement (OPC) is, very basically, made by firing pure limestone and silica[18] together to 1450°C to form Portland cement clinker which consists mainly of the calcium silicates alite and belite[19].

THE LIME SPECTRUM
(Diagrammatic)

Compressive strength, impermeability, brittleness, setting speed.

Cements

Hydraulic Limes

Pure Lime

Firing temperature

Alite

Belite

Lime

Hydraulic limes: Vicat's classification (1820)
"Feebly hydraulic"
"Moderately hydraulic"
"Eminently hydraulic"

Hydraulic limes: classification to EN 459-1: 2001
NHL 2
NHL 3.5
NHL 5

Cements in comparison by date range
1840-1870
1870-1910
1910-1940
1940-2000

Figure 6: The Lime Spectrum [Brocklebank, 2007]

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[18] silica = silicon dioxide, SiO_2.
[19] alite = $3CaO.SiO_2$, and belite = $2CaO.SiO_2$. The Alites are more reactive with water, setting quickly and giving early strength, whereas the belites cure and gain strength more slowly.

As illustrated in Figure 6, as we move from the Pure Lime end of the spectrum towards the Cements, there is an increase in the compressive strength and setting speed of the material, with a corresponding decrease in permeability and flexibility.   Additionally, pozzolans[20] can be added to any of the binders to give a more rapid, hydraulic (ie chemical) set, in other words, to move the material further right along the spectrum, or to change its properties[21].

Similarly, as we move towards the right of the spectrum the manufacturing process for the binders requires higher firing temperatures and is more likely to require mechanical grinding. The very strong modern cements at the right of the spectrum therefore have higher embodied energy and are associated with greater CO_2 emissions than binders at the other end of the scale, but these strong and impermeable cements set very quickly and allow construction in extreme situations.

2.3.3   Embodied energy and carbon emissions

Unfortunately the environmental costs of cement and lime are huge. Exact figures for carbon dioxide emissions from the cement industry are hard to pin down. $0.51 kgCO_2/kg$ are liberated from the raw materials [ICE, 2008, 37] and a similar amount from processing. Figures for the total emissions range from an average for cement of $0.83 kgCO_2/kg$ [ibid] to $1 kgCO_2/kg$ for OPC [Worrell et al, 2001, van Oss, 2002]. The figures for lime are similar. In order to produce 1kg of quicklime from limestone, 0.48kg of CO_2 are released from the raw material but the total emissions range from 0.74 [ICE, 2008, 37] to 1.3 [ref??] $kgCO_2/kg$ depending on the efficiency of the plant and on the fuel used for heat and power. According to the ICE database [2008], lime releases $0.48 kgCO_2/kg$ from the calcination of

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[20] A pozzolan is "a siliceous or siliceous and aluminous material which, in itself, possesses little or no cementitious value but which will, in finely divided form in the presence of moisture, react chemically with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties" [King, 2005, p3]. Particle size is an important feature of pozzolans; generally less than 45 microns with the smallest particles being most reactive. Some pozzolans occur naturally such as diatomaceous earth, others are man-made such as fly-ash (from the chimneys of coal fired power stations), blast furnace slag (from steel manufacture) and rice hull ash. They are generally of volcanic origin or have been highly fired.

[21] Some industrial waste materials can act as pozzolans, for example fly-ash from power station chimneys when substituted for OPC in concrete changes its properties; it reduces both the heat of hydration and the requirement for water, improves workability and reduces shrinkage. Fly-ash concrete takes longer to cure so the setting time is extended. The final concrete is lighter in colour, less permeable and its compressive strength increases with the percentage of fly-ash so the strength of the resulting concrete can actually be higher than for OPC-concrete.

raw materials whereas cement releases 0.51kgCO$_2$/kg. This along with a more favourable fuel mix[22] means that lime has a lower embodied carbon. Despite this the embodied energy is slightly higher. 'Lime is fired in the kiln to a lower temperature than cement, which is often misconceived as proof for a lower embodied energy. Yield, density, and time in the kiln are all vital parameters to total energy consumption' [ibid].

Only one source could be found that compared CO$_2$ emissions for lime and cement directly, stating that lime mortar requires less energy and results in 20% less CO$_2$ output than cement mortar [Greenspec, 2007].

2.3.4   Absorption of CO$_2$ through re-carbonation

Proponents of lime argue that it reabsorbs the carbon dioxide liberated from the raw limestone after construction and therefore the net CO$_2$ output is far lower than cement. However, at most 60-80% of the total CO$_2$ emitted is eventually reabsorbed[23] and that is only if the lime fully carbonates. Furthermore, carbonation may take years to fully complete if indeed it ever does. Samples of lime mortars in ancient buildings have been shown to contain uncarbonated lime deep in the body of a wall. [Schofield, 2005, 10] Hydraulic limes only reabsorb at most 75% of the CO$_2$ in the original limestone [Greenspec, 2007] and interestingly cement also reabsorbs some CO$_2$[24], but this is mainly after demolition [PCA, 2008].

Lime is sometimes portrayed as being a less environmentally damaging binder that should be used in place of cement but this is too simplistic. Judiciously used, cement provides the potential for delicate structures of great strength and span. Air limes (eg lime putty), on the other hand, are soft, permeable and flexible, allowing a building to breathe, respond to changes in its environment and move without cracking; they are ideal for use with organic materials. From the wide range of lime-based binders, it should be possible to select one appropriate for the requirements of most construction projects. But because their carbon footprint is so high we need to ask whether a lime-based binder is required at all. For

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[22] Biofuels can be used to fire lime kilns, but cannot reach the higher temperatures required for cement

[23] Only calcination emissions are ever reabsorbed, not process emissions.

[24] Portland Cement Association [2008] state that concrete will absorb about 57% of the CO2 emitted during the original calcination but only 7% is absorbed during the life of the building, the rest only occurs once the concrete has been returned to fine particles during recycling operations.

domestic housing and low-rise buildings in particular there are alternatives that are far less costly to the environment, as this thesis will demonstrate.

2.4   Hemp-Lime

A relative newcomer to the scene, hemp-lime has been investigated by BRE and found to offer a low-carbon method of construction which provides a breathable wall capable of passively regulating the temperature and humidity in the building. As a combination of hemp hurds and lime, it is argued that the carbon in the hemp offsets the carbon emissions from the lime binder.
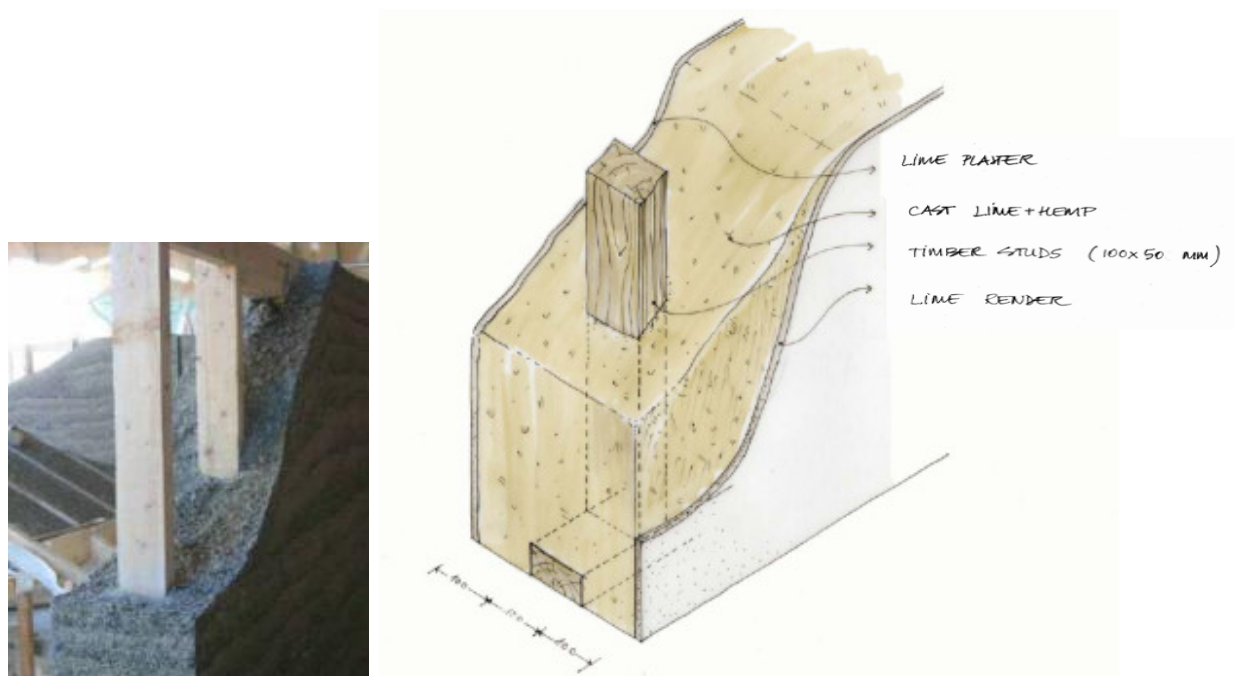
Figure 7: photo and section through a hemp-lime wall

[source: http://www.hempembassy.net/hempe/resources/BuildingwithTradicalHemcrete.pdf]

2.4.1   Benefits of hemp-lime construction.

In addition to the eco-credentials of hemp (sections 2.2.3 to 2.2.6) proponents of hemp-lime's sustainability argue that the monolithic walls are relatively lightweight and flexible, and that construction requires fewer supports and lighter foundations. The alkaline lime preserves the hurds and timber, protecting them from damp, fire and pests. The material can create a solid unbroken mass which reduces thermal bridging and lends itself to achieving airtightness around fittings and openings [Woolley, 2006, 139]. It is also an

effective moisture buffer, creating a healthy indoor environment. Because the method is relatively simple, with familiarity it can be applied quickly. Once the timber frame is constructed, infilling of hemp-lime walls can be completed manually by unskilled labour. It is easy to renovate or repair; any damage can simply be cut out and replaced. It is suitable for renovation works, providing increased insulation to existing buildings. At the end of its life, except where it includes cement additives, it is biodegradable (see section 5.6).

Commercially, hemp-lime can also be sprayed which makes construction very fast (though the embodied energy is higher). According to LimeTechnology [2007] construction costs for hemp-lime "can be lower than for current traditional building materials". Two experimental hemp houses were built in Haverhill for Suffolk Housing Society (Figure 8, left) and their construction and final performance was monitored and compared with similar houses on the same project built using conventional brick/block methods. In the final report [Yates, 2002], the number of labour hours was around 60% higher than for conventional construction, but overall costs increased only 10% because of material savings and the simpler monolithic construction. It was predicted that familiarity with the method would accelerate the build and bring costs down.

Figure 8: hemp-lime buildings: left, Haverhill houses, Suffolk; right Adnams Brewery, Southwold, Suffolk [source: http://www.constructireland.ie/articles/0215limehemp2 and 4.php]

2.4.2   Hemp-lime binders

Concrete is a solid mass formed from aggregate of different kinds held together by a binder: the 'glue'. It has many variations using different binders and different aggregates. Ordinary Portland cement is one of many binders, lime is another. The sand, gravel and stone aggregates can be replaced by alternatives such as expanded clay, perlite, vermiculite, or an organic aggregate such as woodchips or hemp. To make Hemp-lime, or hempcrete, the aggregate is hemp and the binder lime. Different mixtures are specified for different purposes; roofs, walls, floors and plaster.

There are differing opinions about whether hydraulic or air-lime should be used in hemp-lime. The method started in France using air-lime, whereas the Haverhill test houses were built with hydraulic lime. In 2002 there was only one UK supplier of hydraulic limes and much of it had to be imported from France [Yates, 2002].

The main supplier of hemp-lime materials in the UK is LimeTechnology with their Tradical® Hemcrete® [25]. Tradical® Hemp Binder is described as a high purity air-lime blended with "cement and other pozzolanic and mineral additions" [LimeTechnology, 2007] (see section 5.5.1). They justify these additives by claiming to provide the perfect particle size distribution and setting characteristics for hemp-lime construction, with quality control regimes that ensure consistency and conformity, making it suitable for commercial use.

In fact, this use of cement in the binder is highly questionable. The benefits of the cement must be weighed-up against the associated disadvantages and environmental penalties (see sections 2.4.4, 5.4.1 and 5.6.3). The Haverhill hemp houses were, however, built by a commercial practice using unadulterated lime and builders unfamiliar with the material. The additives may therefore be unnecessary though they do mitigate against the weather dependency associated with lime [26].

2.4.3 Embodied energy & carbon sequestration in hemp-lime

To make a cubic meter of wall with a density [27] of 330kg/m^3, Tradical wall mix requires 110kg hurds and 220kg of Tradical® HB binder [Castle Cement, 2009]. This equates to 202kg of CO_2 sequestered in the hurds [28]. LimeTechnology claim that 110kg of CO_2 is sequestered per cubic metre of Tradical® Hemcrete®, therefore the negative load contributed by the binder to the CO_2 balance equates to 92kgCO_2/m^3 or 0.42kgCO_2/kg of binder.

These emissions relate to kiln and processing fuel and transportation; LimeTechnology's figures assume that all the CO_2 emitted from the calcination of limestone is reabsorbed by the walls after they are built. This has been challenged however (see sections 2.3.4 and

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[25] Tradical® Hemcrete® is the product of a collaboration between Lhoist, Lime Technology, Castle Cement and Hemcore

[26] Lime must be cured slowly, preferably in warm humid conditions; it should be protected from direct sun, rain and frost for at least a week, preferably longer [Holmes & Wingate, 2006, 119-126].

[27] This density is used for spray on applications only. The recommended density for shuttered and tamped walls is 460kg/m^3 [LHoist, 2009].

[28] 1.83 tonnes of CO_2 sequestered in each tonne of hemp hurds (see section 2.2.4).

2.4.4), and if it is not the case then the total embodied carbon for the binder, including 0.48kgCO_2/kg from the calcination of limestone, could be as much as 0.9kgCO_2/kg. This would mean that Tradical® Hemcrete® was only slightly better than carbon neutral.

Hemp-lime component	CO_2 emissions per kg	Kg of material per cubic metre of wall	KgCO_2/m^3 of wall
Hemp hurds	-1.83	110	-202
Lime - fuel	0.42	220	92
Lime - calcination	0.48	220	106
Total			-4

Figure 9: Carbon emissions and sequestration in hemp-lime components

We can probably assume that the figures for sequestered carbon lie somewhere in between the two extremes. Rhydwen [2007, 28] calculates that each cubic meter of hemp-lime wall could either sequester 347kg or emit 400kg of CO_2 depending on the embodied energy of the lime used[29]. Even at the high end, however, this is not bad compared with mainstream cavity wall construction methods and materials [30].

The total volume of walls for a typical house might range from 30 to 120m^3, depending on the floor area and thickness of the walls [LHoist, 2009]. To build 40m^3 of wall would require around 4.4 tonnes of hemp hurds, or the annual yield from approx 1 hectare. 40m^3 of hemp-*binder* wall has the potential to sequester up to 8 tonnes of CO_2 if a low carbon binder can be found.

If we also take into account the CO_2 that would have been emitted if conventional materials had been used, then it has been estimated that between 30 and 50tonnes of emissions can be avoided per house [Castle Cement, 2009]. Multiply this by 200,000 new houses per annum and it could make a serious impact in meeting the challenge of reducing our carbon emissions[31].

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[29] These figures have been converted from m^2 of 300mm wall to m^3 figures. "Overall therefore a 300mm wall every metre square potentially locks up ~104kg of CO2 or emits ~120kg of CO2 depending on lime figures used with a mean of ~43kg of emissions" [Rhydwen , 2007, 28]

[30] From Rhydwen [2007, 28]: these are estimated as 100-220kg of CO_2 per m^2 (Ian Pritchett C.A.T. Hemp Conference March 2006, personal calc using Bath ICE 2006 embodied energy figures lime) – NB these figures are not per *cubic* meter

[31] Net CO2 emissions for the UK in 2006 were 555Megatonnes [DEFRA, 2008]

2.4.4   Reabsorption of CO_2 by lime-based binders

Evrard [2006, 1-2] tested properties of the Tradical wall mix using the binder Tradical pf 70®[32]. He showed that the mass of the samples first decreased to a minimum while drying and then increased again as they carbonated. This is to be expected as the mass of carbonated lime (limestone) is 35% greater than non-hydraulic lime. A month after the minimum weight had been reached however the samples had only completed an average of 4% of their theoretical total carbonation. Those that had been heavily compressed had a higher vapour resistance and were carbonating much more slowly than those lightly compressed. If a constant rate of carbonation is assumed it would take over two years for the samples to carbonate fully. It is unlikely that walls of a house would carbonate anything like as quickly – the samples were only 35mm thick. It was also demonstrated that too much water could cause the binder to fail completely [ibid,3]. Cement is likely to slow down carbonation because it decreases the porosity of the material and its ability to transport water vapour [Mosquera et al, 2006].

Robertson (2007) also concluded that while the fresh hemp-lime surface carbonates over a three month period, carbonation within the walls is likely to be slow due to the limited diffusion of CO2 into the core of the hemp/lime matrix, and may not occur fully until demolition. In this regard the environmental credentials of hemp-lime are questionable.

2.4.5   Performance of hemp-lime buildings

The thermal conductivity of Tradical® Hemcrete® wall mix is quoted as 0.07 to 0.11W/m.K depending on the density [LHoist, 2007]. For a 300mm wall this will give a U-value of 0.23 - 0.36 W/m^2.K which falls just outside building regulations[33]. However these are static U-values and buildings are never in a steady state. Unlike mainstream construction methods, the performance of hemp-lime buildings is much better than suggested by the U-value.

Adnams brewery commissioned a 4400m^2 distribution centre using Tradical® Hemcrete® in the walls. The properties of the Hemcrete have negated the requirement for a mechanical cooling or heating system, meeting their criterion that the internal temperature be naturally maintained at between 11 and 13 ^{o}C. [LimeTechnology, 2006, 2]

In the Haverhill houses experiment, the hemp houses performed as well as or better than the conventionally built houses by most measures: structure and durability, permeability,

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[32] Tradical pf 70® contains around 75% non-hydraulic lime [Evrard, 2006, 1], plus cement and other additives.

[33] UK Part L1A 2006 baseline for walls = 0.35 W/m^2.K (typical value to pass building regs = 0.28 W/m^2.K) [Hawton-Mead, 2008]

construction waste, thermal performance. Acoustically the hemp houses were outperformed by the conventionally built houses but they met building requirements. Despite the 200mm hemp walls having significantly higher U-values, 0.58 W/m^2 compared to 0.35 W/m^2 [LHoist, 2009], the fuel consumption was no higher, in fact the hemp houses were consistently one or two degrees warmer for the same heat input [BRE, 2002, 27]. Part of the improved thermal performance was attributed to the monolithic construction method, which lends itself to better air tightness and less thermal bridging [Rhydwen , 2006, 50; BRE, 2003].

These houses were well regarded by the residents and successfully proved the method but were in no way zero-carbon homes. Thicker hemp-lime walls would provide more insulation and lower U-values but they would also require more lime.

2.4.6 U-values: static and dynamic

Heat is lost from buildings through radiation, convection (draughts) and conduction (including thermal bridging). Insulation materials are evaluated for their ability to resist these losses. Static U-values are determined in a laboratory using a hot-box. The material is heated until it is completely dry and a steady-state heat flow is reached. In practice materials will always contain some moisture and buildings are rarely in a steady state.

Static U-values take no account of thermal mass and its ability to retain heat within the structure. Thermal mass provides capacitive insulation [Woolley, 2006, 161]. Research by Evrard et al [2006, 6] showed that the energy lost in the first 24 hours from a Hemcrete® wall-section with a U-value of 0.29W/m^2.K equated to an average heat loss of only 0.11W/m^2.K.

Figure 10 [adapted from Evrard, de Herd & Minet, 2006, 74] shows the performance of wall-sections as they adjust to a sudden drop in the external temperature from 20°C to 0°C (internal temp = 20°C throughout). The heat flow values on the Y-axis are negative because heat is being lost from the inside environment. It shows how the hygroscopic hemp-lime walls (LHC)[34] retain heat for significantly longer than both mineral wool (Mwool) and cellular concrete (Cell).

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[34] The two LHC graphs are distinguished from each other by taking into account (+) or neglecting (-) the latent heat effect from moisture in the material
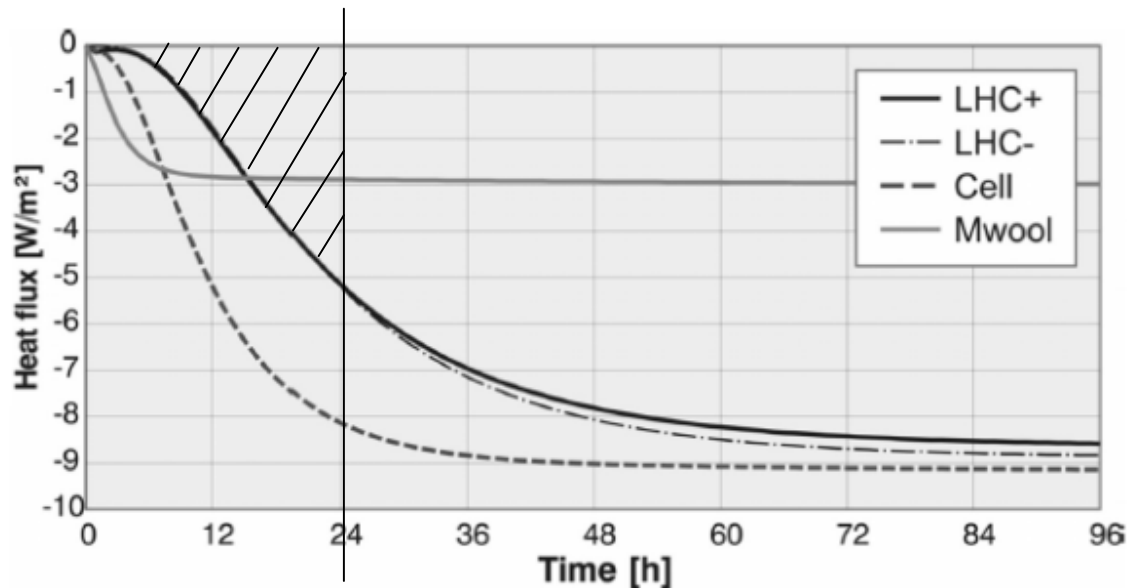
Figure 10: Heat flux through interior surface of 25cm wall elements in hemp-lime (LHC), cellular concrete (Cell) and mineral wool (Mwool)

The area *above* the curves in Figure 10 (shaded) represents the total heat energy lost from the internal environment, and corresponds to the amount of energy required to maintain the internal temperature. For the first 24 hours this is less for hemp-lime than for both other materials. This explains how hemp-lime might outperform the other materials in a domestic situation where heating may be switched on and off twice a day. When the temperature inside drops after the heating is turned off, then the hemp-lime will release heat back into the room. In the heat of summer when temperatures outside are higher than inside, then the situation works in reverse, maintaining cooler temperatures indoors.

Most buildings in daily occupation are exposed to cyclic thermal and hygric variations as heating is switched on and off and people go about their business.   The material properties of a 25cm hemp-lime wall have been shown to completely dampen these variations; Figure 11 shows how the cyclic thermal variation on one side of a wall is progressively reduced and delayed as the heat moves deeper into the wall.
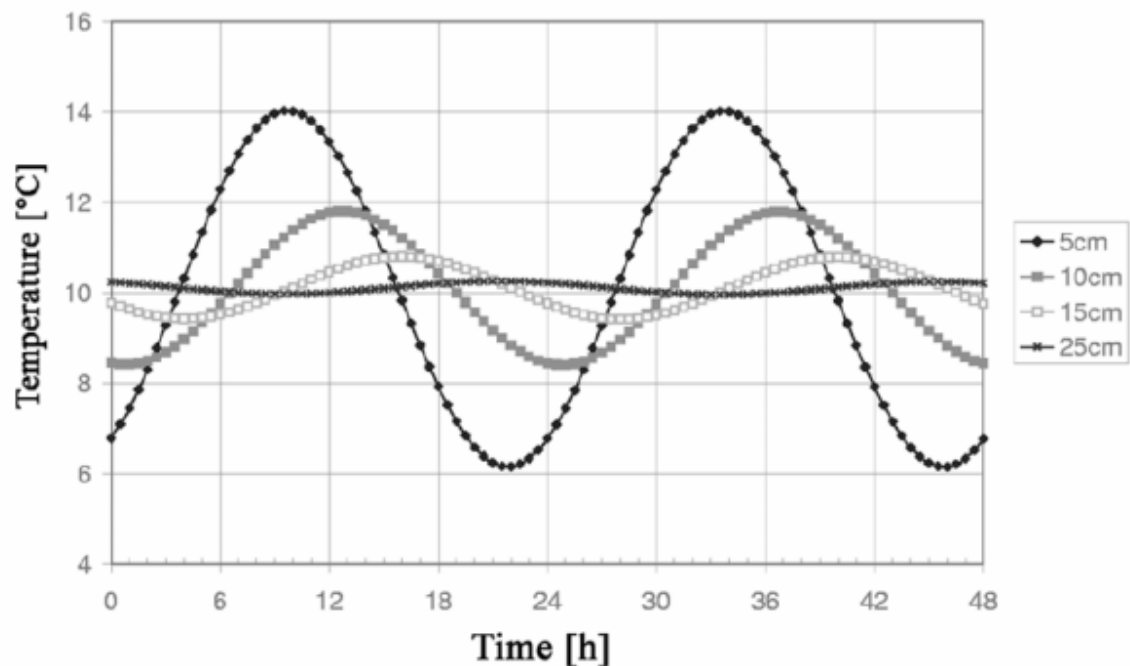
Figure 11: Propagation of thermal wave in a lime and hemp concrete element [Evrard & De Herde, 2005, 29]

Few buildings perform as well thermally as predicted at the design stage; hemp-lime on the other hand exceeds expectations.

To sum up, the method of monolithic hemp+*binder* walls supported by a timber frame has great potential. The amount of carbon sequestered depends partly on the method of application but is mainly limited by the binder. If an alternative low-carbon binder can be found, then the material could greatly improve the chances of the building industry meeting the UK's CO_2 reduction targets.

2.5   Traditional and Alternative building methods

Long before the discovery of lime burning and invention of man-made cements humans relied on local, natural and renewable materials for shelter. The main component of earth that makes is suitable for construction is clay, which acts as a binder. Over 70% of the earth's landmass is clay of some sort [Harris, 1995] and this is the building material (sometimes with the addition of timber, straw and aggregates) that has been used around the world with techniques developed over thousands of years.
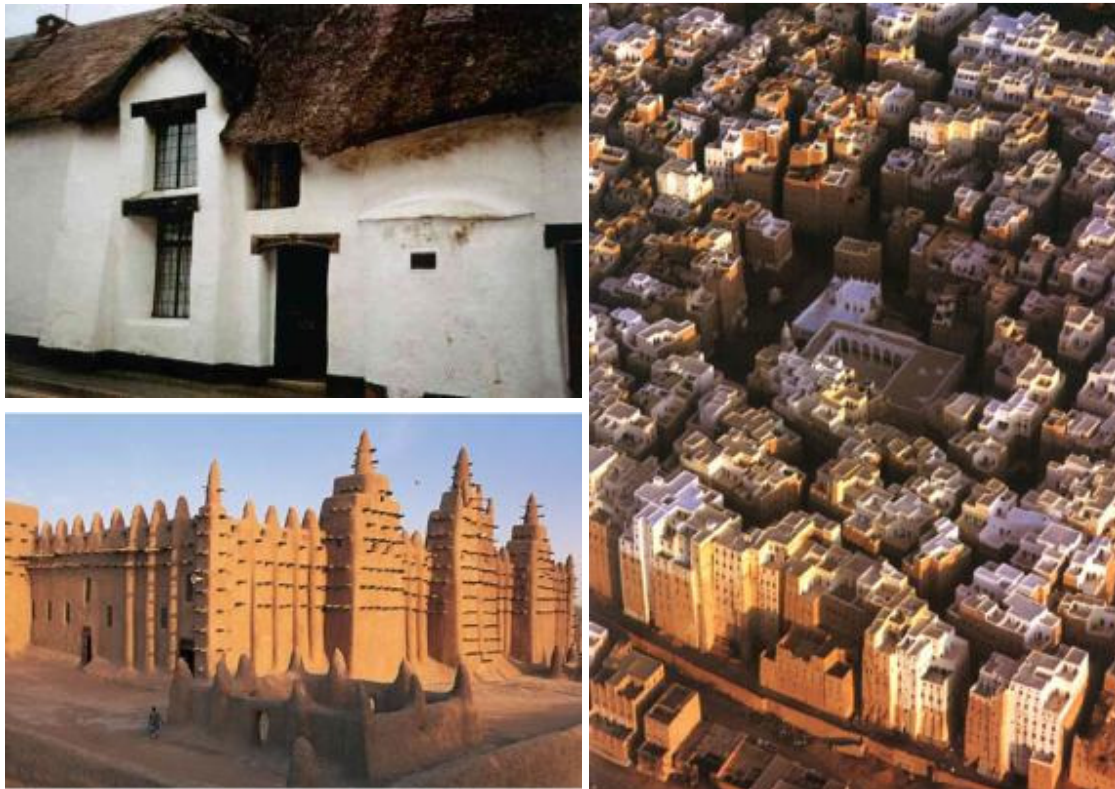
Figure 12: Clockwise from top left: earth buildings from (1) Devon, UK, (2) Shibam, Yemen, (3) Djenné, Mali

In its many guises, including rammed earth, wattle and daub, adobe, mud brick and cob, earth building has stood the test of time, with many buildings still inhabited after several hundred years. Walls, houses, elaborate temples, multi-storey buildings, palaces, pyramids and the Great Wall of China, all have been built from earth. The pictures in

Figure 12 illustrate the diversity of techniques and styles adopted. A third of the world's population, largely in developing countries, lives in earth buildings today.

Recently there has been a resurgence of interest in these techniques in the developed world. Earth has been proved to be an excellent material for regulating internal humidity [Minke, 2006, 16-18]. New techniques using these traditional materials have also been developed, such as strawbale and light-earth construction.

2.5.1   Hemp-Lime compared with Cob, Adobe, Rammed Earth and Wattle & Daub

It is interesting also to compare hemp-lime with cob construction and adobe; these too combine a fibrous material with a binder though admittedly with far less fibre so they provide little insulation.   Cob and adobe are both load bearing, eliminating the need for timber frame, and provide a great deal of thermal mass with minimal embodied energy.

Rammed earth is also load bearing (no timber frame required), but it is similar to hemp-lime in that they both require a temporary formwork and the walling material is tamped in-situ. Rammed earth densities are much higher. For rammed earth the soil must have a well graded distribution of particle sizes to give it compressive strength. Clay soils can if necessary be stabilised with lime (3-10%) to increase their compressive strength [Holmes, 2002, ch9]. Some practitioners add up to 10% cement[35] to stabilise the soil, though others question the necessity of this [Keable, 2007] and it can be argued that stabilised-earth is basically concrete.

Wattle and daub was widely used in the UK for centuries, and many buildings are still inhabited. Similar to hemp-lime it is a comparatively lightweight infill material around a timber frame, but the main timbers tend to be much heavier (largely to accommodate timber joints in the absence of modern fixings). The infill daub uses a lower percentage of fibre (usually straw) and is plastered around a latticework skeleton. Research into the restoration and preservation of historic buildings (some over 700 years old) has shown that the timbers were protected and preserved by the daub. The daub contained a binder (clay or lime), aggregates (earth, sand, stone), reinforcement in the form of plant or animal fibre, and other additives including dung, blood, urine [Pritchett, 2001].

Earth buildings provide excellent thermal mass but their shortcoming is their insulative properties, although their performance is often better than might be expected from U-values alone, see Discussion (section 5.2). Strawbale and light-earth construction attempt to address this issue.

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[35] eg http://www.yourhome.gov.au/technical/pubs/fs57.pdf

2.5.2 Strawbale

Many of the arguments in favour of hemp-lime can be applied equally to strawbale construction: straw is a biodegradable, annually renewable, waste crop. Unlike hemp-lime, strawbales can also be load-bearing, they provide a breathable wall with far more insulation (because they are so thick) and require only a surface render of lime. Furthermore the UK already has an established nationwide supply of straw. It has many of the benefits of hemp without the disadvantages of large quantities of lime. In its current form it is unlikely to be adopted by the mainstream construction industry, but this may soon change with preassembled units using modern methods of construction.

2.5.3 Light-Earth Construction (LEC)

Light-earth construction (LEC) is very similar to hemp-lime. Instead of hemp, the fibre is straw or woodchips, and instead of lime the binder is earth, or more specifically clay. The binding force of clay is one of its key properties, ie its cohesive or tensile strength in its plastic state. Clay is soaked and blended with water into a 'clay slip' which is used to bind the lightweight aggregate. Any lightweight aggregate can be used (expanded clay, perlite, foamed glass, sawdust) but most examples have used chopped straw or woodchips. Walls are monolithic, tamped in-situ in a temporary formwork around a timber frame; some practitioners use permanent reedmat shuttering that is rolled up as building progresses (Figure 13).

Abb. 82 Verlorene Schalung für Holzleichtlehm, Schilf-rohrmatten (BREIDENBACH)

Figure 13: Permanent reedmat shuttering [Volhard, 1995, 74]

Most of the experience with light-earth seems to have been gained in Germany where there is a sizable "leichtlehm" movement. Unfortunately very little information has been

translated into English. The most authoritative contemporary source is "Leichtlehmbau: Alter Baustoff – neue Technik" [36] by Frank Volhard [1995]. This book refers to a 1948 German book by W. Fauth (see Figure 14), so the technique has been around at least 60 years. Germany has building standards for light-earth[37] as does New-Mexico[38].
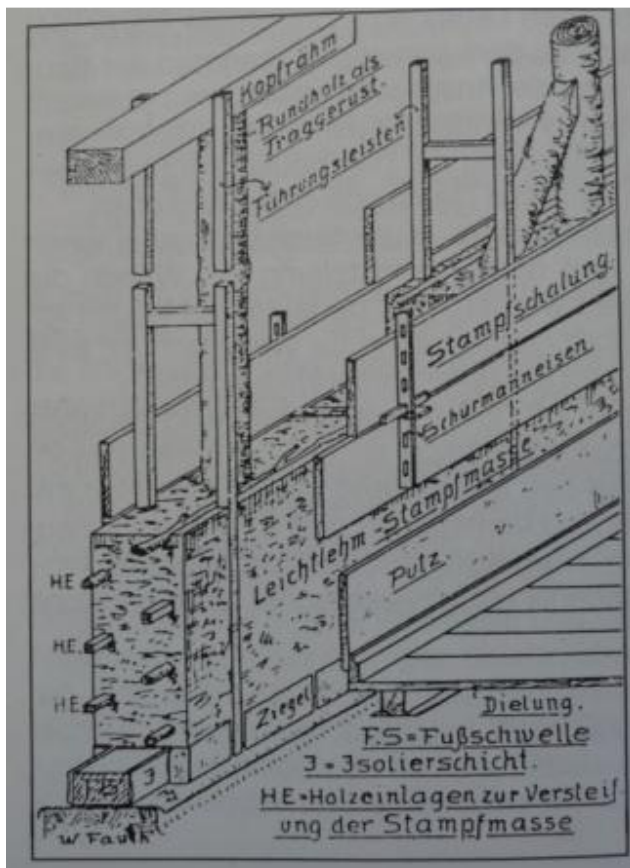
Figure 14: Extract from 1948 book by W. Fauth. [Volhard, 1995, 28]

Little is written in English about LEC. Various articles are available on the internet in grassroots magazines and websites describing projects in Australia, New Zealand, South Africa and USA; it is known by several names, eg slip-straw, light-earth, clay-straw, straw-loam. "Econest" by Baker-Laporte & Laporte [2005] gives some brief technical information and attractively presents some case studies. Australian magazine 'The Owner Builder' ran a

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[36] The book title translated means 'Light loam construction: old building material - new techniques'

[37] 'Lehmbau Regeln' (Earth-building rules): revised edition published in 2009 by the umbrella organisation in Germany for earth building, [Dachverband Lehm e.V., 2009]

[38] See New Mexico Clay-Straw Guidelines in appendix 6.

series of short articles on experiments with light-earth [TOB, 2000-2008]. A couple of articles in the American magazine "Joiners' Quarterly" reported on German experiences [Andresen, 1997]. An article in "Building for a Future" (now "Green Building") described the only research project, if not the only example, in the UK completed by Gaia Architects for the DTI at Eildon in the Scottish borders. The three deliverables of the Eildon project were a demonstration house, a report and a website. The website does not appear to be available yet, but the report is available for a fee on request [Gaia, 2003].

2.5.4   Performance of light-earth buildings and benefits of the method

The benefits of the light-earth method are similar to those for hemp-lime: airtightness is easy to achieve, monolithic walls simplify the process, the benefits of thermal mass are retained while the material provides plenty of insulation. Clay has excellent moisture handling properties, wicking any moisture away from the timber and regulating humidity. It is possible to use small dimension timber to make the structural frame. The infilling can be completed manually by unskilled labour, and the embodied energy and carbon are very low compared with conventional building. On a larger scale light-earth can be pumped into the formwork. Wall densities range from 300 to 1200 kg/m^3 with thermal conductivities ranging from 0.10 to 0.47 W/m.K respectively [Volhard, 1995, 146].

So far there does not seem to be any published report of light-earth using hemp apart from the occasional mention in passing [eg in Woolley, 2006, 140-2]. Invenia [2008] reports that a German company has developed hemp-clay adobe bricks intended for use within a timber frame and is looking for business partners in the construction industry. Their density is 550-600kg/m3, and thermal conductivity 0.2W/m.K.

2.6   Clay

For all un-stabilised earth building, clay is essential. It is locally available in many places, and is globally abundant; it is often a waste material from the foundations of conventional building sites. It has high thermal mass and is highly hygroscopic so will transfer and store both heat and moisture, which makes it perfect for regulating temperature and humidity. Most importantly, its embodied energy & carbon are very low.

2.6.1   Properties of Clay and Earth

Clay is plastic when moist, and relatively impermeable to water. It is used for lining dams and landfill sites. It absorbs pollutants, and helps maintain a healthy environment. Although it vitrifies at high temperatures, becoming impermeable ceramic, this is neither required nor desired for earth building.

Earth requires minimal processing; it does not need to be dried or fired before use, it can usually be sourced from the site or local area, it is simply dug out of the ground. So long as it is not stabilised with cement or lime it is completely reusable. Cement, gypsum and hydraulic limes set with a chemical reaction, a hydraulic set (see section 2.3.2); non-hydraulic limes by set by carbonation. In contrast, earth hardens by evaporation alone which is a reversible process.

Earth is sometimes stabilised with lime or cement[39]. This may be done for various reasons including resistance to abrasion, weathering, water erosion, shrinkage and cracking; also increased compressive strength, mechanical stability, workability, density and cohesion. However stabilization can also be achieved through compaction, or with other additives such as bitumen, aggregate or fibre [Houben & Guillaud, 1994, 118-28; Volhard, 1995, 49]

The percentage of clay in earth varies hugely but for most earth building purposes it is recommended to be between 10% and 30%. In contrast, the clay content in earth for light-earth is very high: at least 50% and preferably 80% or higher [Baker-Laporte & Laporte, 2005, 15].   This is the critical difference between light-earth and other forms of earth building.

Clay particles are very small and electrically charged, and arrange themselves in layers according to electrostatic forces; water molecules in the clay also play a crucial role. The bonds between the clay and water molecules and other inert grains of soil or aggregate are what bind the material together [Houben & Guillaud, 1994, 28].   Volhard categorises different earth samples according to their binding force; those with high clay content are 'fat' or cohesive and those with little clay are 'lean'. This use of 'fat' is similar to its use to describe limes, ie to the ability of the material to hold water[40].

The binding force of earth is determined not only by the quantity but also the type of clay present (see section 2.6.3). It can be tested using '8'-shaped samples as in Figure 15. Acceptable values for building range from 50-100 g/cm^2 at the low (lean) end to 280-360 g/cm^2 at the high (fat) end. However for Light-earth Volhard [1995, 32] recommends a minimum binding force of 160 g/cm^2. In practice, there are simple field tests for clay content that indicate the suitability of the earth for building; if a rolled coil can be formed

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[39] Lime is recommended for stabilizing earth with high clay content, cement for earth with low clay content [Houben & Guillaud, 1994, 118].

[40] Air limes are 'fatter' than hydraulic limes in that they hold and retain more water which makes them more 'workable' [Holmes & Wingate, 2006, 4].

into a ring without cracking it is perfect for light-earth [Baker-Laporte & Laporte, 2005, 15; Minke, 2006, 22-4; Volhard, 1995, 33-7][41]. If it does not have sufficient binding ability then pure clay can be added.
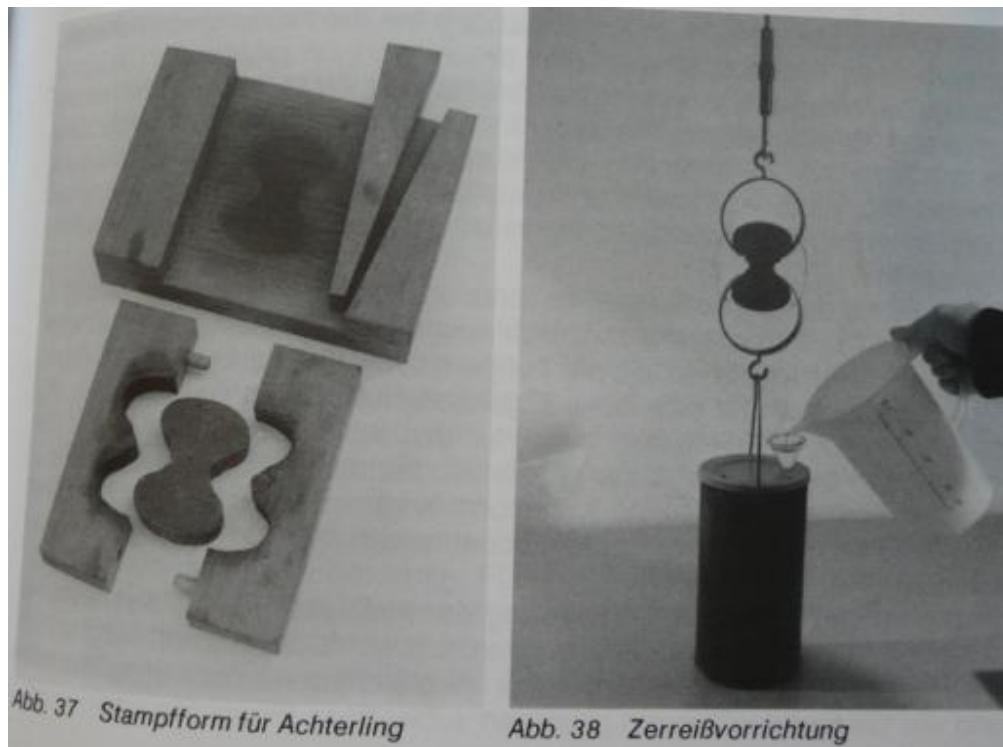
Figure 15: Testing the binding force of an earth sample [Volhard, 1995, 37]

2.6.2 Sources of clay

'Clay can be found in the ground within a mile of most places in North America' [Evans & Jackson, 2007, 30]. If clay is available on the site itself, the house could be designed so that the excavation forms a cellar which could be used for cold storage or to house a biomass boiler. Cellars have been proposed in the search for carbon neutral heating as the best and most likely solution for housing a biomass boiler and pellet store which together take up significantly more space than the domestic boilers we are accustomed to today. [Dunster, Simmons & Gilbert, 2008, 145]. Topsoil could be used on a green roof.

As with all resources we should beware overexploitation. The rapid expansion of the city of Aligarh (Uttar Pradesh, India) is leading to total degradation of the land around the city.

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[41] Weismann & Bryce [2006, 40-9] give detailed descriptions for testing soils for cob construction, however interpretation of the results should be adapted for light-earth since cob only requires 15-25% clay content.

Over 1 million cubic meters of soil are excavated each year for bricks and other building materials. Farmers selling their soil for high prices, shallow clay pits that are not restored to agriculture after clay-winning, and the expanding city itself are resulting in the permanent loss of hundreds of hectares of fertile agricultural land [Der-Petrossian, 2000,5]. The clay should be sourced with sensitivity to local environment.

2.6.3 Types of clay and what distinguishes them

Soils can be categorised by particle size. Clays have the finest particles (< 2microns), next are silts, (2-60 microns), followed by sands (0.06 – 2mm), gravels and pebbles. Clays are classed as phyllosilicates, silicate minerals consisting of thin sheets. Their structure means that water can be trapped between the silicate sheets. Clay particles are (mostly) negatively charged; they attract and readily substitute positively charged ions[42] (cations) in the soil [CUCE, 2007; Mineral Galleries, 2008]. This property known as Cation Exchange Capacity (CEC) is a measure of soil fertility since the cations are available to plants as nutrients. More importantly, for building, these electrostatic forces bind the particles together.

Clay consists mainly of alumina[43] and silica in varying proportions. There are three main types of clay with different particle sizes and structures: kaolinite, montmorillonite and illite, and most naturally occurring clays are mixtures of these with other weathered minerals which give the clay different colours. These three clays have different molecular structures giving them different properties.

Kaolinite (aka china clay) has the largest particles, low shrink-swell capacity and a low CEC. Montmorillonite[44] has the smallest particles, highest CEC and the highest capacity for water; some montmorillonites expand considerably more than other clays. It has high bending and compressive strength. The particle sizes and properties of illite fall between the other two. [Houben & Guillaud, 1994, 25-7; Minke, 2006, 20-21; Ammann, 2003, 98][45].

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[42] such as calcium (Ca2+), magnesium (Mg2+), and potassium (K+), sodium (Na+) hydrogen (H+), aluminium (Al3+), iron (Fe2+), manganese (Mn2+), zinc (Zn2+) and copper (Cu2+).

[43] Alumina = aluminium oxide (Al_2O_3) and silica = silicon dioxide (SiO_2)

[44] Montmorillonite belongs to the family of smectite clays and is the main constituent of the volcanic ash weathering product, bentonite

[45] Further detail in Appendix

2.6.4   Organic additives to clay

Urine and dung were historically added to earth for building. They are believed to add flexibility to the material[46] and also make it more weatherproof [Volhard, 1995, 49]. Dung contains urine, lignin, faeces, bacteria and is widely used in developing countries for its insect repellent and waterproofing properties. Nieden [1986] claims that fresh cow dung from grass-fed cows has a fungicide effect and inhibits mould growth in earth construction. Minke [2005, 41] likewise reports that tests at the Building Research Laboratory at the University of Kassel, Germany, demonstrated that the addition of cow dung and horse urine stabilised earth plaster against water to a high degree, enhanced the binding force of the earth, and acted as disinfectant against microorganisms. Blood, whey, quark[47] and boiled linseed oil have also been shown to improve the binding force of the earth [ibid].

2.7   Conclusion

It has been proposed that by using hemp as a building material it is possible to remove carbon from the atmosphere. The properties of hemp-lime and monolithic nature of construction simplify the building process and provide healthy buildings with low embodied energy and low energy requirements. Organic hemp production increases biodiversity and eliminates the soil depletion, reducing yields, and agrochemical requirements associated with monocultural cultivation.

The major limitation to the ability of hemp-lime to sequester carbon is the high embodied energy of lime. A better alternative would be to replace this with clay. Earth building has been proved throughout the world. Light-earth construction is very similar to hemp-lime construction. It is developing in Germany and New Mexico in particular where building regulations and guidelines have been developed and adopted by the authorities. There seems to be no reason why this technology cannot be imported to the UK. What has not been tested, apparently, is the use of hemp in light-earth construction. This hybrid technique would appear have additional benefits and to result in a net sequestration of carbon.

We need to ascertain the thermal and structural performance of hemp-clay and compare it with hemp-lime. There does not appear to have been any research conducted on hemp-

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[46] Ancient, paper-thin Chinese porcelain is believed to have been achieved by first aging the clay in pits with urine

[47] fat-free white cheese

clay. This thesis investigates the properties of hemp-clay with and without the addition of lime as a stabiliser. It attempts to establish the thermal conductivity and to do some rudimentary strength tests to get an idea of the structural performance.

3 Methodology

3.1 Introduction

The focus of the primary research is limited to the thermal properties of hemp-clay: thermal conductivity and heat capacity.

An initial sample demonstrated that clay could be made to bind the hemp without the use of any lime. A series of experimental blocks were then made and their thermal properties tested. Clay slip was made from clay and water. This was combined with hemp hurds and in some cases quicklime was added. The blocks were made in sets of 3, each set using a different mix of materials with varying quantities of clay, water, hemp and quicklime; a detailed description follows.

Measurements of thermal conductivity and volumetric heat capacity for the blocks were taken using an ISOMET thermal analyzer probe. The results were compared quantitively with each other and with published values for the conductivity of hemp and lime using commercial binders then extended qualitatively to draw conclusions about the viability of clay as an alternative binder.

Additional simple experiments were conducted that explored the strength of the blocks and pH of the material but the main topic of exploration was the thermal properties.

3.2 Raw Materials

3.2.1 Clay

Approximately 300kg plastic clay was obtained from a local brick company. The factory is sited on a clay deposit from which they extract clay containing nearly 80% clay ($21\%Al_2O_3$, $56\%SiO_2$). This clay proportion is far higher than in most earth used in earth building where the optimum clay content is usually between 5 and 30%.

The clay was described as having 25% moisture content and particle sizes having been graded to a max particle size of 2mm.   Larger grit particles were clearly visible when the clay was sliced through (see Figure 16) and in fact, at the bottom of each batch of slip (made up usually from 9 or 12 kg clay) there were a handful of stones up to 1cm across. An explanation for this might be gained from a visit to the factory or asking further questions from the manager but this was not pursued as it didn't appear to be a significant problem in the experiments and was a scenario that could well be encountered if hemp-clay were ever to be adopted on a larger scale.

Figure 16: lump of clay sliced through to reveal grit particles

The moisture content was tested by completely drying out 1kg of plastic clay. Assuming the quoted 25% moisture content figure was a 'dry-basis' figure we would expect 1kg plastic clay to contain 200g water and 800g clay, ie the water is 25% of the dry clay content.

The 1kg sample was broken up and weighed after 3 months of air-drying and found to weigh 814g. After being further dried in a domestic oven for 4 hours at 200°C the sample weighted 791g. According to Oxley and Gobert [2006, 12] for laboratory testing of moisture content the material must be oven dried to 105°C for > 2hrs. Gaia [2003,22] suggest that heating to 200°C can cause sorbed moisture bound by electrostatic forces to be released, which could be what happened here.

3.2.2 Hemp hurds

The hemp hurds used were bought as horse bedding; processed by Hemcore and supplied in large plastic-wrapped 20kg bales. They are treated with citronella to repel insects.

3.2.3 Quicklime

A sample tub (20kg) of quicklime was obtained. This is normally supplied in very large quantities for the purposes of soil stabilization. When quicklime is added to clay slip there is a chemical and a thermal reaction; ie it hydrates, converting from quicklime to hydrated lime[48], and heat is released such that steam is generated. Both these processes result in removing water from the slip which becomes more viscous.

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[48] Quicklime = Ca(OH), and hydrated lime = $Ca(OH)_2$

3.3   Making clay slip

The first sample batch of slip was made by hand, 'mushing' 0.6 kg clay in 1 litre water to produce a thin slip with the consistency of single cream. A sample 'minibrick' produced from this slip proved the feasibility of clay as a binder (Figure 17). After a little more background reading, in particular Gaia [2003, 75] a thicker slip was used. In retrospect, the mini-brick made from this initial slip was one of the more successful mixes and it might be worth pursuing a wetter mix.

Figure 17: sample 'minibrick' made from first test

Various methods were tried for making larger quantities of slip from plastic clay (see appendix). Powdered clays are less available commercially and are fairly expensive, and also have much higher embodied energy as the clay has to be dried and ground so these were ruled out. Initial doubts about the feasibility of making slip by simply soaking plastic clay in water proved unfounded; a paddle mixer for cement and mortar produced an acceptably smooth slip with the consistency of thick cream and without any tangible lumps within 10 minutes (Figure 18). Any sediment of sand and grit was distributed throughout by stirring thoroughly just before use.

Figure 18: Plasterers paddle mixer and clay slip

3.4   Making Hemp-Clay blocks

A frame was constructed from a sheet of 18mm plywood (Figure 19). It provided formwork for up to 6 blocks of 12.5x12.5x40 cm (0.00625m^3 per block)

Figure 19: Plywood formwork for 6 blocks

3.4.1   Methods of mixing

Various methods of mixing hemp with slip were tried (see appendix). The one adopted was to mix by hand in a very large plastic builder's trug. This was simplest as it could be done by one person and didn't take any longer than other methods. The slip was measured into the trug on top of the hemp using a 2 litre plastic measuring jug and mixed by hand until all the hurds were thoroughly coated with slip and the mixture was consistent throughout. The main thing to watch for was clumps of dry hemp, but by digging in with both arms and turning the mix from the bottom these were eliminated.   It was effective but fairly laborious and wouldn't be a suitable method for mixing large quantities. In cases where quicklime was added, it was easiest to mix it into the slip in a bucket before adding both to the hemp.

3.4.2   Quantities and measuring equipment

Initially water was measured in litres using a plastic measuring jug, the assumption being that 1 litre of water weighs 1 kilogram, but in fact it was difficult to reliably measure 1 litre using the jug, and weighing the water proved simpler and more accurate. For larger quantities of slip it was easiest to weigh the water into the bucket on top of the clay. Weights were measured using a hand-held spring balance[49] (Capacity 25 kg x Graduation 100 g).

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[49] SuperSamson Hand Held Spring Balance from ScalesExpress.com.

There was a bit of switching between measuring by volume and by weight. This was not ideal and was partly due to the limitations of the available domestic kit.

3.4.3   Making the blocks – first series

For each mix, a set of three blocks was made using between 2.1kg and 2.4kg hemp; this is roughly 18.75 litres, equivalent to the volume of 3 blocks (the material proportions in the blocks are shown in Table 1 below). The mixture was pushed into the formwork and tamped down by hand. The three blocks were filled up together in a series of layers but the surface of the layers was kept irregular so that each layer keyed in to the one before. The mix was distributed between the three forms by eye and feel, filling them simultaneously and keeping them roughly equally filled all the way up. Only once all the mix had been pushed into the three forms were the top surfaces levelled off and tamped down with a length of wood (Figure 20).

Figure 20: filling the formwork to make blocks

 The blocks were generally left in the formwork overnight and removed once they had had a chance to dry out slightly. One set of blocks was moved prematurely; the formwork was

removed after a couple of hours and they held their shape while in situ but one block collapsed while it was being moved. The mix has no tensile strength until it is at least partially dry, however the mix in the wall is not subjected to tensile forces. Baker-Laport & Laport [2005, 19] recommend that the formwork is removed as soon as possible to speed up drying, and certainly left in place no longer than two days.

3.4.4 Addition of Lime

Lime was added to some of the blocks (see stabilisers in section 2.6.1). Adding lime to slip created a lot of heat and steam and caused a significant change in the viscosity. If 10% lime (compared to the weight of plastic clay) was added then the viscosity changed from that of double cream to that of plaster or polyfilla.   To illustrate further, 9kg of clay with 6 litres water made a slip of a given viscosity. Adding 900g of quicklime (10% of weight of plastic clay) to this made the slip very thick and claggy. In order to return the slip to something approaching its initial viscosity it was necessary to add an additional 9 litres of water (roughly 1 litre water per 100g quicklime). The net result of this was that a given volume of hemp could be bound with less clay than without the addition of lime. The 10% lime slip (after the additional water was added) also had a different quality from the pure clay slip; it was smoother and looked silkier.

3.4.5 Interim conclusions

Before making the second set of blocks further testing was done using clay slip containing fixed proportions of water and clay: 1kg water to 1kg plastic clay (hereafter called 1:1 slip), 1kg water to1.5kg plastic clay (1:1½ slip), and 1kg water to 2kg plastic clay (1:2 slip). A series of samples were made in identical yogurt pots with hemp/clay/lime in different proportions (see Appendix 3.5.2). From these samples the following conclusions were drawn:

- a reasonable volume of slip is required; insufficient means the hemp is not bound together well enough.
- Too much slip made the sample very slow to dry
- Too much slip lead to mould growth.
- The addition of lime 'dried' the slip out making it significantly more viscous, see sections on Addition of Lime above and Measuring Viscosity below.
- Without adding any more water anything over 15% lime was virtually unworkable, very difficult to combine with the hemp.
- It was easier to add larger quantities of lime to the 1:1 slip because of its higher water content.

- A small volume of thinner slip was easier to combine successfully with hemp than a larger volume of more viscous slip.
- On average, a ratio (by volume) of 2 parts hemp to 1 part slip seemed about right.
- The addition of lime did not prevent mould growth; the worst mould was in samples with higher volumes of slip. There was no mould in the samples using 1:2 slip.
- If the viscosity of the slip was too high once the lime was added, it was impossible to blend it in completely.

From the results so far, it was decided that the weight of hemp in each block should be fixed at the volume that could be packed gently into the formwork when dry, and the slip should be about half the volume of the hemp. The next 7 sets of blocks all used 2.2kg hemp (approx 18.75 litres) and 9 litres of slip. It was also decided, following Gaia architects [2003, 75 & section 9.5.3.5], to attempt to maintain the viscosity of the slip. They recommend using a clay slip whose viscosity is such that when 100ml is poured from a height of 100mm it creates a circle of 150mm +/- 25mm diameter. In this way, any variation in the blocks would be limited to the relative proportions of clay, lime and water.

3.4.6 Measuring Viscosity

A simple equipment setup for measuring the viscosity of slip was devised following Gaia [ibid] (see Appendix 3.3 for detail and results). On the basis of the results, a mix of 1:1½ slip was used from then on.

For slip, Gaia give a guide of 40-80 litres of clay to 60 litres of water [2003, 75] which equates to 100-200kg clay[50] to 60kg water or $1:1^3/_5$ - $1:3^1/_3$ slip, so the slip used here was at the very low end of their recommendation.

3.4.7 Making the blocks – second series

In making the second series of blocks the plan was to keep the viscosity constant. After a trial run, the method adopted involved making two large batches of slip, one with no lime and the other with 10% lime. These were blended in varying proportions to create slip containing 0% 2% 4% 6% 8% and 10% lime[51]. In fact, closer consideration of the figures showed that, in order to maintain the viscosity, the 10% lime slip had to have higher water content, so these proportions were not accurate. For reference, further details of the method and the actual proportions in both series of blocks is shown in appendix 3.5.3.

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[50] Pure clay has a density of 2500kg/m^3 [Gaia, 2003,21] so I litre of clay would weigh around 2.5kg

[51] This batch method held a further surprise regarding viscosity, reported in the results.

Mix	Plastic Clay (kg)	Water (kg)	Hemp (kg)	Lime (kg)	Total weight of 3 wet blocks (kg)	Total weight of 3 dry blocks (kg)	Lime:Clay (% by weight)	Average weight per dry block (kg)	Comments
minibrick	0.6	1	0.2	0	1.8	1.19	0.00%		v.successful
First series									
blocks 1	6.3	3.7	2.1	0	12.1	6.16	0.00%	2.052	very crumbly and loose, like muesli bar
blocks 2	11.4	6.6	2	0.114	20.12	13.44	1.00%	4.476	Only 1½ blocks made – quantities scaled up
blocks 3	8	3.5	2.1	0	13.60	8.50	0.00%	2.834	crumbly, not well bound, but better than 1
blocks 4	8	7	2.1	0.8	17.90	9.83	10.00%	3.278	
blocks 5	8	6	2.4	0.4	15.28	8.67	5.00%	2.889	
blocks 6	9	6	2.4	0.45	16.48	9.35	5.00%	3.118	
blocks 7	9	9	2.25	0.45	20.70	10.13	5.00%	3.377	very smooth sides, well bound
Second series									
blocks 8: "pure"	7.36	4.91	2.2	0	14.47	7.62	0.00%	2.538	
blocks 9: "10%"	4.05	6.75	2.2	0.405	13.41	5.87	10.00%	1.955	
blocks 10: "10%"	4.05	6.75	2.2	0.405	13.41	5.91	10.00%	1.971	lime left soaking in slip overnight
blocks 11: "8%"	4.71	6.38	2.2	0.324	13.62	6.19	6.88%	2.064	4 parts 10% slip, 1 part pure clay slip
blocks 12: "6%"	5.38	6.01	2.2	0.243	13.83	6.51	4.52%	2.171	3 parts 10%, 2 parts pure clay
blocks 13: "4%"	6.04	5.65	2.2	0.162	14.05	7.00	2.68%	2.332	2 parts 10%, 3 parts pure clay
blocks 14: "2%"	6.70	5.28	2.2	0.081	14.26	7.50	1.21%	2.500	1 part 10%, 4 pure clay
blocks 15: "2%" + added water	3.78	6.39	2.2	0.058	12.43	5.82	1.52%	1.941	As above + extra water. Smooth sides, v. well bound

Table 1: Proportions of water, clay, hemp and lime in the blocks

3.4.8   Drying the blocks

The blocks were dried during a very wet summer in two mini greenhouses. These were shaded from direct sun but tended to show signs of condensation on the inside of the plastic walls. The doors were left open as long as there was no prospect of rain and extra ventilation holes were made near the top. Nonetheless, the atmosphere inside was quite humid and the blocks were quite close together. This could have contributed to the growth of mould, which was significant (see results), and may have led to cross-contamination of mould between the different mixes.

Figure 21: blocks drying in mini greenhouse

The blocks were made over a period of a month; Table 1 above shows the average weights of the blocks after drying for between 1½ and 2½ months (detail in Appendix 3.5.5).

3.5   Measuring pH

The pH of each batch of clay slip with any added lime was read using a Hanna Instruments Checker pH probe (Figure 22). This measures pH from 0 to 14 to a resolution of 0.01pH and an accuracy of ±0.2pH. The meter was first calibrated using buffer solutions of pH4 and pH7, following the manufacturers instructions.

Figure 22: Hanna Instruments Checker pH probe and buffer solutions

3.6   Measurement of Thermal Conductivity and Thermal Capacitance.

At the proposal stage the plan was to test the material in a calibrated hot-box but there was no access to professionally manufactured equipment. The possibility of building one was considered, but this idea was abandoned due to lack of adequate facilities. Given the relatively small scale of the samples, absence of laboratory conditions, limitations on cost, and inaccuracies due to design, construction, calibration, and sample inhomogeneity, the errors were likely to be very great. The British standard for hot-box design (BS EN ISO 8990:1996) recommends a sample cross-sectional size of 1.5metres square, and the samples were 12.5cm. An alternative method of measuring thermal conductivity was adopted, that being a commercially available transient heat-transfer analyzer probe. This technique has been used previously by Goodhew & Griffiths [2005], and also by Plymouth University on behalf of Gaia [2003,220-2]

3.6.1   Transient Heat Transfer Probe

The Isomet Heat Transfer Analyzer is a portable device for dynamically measuring thermal conductivity and volumetric thermal capacitance in a broad range of solid or liquid materials. Measurements were taken using a needle probe, which sometimes required

drilling a 3mm hole with the supplied drill bit. The needle probe used had a range for thermal conductivity of 0.035-0.20 W/m.K, and the samples were all well within this.

This is a dynamic measurement of thermal conductivity and capacitance, and the samples were not fully dry (unlike in a hot-box). The probe is inserted into the sample, switched on and left for a few minutes until a baseline thermal equilibrium is reached; the probe then emits a series of heat flow impulses and measures the temperature response of the material over time.

Figure 23: Isomet heat transfer analyzer and needle probe

Various factors are expected to affect the results of the measurement including [Isomet user's guide, p5]:

- **Quality of the thermal contact between the probe and measured object**. This was likely to be the most problematic issue because of the muesli like texture of the hemp-clay.   Trials with the probe by Rhydwen [personal communication] in measuring the thermal conductivity of a hemp batt showed that the use of toothpaste on the probe [following Goodhew & Griffiths, 2005, 452] made no difference to the results and therefore presumably did nothing to improve the thermal connection. Furthermore, in eight repeated tests, the results from the probe matched the published value for the hemp batt. It is reasonable therefore to assume that there was good thermal contact.
- **Temperature fluctuations and drift**. An attempt to control this was made by conducting measurements indoors with all doors and windows closed to minimise draughts.

- **Finite dimensions of the measured material sample**. The block dimensions were 125x125x400mm. Measurements were taken near the centre of the block to minimise edge effects. No measurements were taken within 25mm of the edge.
- **Non-homogeneity of the measured material sample**. The mix is unlikely to be perfectly homogenous. Repeated tests were taken on the blocks, working from different faces to attain an average reading for each block and an idea of the distribution of the readings.
- **Anisotropy of the measured material sample**, ie different properties in different directions. The mix itself should not exhibit anisotropy since the hemp hurds lie higgledy-piggledy in all directions, however the dimensions of the blocks are likely to result in edge effects different in the direction parallel to the long axis of the block than the other two dimensions.
- **Humidity of the measured material sample**. The blocks were dried for about 3 months and a moisture meter used to measure their moisture content before thermal conductivity was measured. They were not fully dry and would be expected to dry out further. The results are however more likely to represent the actual conductivity in practice than measurements from a hot-box; thermal conductivity results from a hot-box results would probably be lower.

Results for thermal conductivity, thermal capacitance (volumetric heat capacity), thermal diffusivity and thermal effusivity were derived for each set of three blocks[52]. Each of the three blocks in the set was tested twice, once in the middle of each end. This gave 6 readings which were averaged to derive a single value for the set, and the maximum and minimum readings noted.

A second subset of measurements were taken a month later on one block from each set. These were taken by R.Rhydwen for the purpose of crosschecking.

3.7   Moisture Testing

After 3 months drying the blocks were tested with a moisture probe[53] (see Figure 24). This was done in the same week and in the same location as the thermal conductivity tests (section 3.5 above) for the thermal conductivity and thermal capacitance measurements. The moisture probe gives measurements as percentage wood moisture equivalent (%WME) and also gives an LED display in green (dry), amber (borderline) or red (damp). But in

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[52] Thermal diffusivity = λ/c_v, and Thermal effusivity = $\sqrt{(\lambda c_v)}$ where c_v = volumetric heat capacity

[53] Protimeter Surveymaster.

essence, %WME can be interpreted to give the ambient relative humidity at the tips of the probe (see Appendix 3.7).

Figure 24: Moisture probe, displaying a red (damp) LED warning at 22.6%WME

A series of 3 moisture readings was taken in the centre of each block. These were averaged to give a single value for the block. It is possible that there was variation between the two ends but this was ignored.

As with the thermal conductivity, a second subset of measurements were taken a month later on one block from each set. These were taken by R.Rhydwen for the purpose of crosschecking.

3.8   Strength Testing

Although the hemp-clay in this construction method is not load-bearing, it must be able to bear its own weight up to a height of a single storey. A rudimentary test of the compressive strength of some of the blocks was conducted by placing a board on top of

them and loading them with weights (ie different people standing on them, 96kg max). The force was increased by reducing the area that was taking the weight, firstly the blocks were laid flat lengthways on the ground, then standing on end (Figure 25, left), and then they were supported on a 2cm strip on each end of the blocks (Figure 25, right).

Figure 25: loading the weight (left): on the end of the blocks and (below): on a fraction of their length

4   Results

4.1   Overview

This section firstly describes the material proportions of the test blocks, the mould that grew on them, and the pH testing results. This is followed by a summary of the main experimental results from testing with the heat-transfer analyser probe. The thermal properties are correlated against density and moisture content and compared with published figures for hemp-lime. Finally, observations from the viscosity adjustments are followed by the results from compressive strength testing.

4.2   Material proportions of the test blocks

The relative proportions of raw materials in the blocks[54] are shown in Table 2 below. Most of the blocks shrank slightly as they dried. The length shrank from 40cm to 39 cm and in the other dimensions it was barely measurable. In order to calculate an approximate density the volume of the 3 blocks was assumed to be exactly $0.0183m^3$ (3 * 12.5cm * 12.5cm * 39 cm).

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[54] Exact weights are shown in appendix 3.5.3, and the calculation of the proportions of clay, water and lime used in the second series of blocks is in appendix 3.5.4.

Mix	Water:Clay (by weight)	Water:Hemp (by weight)	Clay:Hemp (by weight)	Lime:Clay (% by weight)	Density Kg/m^3	mould rating 1 to 5	mould comments
minibrick	1.67	5.00	3.00	0.00%	635	1	None
blocks 1	0.59	1.76	3.00	0.00%	336	1	None
blocks 2	0.58	3.30	5.70	1.00%	734	5	the worst by far - black and powdery plus white and furry plus olive green 'lichen' - probably a health risk.
blocks 3	0.44	1.67	3.81	0.00%	465	1	None
blocks 4	0.88	3.33	3.81	10.00%	537	2	white and furry plus black and powdery
blocks 5	0.75	2.50	3.33	5.00%	474	2	white and furry plus black and powdery
blocks 6	0.67	2.50	3.75	5.00%	511	4	white and furry plus black and powdery and rust coloured patches
blocks 7	1.00	4.00	4.00	5.00%	554	2	white and furry plus black and powdery and rust coloured patches and some bright orange
blocks 8	0.67	2.23	3.35	0.00%	416	2	white and furry
blocks 9	1.67	3.07	1.84	10.00%	321	4	white and furry, black and spotty, small rust patches
blocks 10	1.67	3.07	1.84	10.00%	323	4	white and furry, black and spotty, brown patches and some salmon coloured patches
blocks 11	1.35	2.90	2.14	6.88%	338	4	white and furry, black and spotty, few pinkish patches
blocks 12	1.12	2.73	2.44	4.52%	356	4	covered in dark brown spots (looks almost like soil), some white furry patches
blocks 13	0.93	2.57	2.74	2.68%	382	2	dark brown/black and spotty, some white furry patches
blocks 14	0.79	2.40	3.05	1.21%	410	4	white and furry with some black spotty
blocks 15	1.69	2.90	1.72	1.52%	318	3	white and furry, a little black spotty

Table 2: Relative proportions of materials in blocks and mould

4.3   Mould

Mould was found growing on many of the blocks (Figure 26); in Table 2 (above) this is given a rating from 1 (none or negligible) to 5 (very thick), and a qualitative description.   No very clear correlation could be found between mould growth and the proportions of the raw materials (see charts in appendix 4.2), though higher water content did appear to lead to increased mould which is not surprising. Interestingly though, increasing the lime content did not appear to reduce the mould as would be expected, given that the pH is around 12 when lime is added.

It appears that the mould is largely surface mould; when block 2a was cut up the mould penetrated the outer 1cm depth, where the cavities were exposed to the air, but inside the block there was little sign of mould. It is possible that the surface hemp didn't retain the full coverage of slip, or that in the warm, humid conditions the spores in the hemp at the surface were able to establish themselves despite the alkalinity.

Figure 26: mould growing on the blocks as they dry

4.3.1   pH readings of clay slip with added lime

It had been expected that the alkalinity of the lime would protect the blocks from mould, but this was clearly not the case. The pH of the slip without lime was 8.2, but as soon as even 1% lime was added then the pH rose to around 12.8, and adding more lime made almost no difference to the pH (Figure 27) (Further detail in Appendix 4.1).
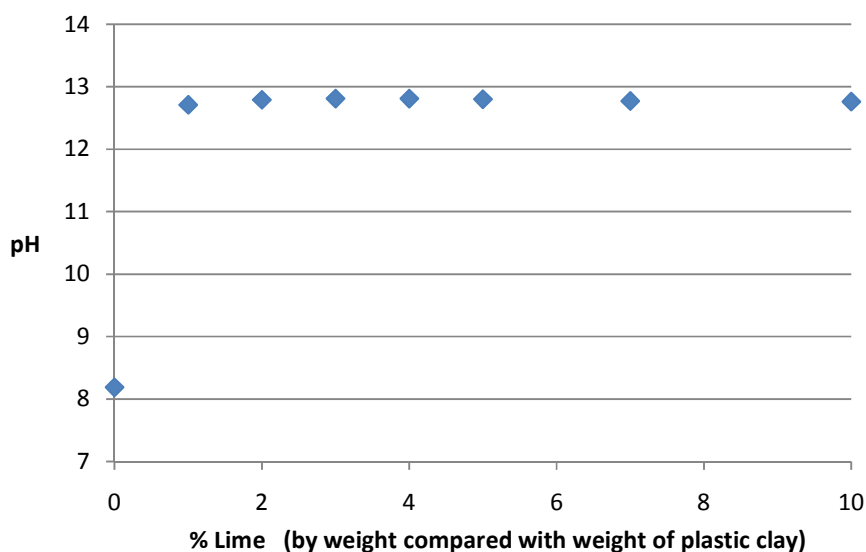
Figure 27: response in pH of clay slip to the addition of lime

4.4   Thermal conductivity, heat capacity, diffusivity and density

Thermal conductivity and volumetric heat capacity of the blocks both track density quite closely as shown in Figure 28. Since volumetric heat capacity is calculated by multiplying the specific heat capacity and density we can assume that the specific heat capacity is fairly constant across the various mixes.

Thermal conductivity

Volumetric heat capacity
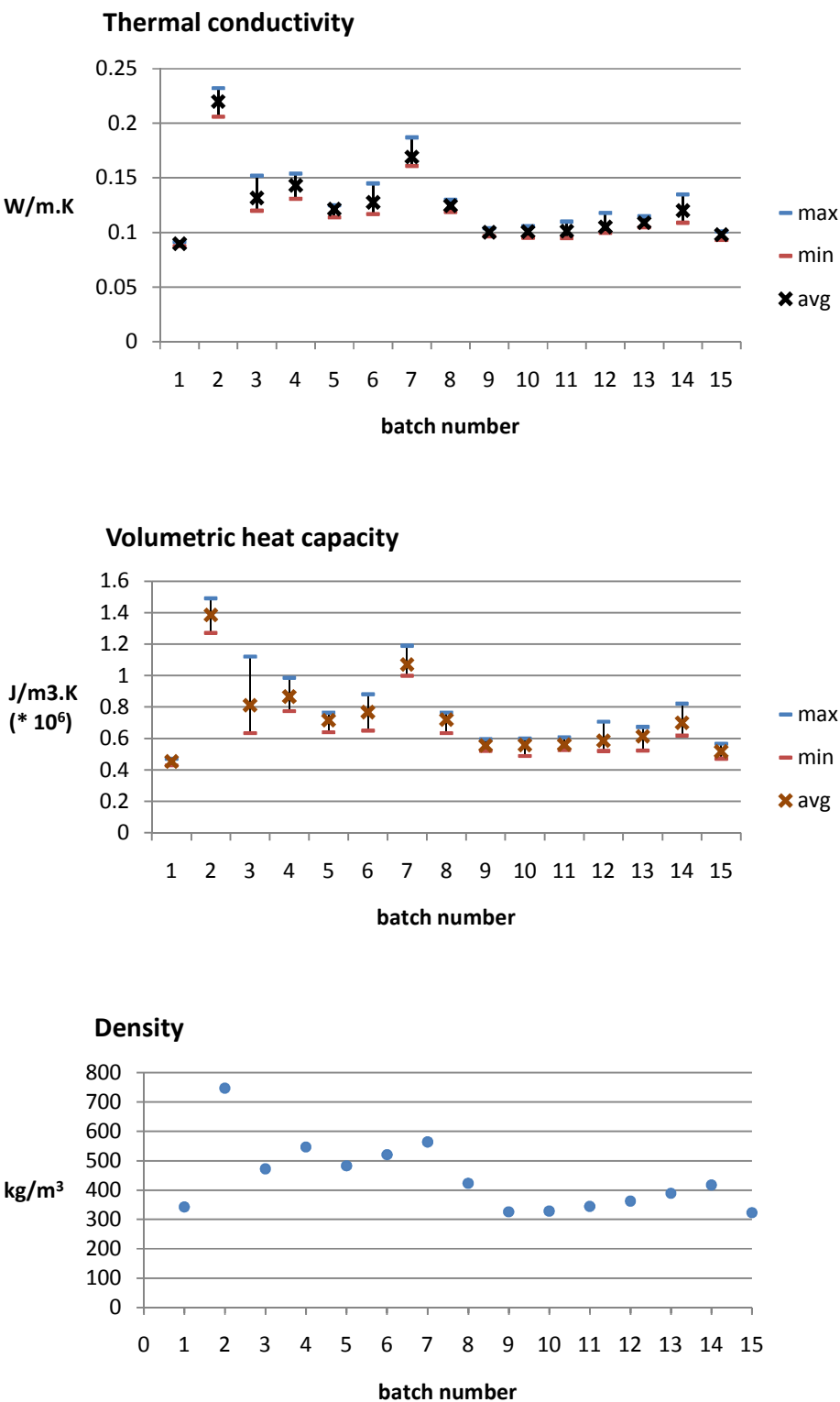
Density

Figure 28: thermal conductivity & volumetric heat capacity tracking density for the test blocks

Thermal diffusivity is by definition inversely related to density[55] and directly related to thermal conductivity. As might be expected, it is fairly consistent across the blocks regardless of the mix (Figure 29). Values range from 0.135 to 0.211 * 10^{-6} m2/s.
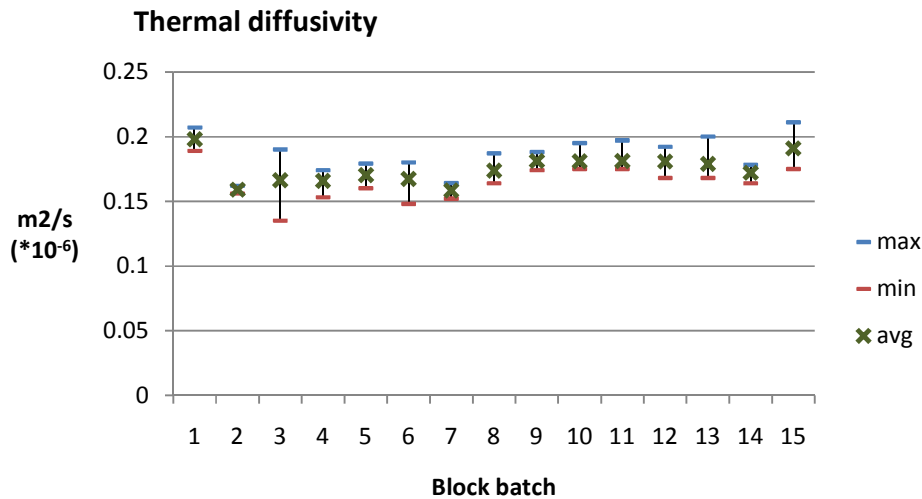
Figure 29: Thermal diffusivity for the test blocks

4.4.1   Thermal conductivity against Density, compared with published results for light-earth

If the thermal conductivity is plotted against density (Figure 30) the results obtained agree closely with figures published in Volhard [1995, 146] and Gaia [2003, 41]. Volhard (shown in red) quotes 0.1 W/m.K for 300kg/m^3 and 0.25 W/m.K for 800kg/m$^{3.}$ Gaia quote their density as dry density which cannot be assumed here since the blocks were not completely dry (see section 4.5) but the figures agree nonetheless. The thermal conductivity of hemp-clay may in fact be lower than straw-clay since the results are already on the low side and, as the blocks dry further, might be expected to fall lower.

A trendline added to the chart including the R-squared value shows there is excellent correlation for the blocks between density and thermal conductivity. [56]

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[55] thermal diffusivity = thermal conductivity / (density * specific heat capacity)

 = thermal conductivity / volumetric heat capacity

Thermal Conductivity (W/m.K)
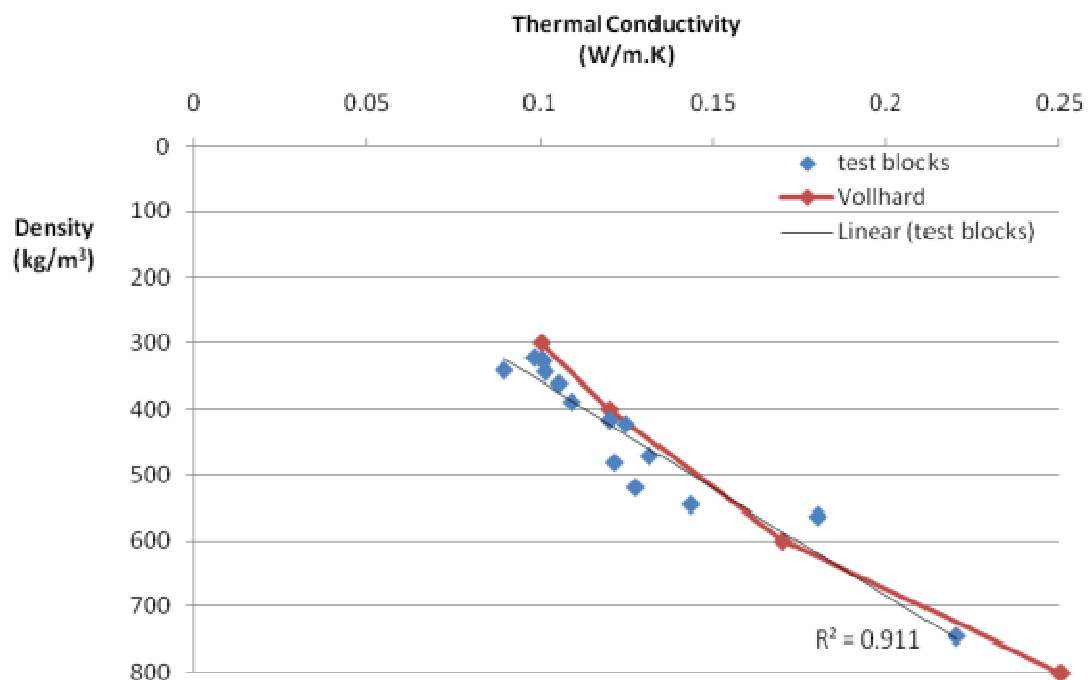
Figure 30: Thermal conductivity plotted against density for the test blocks

4.4.2 Thermal conductivity and density

There are two ways to increase the final density of light-earth (assuming that the construction water all eventually dries off) one is to add more clay and the other is to compress it more in the formwork. In the test blocks, most of the volume comes from the hemp hurds; the much smaller clay and lime particles fill in the gaps between them[57]. Therefore, since the volume of hemp in each set of blocks was approximately constant (especially in the second series of blocks), and the blocks were all the same size, it can be assumed that the compression was fairly constant.

If the blocks were completely dry we could assume, therefore, that the difference in density between the blocks was due to the clay (and lime) content. The moisture content was measured at the same time as the thermal conductivity, and a subsequent sub-set of

—————————————————— (footnotes continued) ——————————————————

[56] R^2 value is a statistical tool (automatically calculated by MS Excel) that is used to evaluate the strength of a relationship; a perfect correlation should give a value of 1.0, >0.5 is very significant, and 0.0 indicates no correlation.

[57] This is an assumption, borne out by .

moisture and thermal conductivity readings taken a month after the main readings for crosschecking purposes. From this second set of measurements it became apparent that most of the blocks had continued to dry in the intervening period (see section 4.5).

The clear connection between thermal conductivity (λ) and density of the blocks is shown again in Figure 31. It is not clear however whether the higher values relate to excess moisture in the blocks or higher clay content, since the blocks were not fully dry when the conductivity was measured.
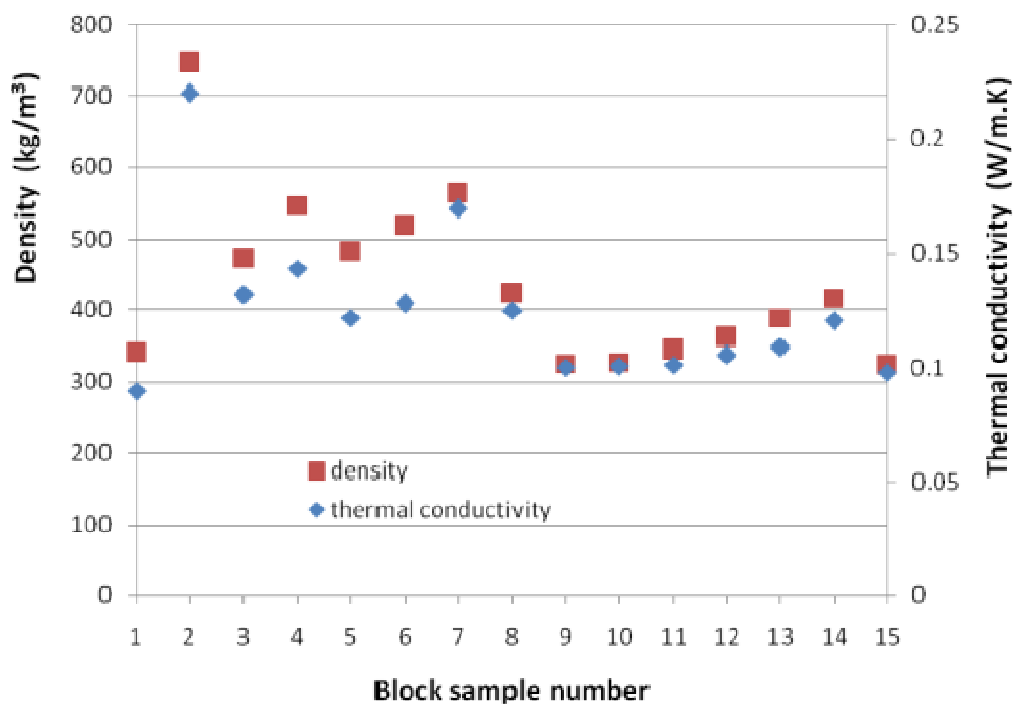
Figure 31: Density and thermal conductivity for the test blocks

Figure 32 shows λ in combination with the initial weights of clay and (construction) water; it appears that there is correlation with both. Blocks 3 and 4 contained the same weight of clay but 4, which initially contained twice as much water (plus quicklime), shows higher λ. On the other hand, blocks 4 and 10 contained the same weight of water but 4 initially contained twice as much clay (plus quicklime) and shows higher λ. There is possibly closer

correlation with clay content than water; since the thermal conductivity for unfired clay (0.7-2.1 W/m.K)[58] is higher than for water (0.61 W/m.K), this is perhaps unsurprising.
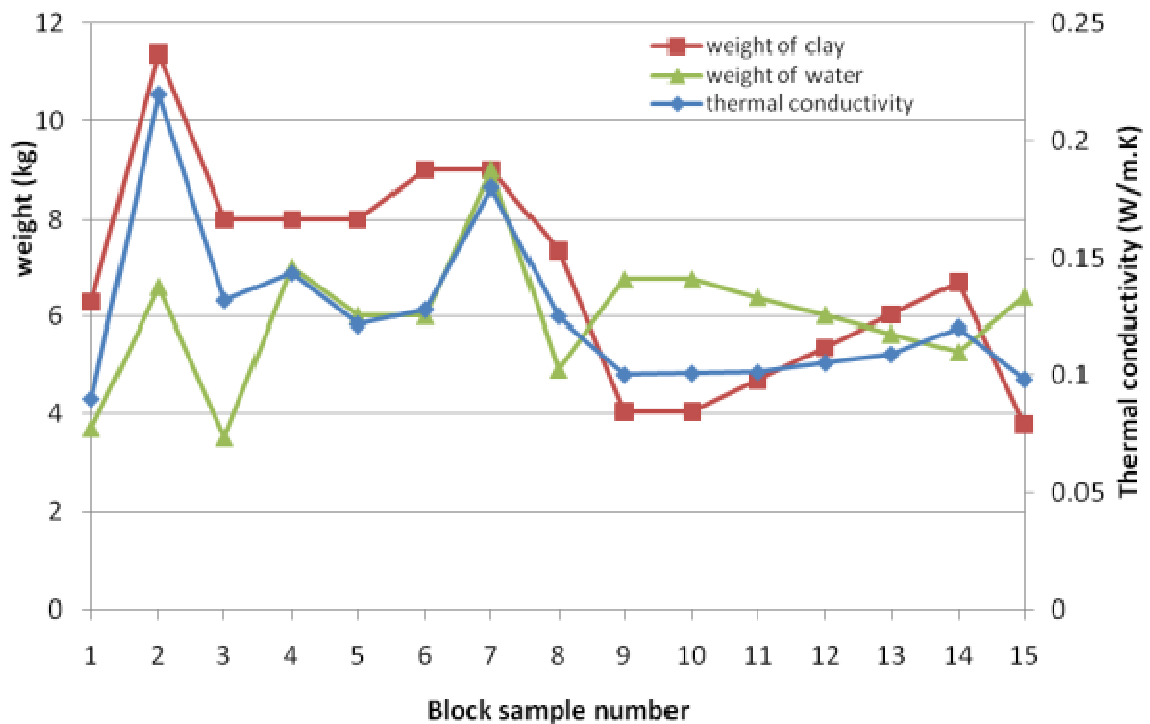
Figure 32: thermal conductivity with weight of clay and water in test blocks

The water data in Figure 32 refer to the amount of water used in construction. This is really only useful as an indication of how quickly the bricks will dry, and whether (before they are dry) one block is more likely to have a significant water component in the density than another. We really need to look at the moisture content at the time the thermal conductivity was measured.

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[58] An internet search for a thermal conductivity of clay was unhelpful. Bentonite was quoted values from 0.7 to 2.1 W/m.K, and soil 1.5 W/m.K (Wikipedia). Generally though values were higher than for water.

4.5 Thermal conductivity and moisture reading

Figure 34 shows the thermal conductivity and moisture readings for the blocks. There were three blocks in each batch, each with one moisture reading[59] and two conductivity readings (one from each end). Also displayed is a second series of readings for conductivity (in yellow) and moisture (in red). These were taken on one block from each batch, approximately a month later for the purposes of crosschecking.

Figure 33 shows the same results for the 'a' blocks only, ie those that were cross-checked after 1 month. For block 1a the moisture reading had increased, for 3a and 11a it had risen very slightly, but all others had fallen. The thermal conductivity had also fallen, with the exception of block 1a which remained almost constant.

From Figure 33 and Figure 34(overleaf), there is clearly some correlation between moisture reading and thermal conductivity, regardless of the make-up of the block.
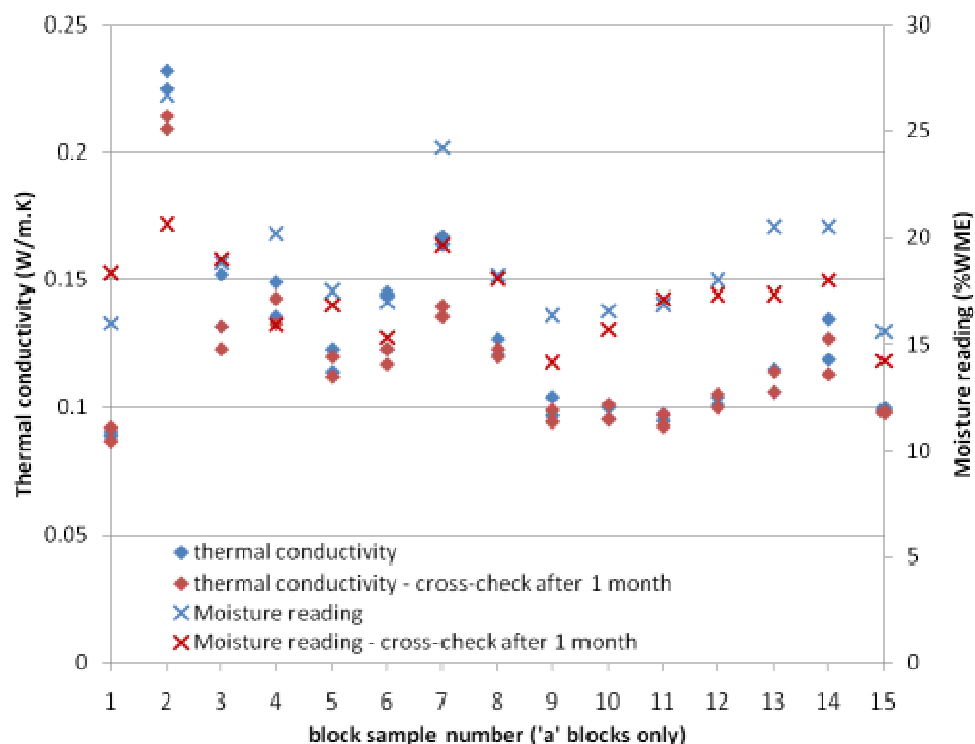
Figure 33: Moisture reading and thermal conductivity for 'a' blocks

[59] There was only a single averaged moisture reading for each block. Blocks 2 and 15 only had 2 blocks in the batch.
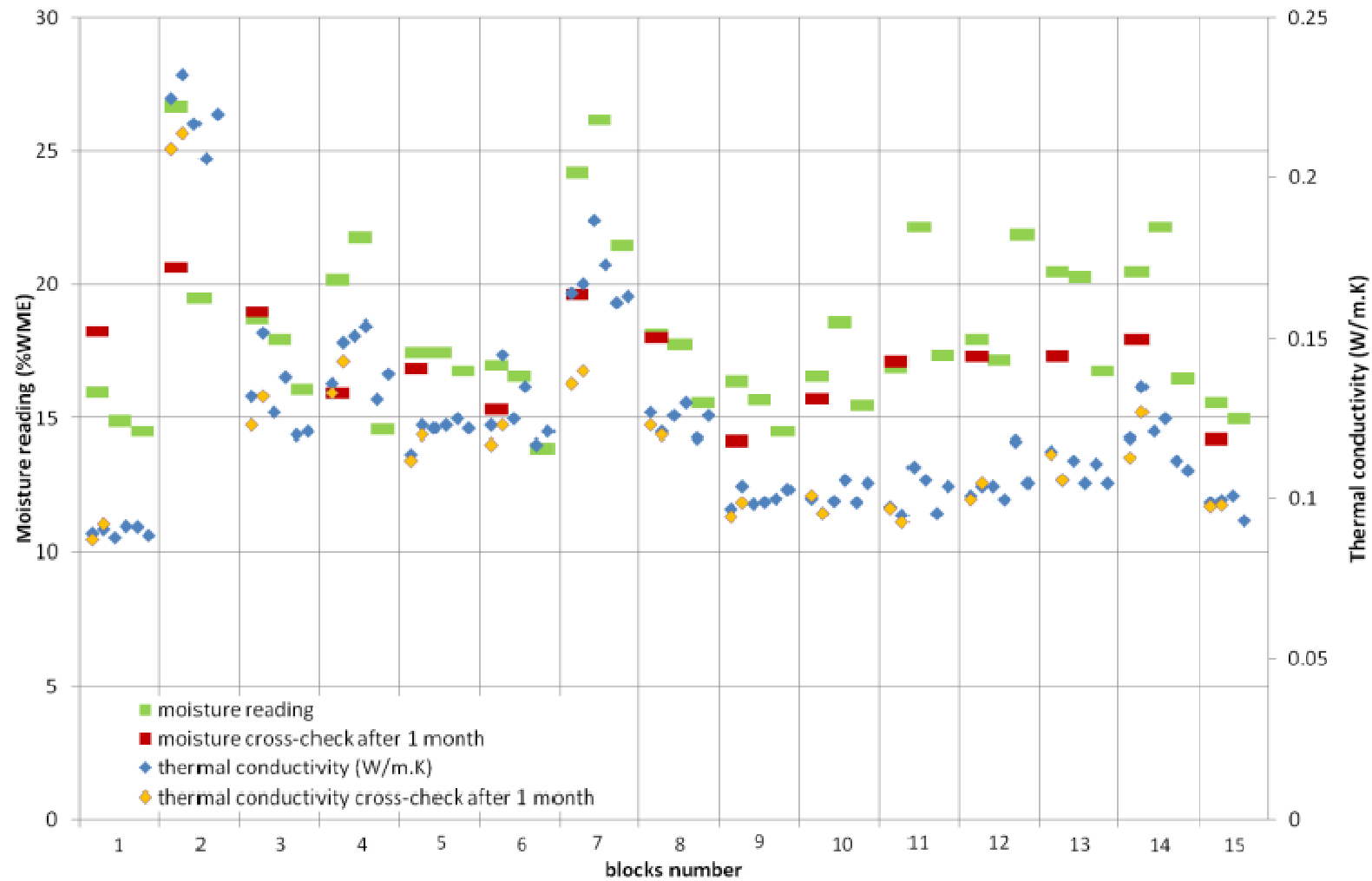
Figure 34: Moisture reading and thermal conductivity for all samples

 This correlation is more obvious when moisture reading is plotted against thermal
conductivity (Figure 35). The graph shows that blocks 7a and 2a (for example) moved down
and left towards lower conductivity as they dried. For 3 blocks however the moisture
content actually increased, in particular for block 1a. It may be that it had finished drying
and had reached its equilibrium moisture content which was changing in response to the
relative humidity of its surroundings (see discussion).
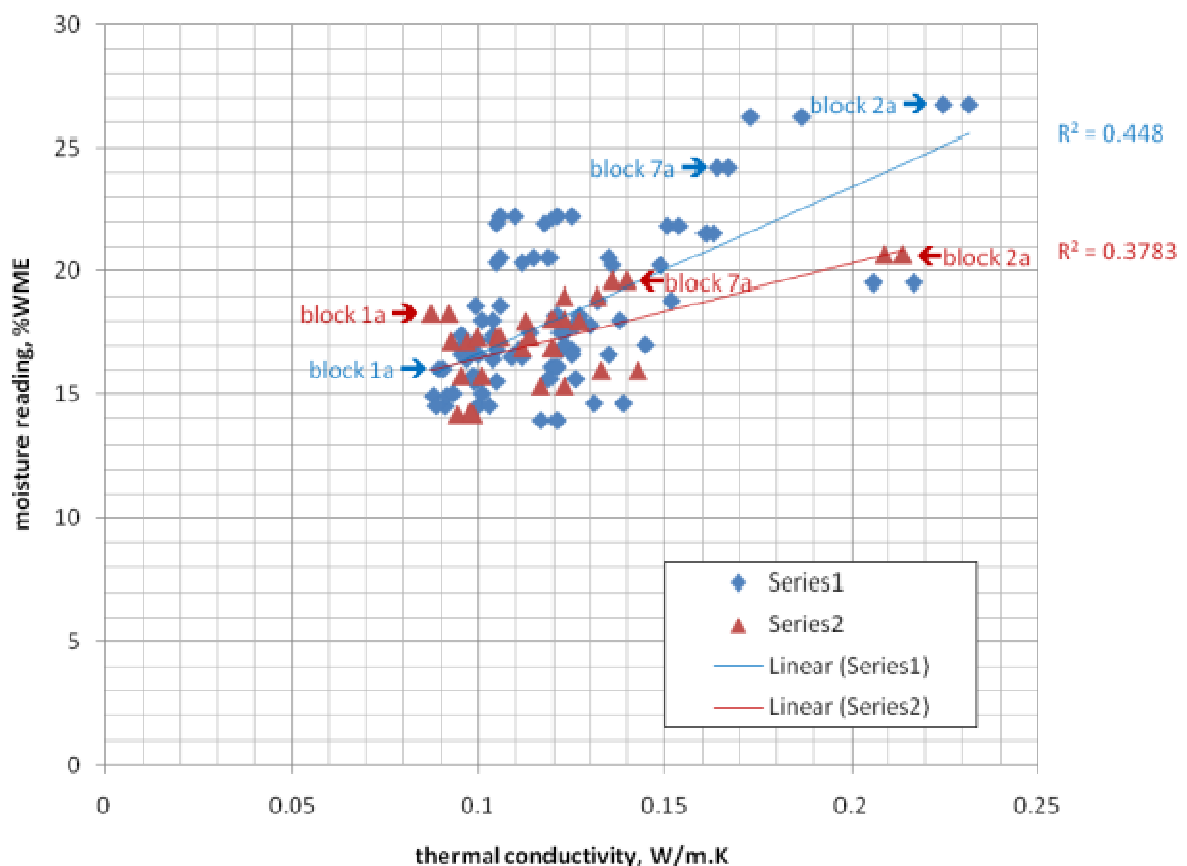
Figure 35: thermal conductivity against moisture content; series 2 measurements ('a' blocks only) were approx 1 month later than series 1

A trendline was added to the chart including the R-squared value. There is a fairly good
correlation between thermal conductivity and moisture reading[60], so one could expect that
if the blocks were to dry further their thermal conductivity would also fall. If thermal
conductivity values were measured after the material had been fully dried out in a hot-box,

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[60] The lower R-squared value for the second series may be partly due to the smaller sample size.

then they could be lower still. It was not possible to determine whether the values given in Volhard (see 4.4.1) were for oven dry material or not, but it looks possible that hemp-clay may have lower thermal conductivity than straw-clay.

4.6 Viscosity

There was an interesting result from the batch method adopted in the second series of blocks for mixing slip with lime at different concentrations. In order to make 9 litres slip with an 8% lime concentration, 4 parts (7.2 litres) slip with 10% lime[61] were combined with 1 part pure clay slip (1.8 litres).

The viscosity of the two batches of pure-slip and 10%-lime-slip had been carefully adjusted to acceptable values, and the assumption was that when they were combined the viscosity of the blend would lie somewhere between the two. When the two slips were combined however the viscosity changed again. The batches were made in order of reducing % of lime and it was not until the 4% batch was made that the effect became really noticeable. In the 2% batch the result was dramatic; the blended slip was considerably more viscous than either of the source batches. To prove this point two small fresh batches of slip were made and the viscosities were tested again (Table 3).

Mix	Viscosity circle diameter
Pure clay slip	14.2cm
10% lime slip	12.6 cm
1 part 10% lime slip + 4 parts pure clay slip	thick custard, won't flow through the funnel at all!

Table 3: viscosity for different slip mixes

These results were very surprising. Perhaps there is so much lime in the 10% mix that there is not sufficient clay for it to react with, and as the clay proportion in the mix increases more and more of the lime is able to combine. This would suggest that a slip with a high proportion of lime has 'free' lime in it that will presumably carbonate in the air as it dries out, whereas a smaller proportion of lime will be completely used up in chemical reactions with the clay. In other words the clay becomes saturated with lime at some point and then any additional lime remains in suspension. The percentage at which saturation point is reached is not clear but it must be less than 10%.

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[61] As a percentage of the weight of plastic clay

4.7 Strength Testing

All the blocks, lying on their bases, could withstand the weight of a 96kg man with no deformation. The least dense block (15b) and second-most dense (7b) were loaded on their tops (39cm * 12.5cm = 0.049m^2), on their ends (0.125*0.125 = 0.016m^2), and on a 2cm strip at each end of the base (0.125*0.02*2=0.005m^2). The results are shown in Table 4, Figure 36 & Figure 37.

Block	Density (kg/m^3)	Area exposed to weight (m^2)	Weight (kg)	Pressure[62] (MPa)	Comments
7	554	0.049	96	0.02	No obvious effect
7	554	0.016	96	0.06	No obvious effect
7	554	0.005	96	0.19	Slight indentation (Figure 37)
15	318	0.049	96	0.02	No obvious effect
15	318	0.016	96	0.06	No obvious effect
15	318	0.005	96	0.19	Significant deformation (Figure 36)

Table 4: results of strength tests

Figure 36: compression damage to block 15: the least dense block (318 kg/m3)

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[62] Pressure (N/m^2 or kg/m.s^2) = mass (kg) * gravity (9.81m/s^2)/area (m^2)

Figure 37: compression damage to block 7: the second densest block (554 kg/m3)

 BRE [2002, 22] conducted compressive-strength tests on the hemp-lime 'wall' mix at Haverhill. The compressive failure strength was defined as the compressive stress at which 10% relative deformation occurred. For a density of 550 kg/m3 the compressive strength was 0.458 MPa.

Both blocks were able to take 96kg on their ends without effect. Block 15 was seriously deformed in the most severe test. Block 7 was marked but did not show a 10% relative deformation. The stress applied to block 7 was just over 40% of that at which the hemp-lime failed in the tests by BRE [ibid].

In an effort to ascertain the effects of lime stabilization on the compressive strength, two pairs of blocks were tested. In each pair the blocks had very similar densities but one contained lime and the other did not. Between blocks 3 (0% lime, density 465kg/m^3) and 5 (5% lime, density 474kg/m^3), block 5 was definitely stronger.   However between blocks 8 (0% lime, density 416kg/m^3) and 14 (1.2% lime, density 410kg/m^3), block 8 was stronger (block 14 crumbled at the ends in the most severe test). So results were not conclusive.

These amateur tests were not ideal as the block was loaded on just a narrow strip at the ends which were more fragile anyway; some of the less successful blocks crumbled slightly at the edges when handled. It is possible that in more controlled tests the hemp-clay could perform as well as hemp-lime.

5   Discussion

5.1   Overview

This investigation has focused on the thermal properties of hemp and clay. The results are discussed below. The material is not intended to be load bearing, and compressive strength was only addressed in a token manner, but the blocks proved to be fairly robust (section 4.7). Mould is discussed in section 5.3 but is unlikely to be an insurmountable problem; different types of clay and additives that may address the mould issue are discussed in section 5.4.

The embodied energy and net carbon sequestration are discussed in section 5.5 and the overall environmental impact of the method is addressed in 5.6. Other more general issues are covered in section 5.7.

5.2   Thermal performance

5.2.1   Comparison of experimental results with published figures for hemp-lime

From the experimental results, the thermal conductivity of hemp-clay closely correlates to density and ranges from 0.09 to 0.22 W/m.K for densities ranging from 320 to 750 kg/m^3. Absolute figures for the thermal performance of hemp-*lime* are elusive. Data published by the Tradical group of companies for hemp-lime is inconsistent, even from the same source. They frequently refer to research by Evrard, De Herde & Minet, who themselves produce different figures again (see Figure 38, sources in footnotes).

Hemp-lime Mix	Density kg/m^3	Thermal conductivity W/m.K	Thermal capacity J/kg.K
Wall-mix (sprayed) [63]	330	0.09	
Roof-mix	220	0.08	
Floor	375	0.11	
Render	700-950	0.12 - 0.13	
Wall (sprayed) [64]	330	0.07	1400
Wall (shuttered & tamped)	480	0.11	1550

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[63] http://www.lhoist.co.uk/tradical/pdf/walls.pdf, (and similar for roof-insulation, screeds & renders--plasters)

[64] http://www.lhoist.co.uk/tradical/documents/TheThermalPerformanceofTradicaHemcrete.pdf

Hemp-lime Mix	Density kg/m^3	Thermal conductivity W/m.K	Thermal capacity J/kg.K
Wall[65]	480	0.12	1550

Figure 38: Variation in published figures for Tradical hemp-lime

The final density given by LHoist is basically the sum of the weight of hurds + weight of binder, eg wall mix is 110kg hurds[66] with 220kg binder to give a density of 330. This is an unlikely result since the construction water cannot be assumed to dry off completely; there will always be some bound water in the material. Also the density immediately after construction will be lower than the final density, due to carbonation.

Because it is absorbing CO_2, we would expect that each kilogram of the binder (if it fully carbonates (see 2.4.4)) will increase its weight to 1.35kg [67]. Hence, for the wall mix (110kg hurds + 220kg binder) the final density, ignoring water, would be 407kg rather than 330kg.

This higher density might be expected to lead to an increase in thermal conductivity. Evrard et al [2006, 72] confirm that as the walls get denser through carbonation, thermal conductivity increases 1.5% for each increase of 1% in mass. Freshly cast hemp-lime with density=330kg/m^3 and conductivity=0.07W/m.K, would from this calculation result in a fully carbonated wall with density=407kg/m^3 and conductivity=0.09W/m.K. None of these factors are made explicit in the promotional literature.

Furthermore, for Evrard & DeHerde [2005, 28] the dry thermal conductivity was 0.11W/m.K whereas at 50% relative humidity it increased to 0.12W/m.K.

For comparison, the walls of the WISE building[68] were measured after 6 months drying (in damp west Wales) and found to be still damp with a very high average thermal conductivity of 0.21W/m.K[69] [Rhydwen , personal communication, Nov 2008].

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[65] Evrard, DeHerde & Minet [2006]

[66] 1m^3 of packed hurds weighs roughly 110kg

[67] Uncarbonated lime is $Ca(OH)_2$, molecular weight=74 ; and carbonated lime is $CaCO_3$ molecular weight=100

[68] Wales Institute for Sustainable Education, nearing completion in Jan 2009. Walls used a mix of 22kg hemp, 55kg binder and 40-50 litres water [Rhydwen , personal communication]

[69] (thermal conductivity ranged from 0.2 to 0.5W/m.K (but the probe was only marked for use up to 0.3W/m.K) with moisture between 50 and 89%RH)

All this makes it difficult to draw anything other than general conclusions. However, comparisons are made in Figure 39 and Figure 40 between hemp-clay (using a sample from the experimental results) and hemp-lime using values provided commonly by the Tradical group.

The hemp-lime thermal conductivity measurements are derived in a hot-box. The hemp-clay blocks in this thesis were not, and therefore direct comparisons are biased towards hemp-lime. It is to be expected that the thermal conductivity for the hemp-clay blocks would fall if they were dried out fully in a hot-box, and for hemp-lime they may rise through carbonation.

Material	Density kg/m3	Volumetric heat capacity $J/m^3.K$	Thermal conductivity W/m.K	Thermal effusivity $J/m^2.s^{1/2}.K$	Thermal diffusivity $m^2/s *10^{-7}$
Test blocks					
Hemp-clay (lightest: 15)	318	517000	0.10	225	1.90
Hemp-clay (no-lime: 8)	416	720000	0.12	720	1.7
Hemp-clay (heaviest: 2)	734	1390000	0.22	553	1.58
LHoist					
Hemp-lime (roof)	220	308000	0.08	157	2.60
Hemp-lime (walls)	330	462000	0.09	204	1.95
Hemp-lime (floor)	375	525000	0.11	240	2.10
Hemp-lime (plaster)	825	1155000	0.13	387	1.13

Figure 39: Comparison of the thermal properties of hemp-clay and hemp-lime.

As with thermal conductivity, for thermal diffusivity and effusivity lower values are better.

The conductivity, heat capacity and effusivity figures were higher on average for hemp-clay than for hemp-lime, while diffusivity was lower[70].

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[70] Thermal diffusivity = λ/c_v, and thermal effusivity = $\sqrt{(\lambda c_v)}$, where c_v is volumetric heat capacity and λ is thermal conductivity
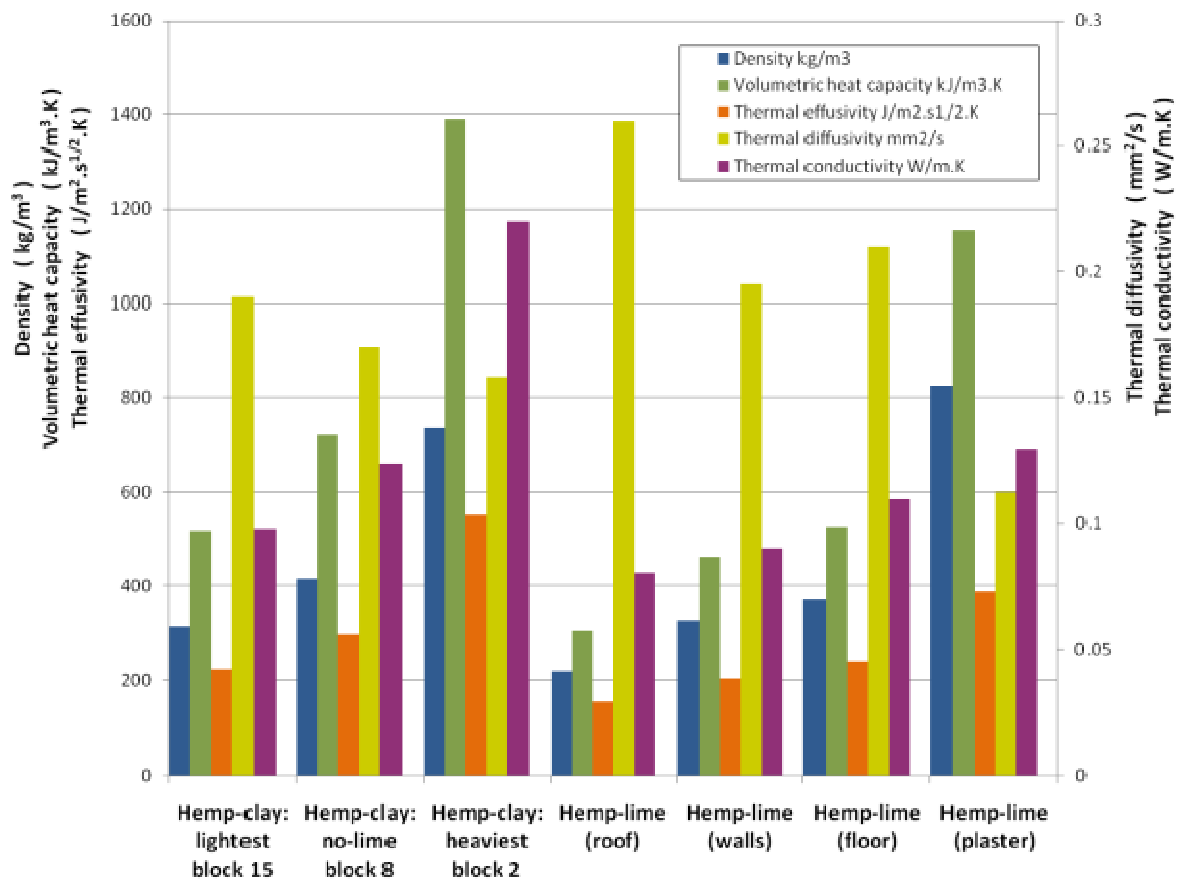
Figure 40: Graphic comparison of the thermal properties of hemp-clay and hemp-lime

5.2.2 Thermal Diffusivity and Thermal Effusivity

U-values describe the amount of heat energy transferred through a building element when it is in a steady state, but this situation rarely if ever arises in reality. Thermal diffusivity (the rate at which a change in temperature on one side of the material is propagated through it) and thermal effusivity[71] (the rate at which a substance will exchange heat energy with its surroundings) are more meaningful measures of actual performance.

If walls have a low thermal diffusivity then the temperature difference may not have been transmitted to the other side of the wall before the temperature gradient reverses. Walls with a low thermal effusivity will be warm to touch, and contribute to feelings of thermal comfort (see 5.2.4).

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[71] See glossary for fuller definitions

The results above suggest that hemp-clay is likely to perform in a similar way to hemp-lime, as explained in section 2.4.6.

5.2.3   The effect of moisture in porous building materials

Moisture in building materials plays an important role in their thermal performance. There are several properties relating to storage and transport of moisture in building materials [May, 2005, 1]

- vapour permeability - the ability to allow water vapour to diffuse through
- hygroscopicity - the capacity to absorb and desorb water vapour in response to changes in relative humidity (RH)
- capillarity - the absorption/desorption of liquid water

All three properties are connected to the porosity of the material; vapour permeability and hygroscopicity with micro pores and capillarity with larger pores.

Some materials can absorb more water than others before they are damp (see Table 5). Therefore, a more useful measure than moisture content is the equilibrium moisture content[72] (EMC) of a material. Any material that is in contact with another, including air, will exchange moisture with it until the two materials are in moisture equilibrium. The amount of moisture exchanged will depend on the hygroscopic and capillary properties of the two materials.

Material	Moisture content %	Interpretation
Wood	4	Extremely dry
Some mortar	4	Dry
Other mortar	4	Damp
Some bricks	4	Damp
Other bricks	4	Wet
Plaster	4	Very wet
Wood	12	Air-dry
Brick	12	Saturated
Plaster	12	Not possible

Table 5: Moisture in various building materials [Oxley & Gobert, 2006, 89]

At 65% RH timber would be expected to contain 12% moisture. Plaster and brick in moisture equilibrium with this timber, if measured with a moisture meter, would have a

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[72] The EMC is defined as the amount of water contained in the material when it is in moisture equilibrium with air at a specified temperature and relative humidity.

moisture content of 12%WME. However, the *actual* moisture content of the plaster would be about 0.5% and the brick about 1% [Oxley & Gobert, 2006, 88]. If the RH increased to 92% for an extended period, eg through penetrating damp, then the materials would reach equilibrium at 22% for the timber, 2-5% for the brick and 1-3% for the plaster [ibid].

Hygroscopic materials have a higher equilibrium moisture content and can therefore store more water before they become damp. Denser hygroscopic materials can hold more water than less dense ones. Furthermore, some materials absorb water more quickly than others. Table 6 compares the moisture handling properties of lime, clay, hemp and timber [May, 2005, 10-13]. Interestingly, lime is not very hygroscopic. Figures for hemp hurds were not available but are probably similar to end-grain timber since their structure and composition is similar [Evrard, De Herde & Minet, 2006, 70].

Material	Hygroscopicity (% increase in mass[73]) (Speed of response)	Hygroscopic capacity (Kg/m^3)	Vapour Permeability[74] (GN.s/kg.m)	Capillarity (kg/m^{2}h$^{\frac{1}{2}}$)
Lime	1.75% Slow	28	75	1
Clay	3% Very fast	52	40	2
Hemp fibre	9% Fast	2.25	5	1-2
Timber[75] (transverse)	9% Slow	54	200	0.2
Timber (end grain)	9% Fast	54	200	1.2
Hemp hurds	N/A (probably same as end-grain timber)	N/A (probably similar to end grain timber)	N/A (similar to end grain timber?)	N/A (probably similar to end-grain timber)

Table 6: Moisture handling properties of lime, clay, hemp hurds and timber (adapted from May [2005, 10&13])

What all this means for buildings is that if hygroscopic, capillary open, and vapour permeable materials are used then they will naturally regulate relative humidity changes due to temperature fluctuations and the activities of the occupants (showers, kettles,

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[73] Increase in mass due to absorbed water, when relative humidity is increased from 50% to 85% (at 20°C)

[74] Units for vapour permeability, measured as resistance to moisture movement, are 'giga Newton seconds per kilogram metre' (GN.s/kg.m) [May, 2005, 3]

[75] Depending on orientation: absorption through the end grain is fast, but transverse absorption is slow

breathing!) Unfired clay and hemp are not only highly hygroscopic but also have a very fast response to changes in RH, which makes them ideal for moisture buffering.

Padfield [1998] found that for regulating humidity, clay and wood were the most successful of a selection of tested materials[76]. However, clay can in fact be very *impermeable* to water (hence its use for lining ponds and landfill sites) so the structure of the clay must be opened up[77] [Padfield, 1998, 72]. Likewise for timber, the end-grain must be exposed. Both these observations indicate that hemp-clay will have excellent humidity buffering properties. Interestingly, the least successful material tested by Padfield was lime-plaster.

Although thermal conductivity increases with moisture content indicating a lower insulative value, this again ignores the behavior of hygroscopic materials and fact that the building is never in a steady state. Additionally, latent heat effects, from water changing state as it is absorbed and released, compensate for the increase in conductivity [May, 2005, 20].

In modern buildings, lack of understanding of how moisture behaves, as well as poor execution and detailing, often lead to moisture problems. An estimated 75% of building failures are attributed to water in one form or another [May, 2005,16].

May [ibid] shows how external cladding with hygroscopic, vapour permeable materials (such as wood-fibre insulation) can improve thermal performance and reduce internal and interstitial condensation. Capillary open materials absorb and disperse condensation allowing surfaces to dry out. The high capillarity of clay may mean that it dries out the hemp more quickly than lime.

In contrast, the use of non-hygroscopic and vapour resistant cavity-wall insulation frequently leads to cold-bridging and condensation with a reduction in building performance. Conventional timber-frame practice can similarly result in an accumulation of water in the building fabric, leading to moulds and decay.

5.2.4 Thermal comfort.

Three modes of heat transfer affect the thermal comfort of occupants in a building: heat radiated from surfaces around the room (approximated by the mean radiant temperature),

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[76] The other materials were timber planks, gypsum plaster, cellular concrete, fired and unfired clay bricks and wool.

[77] Padfield's created a composite material made from bentonite (80% montmorillonite clay) and perlite (expanded volcanic glass), which proved to be the best performer of those tested.

heat transferred by convection currents (affected by both air temperature and air velocity), and heat lost through evaporation (the rate of which is affected by the relative humidity).

Assuming there are no draughts, then the temperature of a room as perceived by the occupants, can be derived from the formula

$T_{comfort}$ = ½ T_{wall} + ½ T_{air}

where T_{wall} is the mean radiant temperature of the room surfaces and T_{air} is the air temperature[78]. This highlights the importance of having warm walls.

Mean radiant temperature	Air Temperature	Comfort Temperature
15°C	27°C	21°C
20°C	22°C	21°C

Table 7: The importance of warm walls for thermal comfort

To maintain a comfort temperature of 21°C, external walls with a surface temperature of 20°C allow for a significant reduction in air temperature than walls at 15°C [McMullen, 2002, 67-8]. Furthermore to avoid stuffiness T_{air} should be maintained within a 3°C margin of T_{wall} [ibid]. Materials with a low effusivity are ideal in this situation.   Because the air temperature can be lower, and the walls retain their heat for longer, the heating system and overall energy consumption of the building can be reduced [Evrard, 2003, 95].

To fully utilise the moisture buffering capacities of hemp and clay, airtightness is important to avoid water vapour transport through mass air movement. These natural materials can deliver savings by making mechanical ventilation systems redundant. [Padfield, 1998, 146].

Air-tightness is also critical to energy efficiency, and Gaia [2003, 37] report tests from Finland showing that very-light-earth can be relatively permeable to air; in some cases failing to meet the minimum standard for Finnish buildings. When rendered inside and out, however, the permeability is reduced to virtually nil so airtightness need not be compromised. Different mixes for different purposes will need to be investigated.

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[78] Obviously other factors also affect thermal comfort of occupants, such as their activity level and the clothing they are wearing.

5.3   Mould

Most of the blocks grew mould in some form, as shown in the results. Unless this can be overcome, it will undermine confidence in the method and prevent it from ever being adopted on a wide scale.

5.3.1   What are moulds and how do they grow?

Moulds are a type of fungi. They grow by producing fine filaments (or hyphae) which spread into a network (or mycelium), and they reproduce by developing thousands of microscopic spores (1 - 100 microns in diameter) which can lie dormant for years. There are thousands of species of moulds, usually accompanied by bacteria, and some of them with their products are beneficial (eg penicillin). Moulds can grow in a huge range of conditions; they are everywhere. [CDISH, 2004; USEPA, 2007; KnowMycotoxins, 2008]

In order to grow, moulds need oxygen, warmth, moisture, and a source of food (usually dead or decaying organic matter). The range of conditions that different moulds can tolerate is very wide, but in general, most fungi need at least 1-2% oxygen, temperatures between 15 and 30°C (though some can grow at 0^oC and 45^oC), 13-18% moisture (a relative humidity in excess of 55%), and pH 3-7 (though some grow happily at pH 10) [KnowMycotoxins, 2008; MBCL, 2008; Panasenko, 1967]. They can start growing in damp materials within 24-48 hours.

Lime itself does not appear to prevent mould growth, despite its high pH. Volhard [1995, 48-49] found that in unfavourable drying conditions the addition of lime to light-earth exacerbated the development of mould. In hemp-lime construction also, care should be taken to prevent fungal attack. Hemp-lime should be dried as quickly as possible and brought down to 18% moisture within 6-8 weeks, accelerating drying if necessary with warm moving air [Allin, 2005, 172-3]. Any moisture ingress must be addressed as quickly as possible. Like timber, if the hurds have a moisture content at or above 20% for prolonged periods they will rot. Various fungi have been found growing on hemp-lime walls while they are drying [Rhydwen , personal communication] but they die off as the moisture content falls below that required to support life. Nonetheless, the presence of mould spores, living or dead is unsettling.

5.3.2   Health effects

Moulds in buildings are taken very seriously. Many have been blamed for a range of health problems including the growth in respiratory tract diseases and allergies and even

deleterious effects on the central nervous and immune systems[79]. The apparent increase in these illnesses has been associated with the rise of energy-efficient homes[80], in particular, with airtightness in buildings (achieved essentially by tightly sealing the building in a plastic bag) in combination with poor ventilation and high relative humidity.

It is generally accepted that, for a healthy environment in regard to a range of health considerations, the relative humidity in buildings should ideally be maintained at around 50% (see Figure 41).
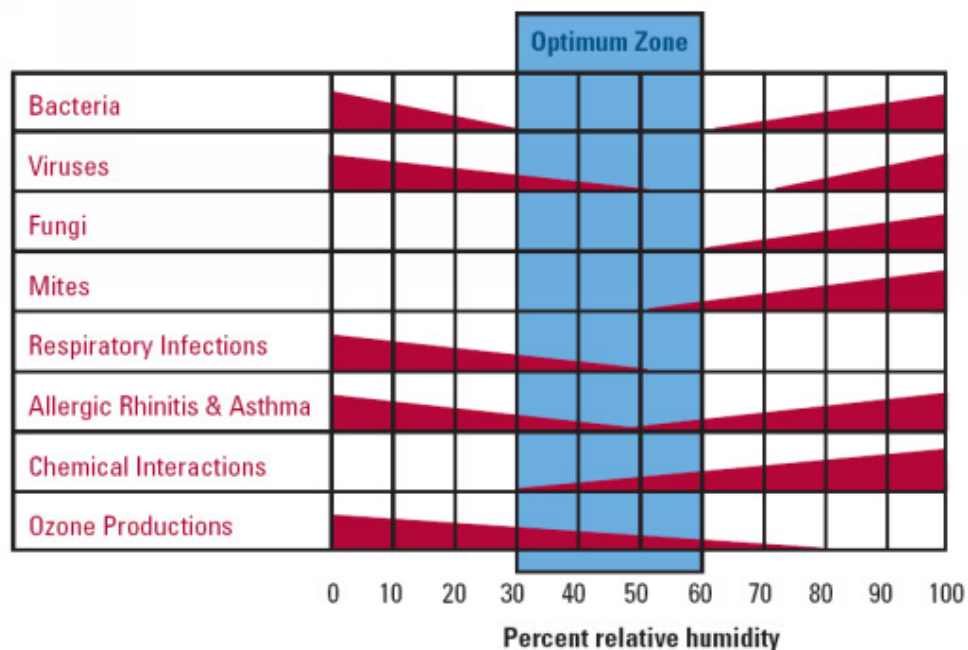
*ASHRAE: American Society of Heating, Refrigeration & Air Conditioning Engineers

Figure 41: Effect of relative humidity on health factors: a decrease in bar height indicates a decrease in effect for each of the items. Optimum RH range shown in blue. [ASHRAE]

The primary approach for dealing with a mould problem is to cure the moisture problem. Dampness is also associated with a range of other problems, such as mites and bacteria. However even when dead, moulds and mould spores can trigger allergic reactions so they

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[79] See Appendix 5.1

[80] http://www.articlesbase.com/environment-articles/toxic-mold-a-growing-concern-544266.html

http://www.moldinspectionandtesting.com/mold_faqs.html

must not only be killed but also removed[81] [USEPA, 2007, 23]. Ideally of course they should never be allowed to grow in the first place.

It is claimed that clay walls help to keep the internal atmosphere of buildings healthy, and this is backed up by research by Padfield [1998] which demonstrates that clay is effective in regulating the internal relative humidity of buildings. In addition, it is interesting that moulds are also a problem in animal farming, entering the system via feed or bedding, and one of the solutions is the addition of powdered clay to the feed [Huwiga et al, 2001]. This adsorbs the moulds so they are excreted without harming the animals. Clays also have widespread industrial and pharmaceutical use as filters, and absorbents

5.3.3 Mould inhibitors

Various genera of moulds have been identified on hemp crops[82] in the field and the spores will remain on the crop when it is dry; these cannot be avoided. Moulds can grow inside porous materials so if they are allowed to grow and multiply while the walls are drying they may subsequently be impossible to remove completely.

Therefore measures should be taken to inhibit their growth until the walls are dry enough to no longer be at risk. To prevent mould when building with light-earth, Baker-Laport & Laport [2005, 21] recommend adding borax, a natural mould inhibitor[83], in the ratio of roughly 100g per 35 litres water.

Volhard [1995] instead suggests the use of deflocculants such as washing soda and waterglass with the consequence that less water is required in the slip (see section 5.4.1 on Additives to clay). Furthermore, building work should be planned so that the walls can dry as quickly as possible

Minke [2006, 84] warns against using a mix that is too light. He reports a 30cm thick very light straw-loam wall 350kg/m^3 that had started rotting internally despite being apparently dry on the outside. Also there is a risk that woodlice may attack the straw at low densities. He recommends that densities should exceed 600kg/m^3 in walls thicker than 25cm. The

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[81] See appendix 5.1

[82] Including Pythium Disease (Pythium debaryanum), Hemp Canker (Sclerotinia sclerotiorum), Grey Mold (Botrytis cinerea), Hemp Rust (Melampsora cannabina) [Innvista,2008].

[83] It is also used to treat natural fibres and wood for fire and insect resistance. It is widely used in our environment and considered safe by the USEPA [2006]

test sample pots using a thicker clay slip showed no mould growth, so the clay itself might be enough to prevent it if the blocks are dense enough.

It appears that drying times are crucial. Minke [2006, 84-5] reports the restoration of a historic building whose 50cm thick walls had taken over a year to dry.   In the process the wooden members of the frame were destroyed by fungus.

Interestingly the initial mini-brick never showed any signs of mould. The slip had a much higher water content, and there was no lime, but it was significantly smaller than the blocks and therefore dried more quickly.

5.4   Clay

Research is needed to determine the type of clay that would be best suited to this purpose. The binding force varies between different clays; montmorillonite clays, due to their smaller particles, have the largest chemically active surface area. The binding mechanism is usually explained in terms of electrostatic forces, however an alternative may be suction. In a recent study [Jaquin et al, 2008 & 2008b] the strength and cohesion of rammed earth walls is attributed to suction in the pore water which gets stronger as the material dries.

It could be that the interlocking hemp particles will mitigate against the effects of the high shrink-swell behaviour of montmorillonite, while the stronger binding force of this clay may make it the most suitable. This remains to be investigated.

In practice, and to minimise the environmental impact of using clay, local supply is likely to be the most appropriate. In order to modify the properties of the local clay various additives may be necessary.

5.4.1   Additives to clay

Adding lime or cement to clay interferes with its binding force [Minke, 2006, 45; Volhard, 1995, 48]. Volhard in fact states that it is inappropriate to add lime to light-earth at all, though it has possible benefits in more dense methods like cob[84] where it can be used to weaken the clay and reduce shrinkage and cracking.

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[84] Volhard [1995,146] makes the distinction between Leichtlehm (Light-earth: densities 300-1200 kg/m^3), Strohlehm (straw-earth or Cob?: densities 1200-1800 kg/m^3) and Massivlehm (Heavy-earth or Rammed Earth?: densities over 1800 kg/m^3)

In the test blocks, the addition of a small amount of lime meant that the hemp could be bound with significantly less clay. However, it was not possible in this thesis to ascertain whether the lime affected their strength, since the stabilised and unstabilised blocks had different densities. This is an area for further investigation.

Deflocculants (such as washing-soda and waterglass[85]) act as electrolytes, causing the clay crystals to repel each other so that they slide over each other more easily.   Their addition to clay slip reduces the requirement for water and thereby accelerates drying and reduces shrinkage [Volhard, 1995, 47; see Appendix 2.2 for more detail].

5.5   Carbon sequestration and Embodied energy.

In 2004 in France 6000 tonnes of hemp hurds (20% of the total produced) were used in construction [Rhydwen , 2004, 43], equivalent to 10,980 tonnes of CO_2. As stated previously, the net balance of carbon emissions against sequestered carbon depends very largely on the choice of binder; and clay has very low embodied carbon. The potential for carbon sequestration using hemp-clay is very high.

There is no international consensus on methodology for calculating embodied energy (EE) or embodied carbon (EC) and therefore figures vary widely for the same material. The contributions to the EE for any given material or item are not universally defined; where do we stop counting the cost? For the sake of consistency a single source was used where possible: the ICE database from Bath University [2008].

5.5.1   EE of hemp-clay, hemp-lime and other composite materials

The proportion of cement in the Tradical®HB binder has been quoted as 15-20% [Ian Pritchett, Limetec meeting 2006, from Rhydwen in personal communication]. But though this increases the EC of the binder, depending on the source of the lime it could in fact reduce its EE. It is instructive to compare the EE and EC of various forms of mineral and organic 'concrete'.

A cubic meter of spray-applied wall-grade Hemcrete contains 110kg of hemp and 220kg of binder. Light earth would use a similar volume of hemp. In concrete, cement only makes up 7-15% of the total weight [PCA, 2008]. The ICE database [2008] gives the following figures for EE and EC (Table 8). No figures were available for unfired clay so the figure for

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[85] These are widely used in the ceramics industry for thinning clay slurries and permitting a reduction in water content, thereby reducing shrinkage. Washing-soda = Na_2CO_3 and waterglass = Na_2SiO_3

aggregate was used[86]. Hemp figures are from previous calculations in this thesis (sections 2.2.4 & 2.2.5).

	embodied energy (EE), MJ/kg	Embodied carbon (EC), kgCO$_2$/kg
OPC	4.6	0.83
Lime	5.3	0.74
Aggregate	0.1	0.005
Hemp hurds	0.0014	-1.8
Clay	0.1	0.005

Table 8: Embodied energy & carbon of various 'concrete' binders and aggregates/fibres

Using these figures to compare the EE and EC of 1 cubic meter of various hypothetical composite materials we get the following:

	Binder EE MJ/m^3	Aggregate / Hemp EE MJ/m^3	TOTAL EE MJ/m^3	Binder EC kgCO$_2$/m^3	Aggregate/ Hemp EC kgCO$_2$/m^3	TOTAL EC kgCO$_2$/m^3
Hemp-Lime with 15% OPC in binder: density 330kg/m^3	1142 (151+991)	0.15	**1142**	165 (27+138)	-198	**-33**
Hemp-Lime without OPC: density 330kg/m^3	1166	0.15	**1166**	163	-198	**-35**
Concrete 15% OPC, 85% aggregate: density 2200kg/m^3	1518	33	**1551**	274	9	**283**
Concrete 7% OPC, 93% aggregate: density 2200kg/m^3	708	15	**724**	128	10	**138**
Lightweight concrete 15% OPC, 85% aggregate: density 600kg/m^3	414	9	**423** [87]	75	3	**77**
Hemp-Clay: 110kg hemp, 490kg clay density 600kg/m^3	49	0.3	**49**	2.45	-198	**-196**

Table 9: Comparison of the embodied energy & carbon of concrete, hemp-lime and hemp-clay

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[86] EE figures are quoted per kg. According to SiMetric [2008], wet excavated clay has a density of 1800 kg/m^3 and gravel around 2000 kg/m3; the density given for aggregate in the ICE [2008] database is 2240 kg/m3. This difference was considered insignificant here.

[87] This calculation ignores the energy used to aerate the concrete. Autoclaved aerated concrete blocks have up to 5 times more embodied energy *per kilogram* than standard concrete blocks [ICE, 2008].

While the exact figures are debatable, this table clearly demonstrates the low environmental impact of hemp-clay when compared to all others. Also, it highlights the fact that the eco-credentials of hemp-lime are entirely derived from the hemp. In fact, concrete has comparable embodied energy to hemp-lime.

5.5.2 Embodied energy of additives to clay

The embodied energy of Borax could not be found but it is a naturally-occurring mineral salt and it is used in very small quantities[88] so is unlikely to be a large contribution to the total. Washing soda and waterglass likewise are used in such small quantities[89] that their contribution to the whole will be minimal.

5.6   Overall Environmental Impact

Several criteria for assessing environmental impact were listed in section 1.3 [Harris, 1998, 159]. The first, embodied energy, has been dealt with above. The others were as follows.

5.6.1 Raw materials consumption: how much raw material is consumed

For its strength, and compared with other construction materials, timber has very low embodied energy [Der-Petrossian, 2000,11]. Measures should be taken to avoid deforestation, but it should be possible to use smaller dimension timber from sustainable sources for the framework in the hemp-*binder* method, and possibly roundpole timber (as indicated in Figure 14).

Any kind of quarrying has an unwanted environmental impact in terms of noise, dust, loss of plants, destruction of wildlife habitat and disruption of natural amenity. Topsoil is unsuitable for building purposes and efforts should be made to minimise the disturbance to this life-zone. With care, it could be feasible to excavate clay from the sub-soil on local farmland, and then return the top-soil to production: for growing hemp perhaps!

Globally, buildings consume 16% of the world's fresh water [Der-Petrossian, 2000,4]. The virtual (embodied) water in buildings is very high, up to 20100 litres per square metre of floor area [McCormack et al, 2007]. This is largely determined by the elements and materials selected for their construction, steel and concrete being the main offenders[90].

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[88] 100g per 35 litres water

[89] <4g per kilo of plastic clay

[90] Steel has a relatively high water intensity, and cement (though it has a comparatively low water intensity) is used in large volumes.

By eliminating the need for highly processed materials hemp-clay can also reduce our water consumption.

5.6.2 Scarcity factor

Clay is one of the most abundant materials in the ground. Hemp could be very widely grown with beneficial effects on the environment. Buildings are probably a more advantageous use for the hurds than animal bedding.

5.6.3 Recycling potential

It is claimed that at the end of their useful life the hemp-lime buildings require less energy to demolish than conventionally built houses and that the materials are recyclable or biodegradable [SHS, 2007, 11; LimeTechnology, 2007, 13; BRE, 2002, 21]. This second point is questionable if the binder includes a high proportion of cement.

 Elements of the timber frame could be reused though this would depend on whether cement was used in the mix and how the frame was constructed. As for the hemp-lime infill, the lime has either undergone a chemical reaction or has carbonated or both; neither of these processes are reversible. Unless hemp-lime is used to make blocks which could be reused then it cannot really be considered recyclable. It cannot simply be reused in a new wall. The hemp-lime mix can, however, be crushed, mixed with more binder and reused. This process would however result in down-cycling (the quality of the material deteriorates over time [McDonough, 2002, 56]) rather than re-cycling.

The hemp-lime could be left to break down naturally in the ground but the lime will slow the process down; an un-rendered section of hemp-lime wall left exposed to the rain and weather in Ireland showed very little deterioration after two years [Woolley, 2006,135].

In comparison, provided it has not been stabilised with lime or cement, earth is supremely recyclable. Hemp-earth could be re-moistened and reused, either for renovation or in another building. Otherwise, if demolished, the earth in the walls would return to its original state in the ground and the hemp would biodegrade.

5.6.4 Effects on occupants of building or handlers

As discussed in section 5.3.2 breathable walls can improve indoor air quality, and the use of natural materials virtually eliminates any toxic hazards. If lime or borax are to be included, then there may be a requirement for builders to wear protective clothing, otherwise the material is benign.

5.6.5   Potential for using recycled materials.

The use of recycled components such as windows and doors, provided they can be attached to the frame should be quite possible as the hemp-clay can be used to fill up to and around them, sealing any gaps. The frame is hidden so, provided they can be made structurally sound, it should be possible to use second-hand timbers.

5.6.6   Influence on energy consumption.

As discussed (section 5.2), hygroscopic materials contribute to thermal comfort thereby permitting smaller heating systems. The walls will absorb and store heat and moisture, buffering against temperature and humidity fluctuations. Mechanical ventilation systems can be eliminated.

Compared with conventional buildings and with hemp-lime, because it requires hardly any non-renewable resources, the environmental impact of hemp-clay is very low.

5.7   Other comments on the hemp-clay construction method.

There seems no reason why light earth should not be commercially produced. Certainly pre-prepared light earth mix and blocks are available in Germany. Light-earth blocks and possibly panels could be easily manufactured in a factory, though transportation would increase their embodied energy. Prefabricated modules that guarantee consistency and reproducability would be more likely to be adopted by the mainstream construction industry if they can be proven to be effective and reliable.

Hemp-clay seems to have some advantages over hemp-lime. Any hydraulic binder has to be used very quickly. From the Haverhill report, "The short 'shelf life' of the mix and the need for cumbersome protective clothing took some getting used to" [BRE, 2002, 4]. Hemp-clay is completely safe to handle and can be left and remoistened later.

Also, according to Evrard [2003] "prolonged contact between hemp and non-hardened lime is to be avoided; hemp is highly sensitive to alkaline substances. After hardening, the lime becomes less alkaline". If the walls do not fully carbonate this could be a serious issue. Again, clay avoids the problem.

Hemp-clay (and hemp-lime) walls may take a long time to dry out completely, but it is estimated that construction water in conventional buildings can also take as long as 3 years to dry off.

Hemp-clay would, like hemp-lime, be so flexible that it eliminates need for expansion joints. However, shrinkage is an issue which may affect both methods. Inspections of the

Haverhill houses six months after completion revealed internal and external cracking due to settlement and drying, but these were only in the render and were straightforward to remedy [BRE, 2002 ,37]. Minke reports that a one metre high test wall of light-earth (using straw) showed a settling of 9% when it dried so walls need to be inspected and refilled where necessary [2006, 83]. In the test blocks, no cracking was observed and shrinkage was only around 2.5%. The structure and durability of the hemp homes at Haverhill were at least equal to their conventionally built counterparts [BRE, 2002].

There is a risk (to both methods) that occupants may apply impermeable surface treatments which would impair the performance of the building; education may be required about the building materials and their function. Nonetheless the risks are lower than for conventional building where such things as impermeable membranes can be damaged during the building process, or through DIY efforts, or simply through deterioration with age [May, 2005, 33].

5.7.1   Hemp or straw

At the moment the UK grows only enough hemp for a limited number of buildings; the UK cultivated only 3000ha in 2005 [Rhydwen , 2007, 2]. For hemp-clay (or lime) to be adopted on a wide scale, UK production will have to increase or hemp will have to be imported.

Hemp is likely to be a better insulator than straw due to its woody core, but in the short term straw might be a better bet for the UK since we have an abundance of it already and it is cheaper. Straw for use with light-earth can be bought in large round bales that are not suitable for strawbale building, and are more available and probably cheaper. Also since the straw will be coated in slip it is not so essential that the bales are kept absolutely dry which is one of the major limitations of strawbale building in the UK.

Hemp-lime has the advantage that it can be blown into or onto walls. This may be possible also with hemp-clay though it has not been tried. However light-earth using woodchips is sometimes pumped into formwork, and the short hurds should also lend themselves to this process.

5.7.2   Possibilities for renovation of existing buildings

There would seem to be great potential for cladding existing buildings with light-earth. Depending on the existing structure of the building this could be internal or external [May, 2005], though obviously thought will have to be given to detailing. Literature from the German umbrella organisation for earth building, Dachverband Lehm, indicates that this is already being done (see Figure 42).

Existing wall,
light clay (loose fill),
supporting construction,
reed matting

Light earth wall linings
LR 4.3.4
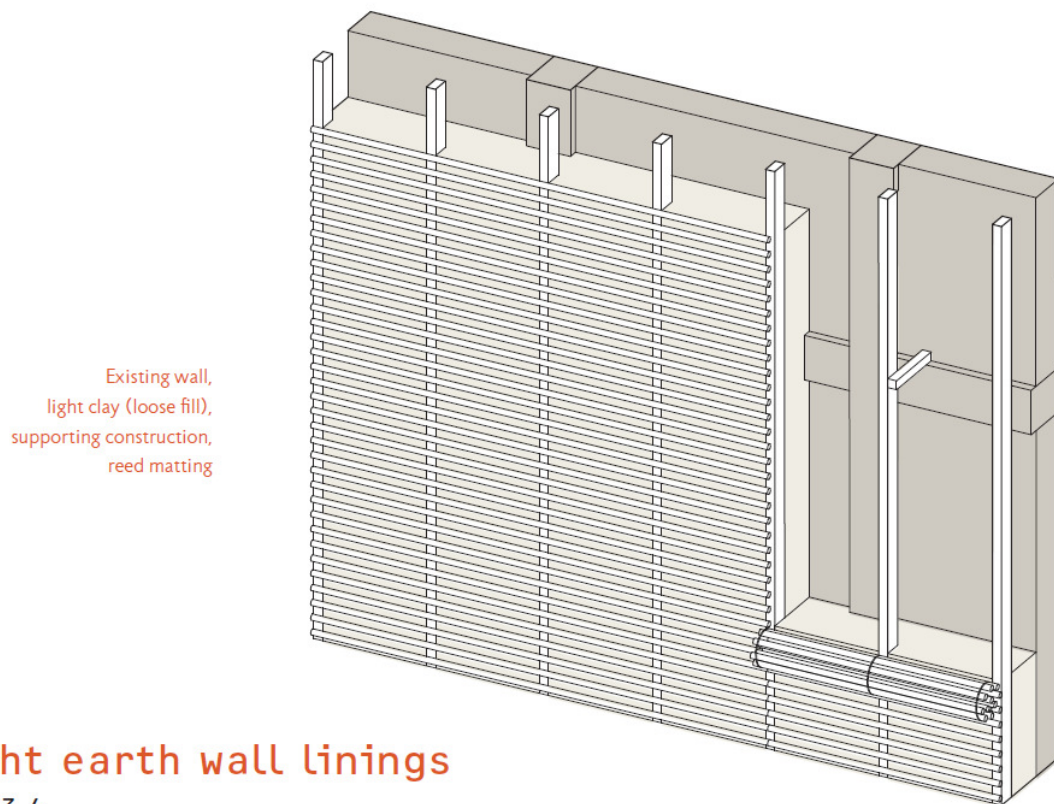
Figure 42: light-earth wall linings from Dachverband Lehm brochure [2004]

5.7.3   Passive Design

 Improvements in the energy performance of buildings through the design are vital. Hemp-clay should be able to provide a well insulated and airtight building fabric. However, buildings should also be oriented and designed for maximum daylight, passive solar gain in the winter and shade in summer. Energy efficient windows and natural passive ventilation (eg windcatchers, stack ventilation) should also be used where possible. These should be the first priorities in building, before adding technologies such as solar water heating etc [AECB, 2009; PassivHausUK, 2009].

5.7.4   Developing countries.

Concrete is symbolic of western wealth and affluence; developing countries aspire to emulate the modern, western style of building, and people there dream of escaping from their mud/straw houses into 'better' and 'proper' concrete houses.   Earth has a very low status. Our attachment to cement and other high energy materials reinforces these ideas.

Much of our addiction to lime-based binders could be substituted with alternatives such as timber, earth and straw which could eliminate the use of fired binders altogether. Rather

than expecting those less well off than ourselves to sacrifice the 'benefits' of living in modern houses, we should learn from, and develop, the methods and materials of the developing world vernacular. If they were widely adopted in the developed world then their image would change from eco-fringe to practical, environmentally sensible and responsible, comfortable and desirable.

5.7.5 Community and skills

If hemp-clay were adopted and materials made widely available through a network of local hemp producers and processing plants, local economies would develop, supporting farming and strengthening links between rural and town communities.

For some reason, the UK has a very low percentage of owner builders; it is far more common in other European countries, Canada, the USA and Australia. The low material costs of hemp-clay facilitate affordable housing.   Apart from the timber frame, it requires low skilled labour, creating opportunity for community groups and owner builders to involve their families and friends. The education, understanding and knowledge that would be derived are likely to lead to a heightened sense of ownership and responsibility, and local community networks would be strengthened.

In their guidelines for a sustainable society, Meadows et al in 'Beyond the Limits' [2004, 22] exhort us to act as quickly as possible to 'Minimise the use of non-renewable resources' and 'Use all resources with maximum efficiency'. With hemp-clay we could do this, and make significant moves in the transition to a low carbon economy.

6 Conclusion

Mainstream methods of improving building performance rely on excluding moisture from the building fabric. They use complicated, actively controlled, high tech and expensive systems and materials with high embodied energy and carbon. In comparison, monolithic hemp-*binder* walls simplify the building process and create a warm, breathable building fabric due to their porous and hygroscopic nature. Hygroscopic, capillary open, vapour permeable materials will buffer moisture and maintain humidity within healthy levels, and reduce the requirements for mechanical/powered heating and ventilation services.

Hemp has many environmental benefits and is a renewable resource. Hemp-lime is an innovative construction material and method, with excellent eco-credentials compared with conventional construction, and hemp-lime may result in the net sequestration of carbon. However, although limestone is one of the most abundant and widely distributed minerals on the planet [Gartner, 2004, 1494], it is nonetheless part of the fossil reserves. The carbon locked up in it was laid down from the remains of living creatures over geological time. In the process of calcination of limestone we are releasing carbon from the fossil reserve in much the same way as when we burn fossil fuels like coal or oil.

Clay is widespread, cheap and requires minimal processing. With unfired clay as a binder, monolithic hemp walls are convincingly carbon-negative. Earth is a variable and (in the West) poorly understood building material, unfamiliar to the construction industry except as a waste product to be dumped. But it is used successfully in Germany for light-earth construction, a method with many similarities to hemp-lime, in a climate similar to the UK.

This thesis investigated and compared the properties of clay and lime in relation to their role as a binder in monolithic hemp walls.   Their thermal properties appear to be similar. The thermal conductivity of hemp-clay correlates closely with density and appears to be slightly higher than for hemp-lime, but if tested in a hot box might prove to be similar. Its thermal capacity and therefore its thermal effusivity may also be slightly higher. Materials with low thermal diffusivity help to dampen cyclic variations in temperature and for hemp-clay thermal diffusivity seems to be slightly lower.

The results of the experimental research and literature review are summarised in Table 10.

Benefit / Property	Lime-binder	Clay-binder	Winner?
Thermal conductivity	Slightly lower?	Slightly higher?	Lime?
Thermal capacity	Slightly lower?	Slightly higher?	Clay?
Thermal effusivity	Slightly lower?	Slightly higher	Lime?
Thermal diffusivity	Slightly higher?	Slightly lower?	Clay?

Benefit / Property	Lime-binder	Clay-binder	Winner?
Hygroscopic	Not really	Highly	Clay
Capillary open	Good	Better	Clay
Vapour permeable	Yes	Yes	Neither
Humidity buffering capacity	Questionable	Excellent	Clay
Embodied energy	High	Low	Clay
Associated CO_2 emissions	High	Low	Clay
Carbon sequestration	Neutral to good	Very good	Clay
Cohesive/Binding force	Good	Good	?
Compressive strength of composite material	Poor	Possibly less good?	Lime?
Preservative – of timber and hemp	Yes (probably [91])	Yes	Neither?
Stability	Good	Less good	Lime
Recyclability	Questionable	Good	Clay
Reusability	Doubtful unless in block/panel form	Good	Clay?
Commercial potential	Good	Possibly less good?	Lime?
Use as infill	Yes	Yes	Neither
Use as blocks	Yes	Yes	Neither
Use for spray application	Yes	Probably	Neither?
Locally available	Yes – probably	Yes – probably	Neither?
toxicity/handling risk	Caustic in construction	Good	Clay

Table 10: Summary of comparison of lime and clay binders in the hemp-binder method

In most ways clay equals or outperforms lime. Its main weakness is the fact that unstabilised earth (and clay) requires protection from rain. A wide overhang may be sufficient, but limewash or lime render could be added for extra protection, and weatherboarding may be recommended in exposed situations.

Perhaps because it is a 'low value' material, no one in the UK has yet developed a commercial product.   In Germany, however, it is possible to buy bags of dry clay and woodchip, ready for use in light-earth.

Hemp-clay provides breathable walls using simple, low tech, cheap materials with low embodied energy and carbon, and clay significantly increases the potential for monolithic hemp walls to sequester carbon. Hemp-lime has positive attributes, but the lime might be better used to stabilise clay-poor earth, or to render thicker, more insulating materials such

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[91] See comments from Evrard re uncarbonated lime in 5.7. This is also questioned by Volhard.

as strawbale. Hemp-clay is more commensurate than strawbale with conventional building methods, and it is possibly more suitable for the UK climate; the timber frame and roof can be built first, reducing the susceptibility to rain.

Experimental buildings are required to prove the concept in the UK. It is likely to be adopted by self-build projects before, if ever, being adopted in mainstream construction. It is very suitable for owner builders: the skilled timber frame work is not dissimilar to conventional building and can be contracted out, with the infilling completed by the owner builder. Post-occupancy monitoring will be necessary to demonstrate the performance of the buildings and establish the credibility of the method.

Zero pollution, zero embodied energy and maximum carbon sequestration: these are perhaps unattainable goals but they should be the principles that guide us. Our aim must be to minimise the embodied energy of buildings, and to maximise the carbon removed from the atmosphere, without compromising the requirements for airtightness and insulation. Alternative environmentally responsible materials could help meet the British government's pledge to reduce carbon dioxide emissions by 80% by 2050 [DEFRA, 2008b]. The potential of hemp-lime is restricted by its reliance on large volumes of energy-intense lime. Hemp-clay shows greater potential; numerous questions remain, but further investigation should prove fruitful.

6.1   Limitations of study

Due to time shortages, no hemp-lime blocks were made.   It would have been a valuable exercise to compare direct experimental results for both materials with published results for hemp lime.

Weighing and measuring were conducted using domestic tools which had limited precision. The blocks were not produced concurrently and were dried in different locations and weather conditions. Although additional vents were cut into the plastic coverings of the mini-greenhouses, humidity levels were quite high, certainly higher than they would have been if the blocks were in the open air but under cover.

The difference between the two sets of experimental data taken one month apart (see section 4.5) could possibly be attributed to subjective inter-experimenter differences. Ideally cross-checking should be conducted on the same day and in the same place (as the blocks respond to climatic changes).

The embodied energy & carbon of renders were not taken into account, and there was insufficient data for rigorous statistical testing of the results. There is a lack of availability

of consistent hard statistics about building materials, particularly new and innovative ones, so any figures and calculations are accordingly questionable.

Further measurements on the test blocks after a longer drying period would have been instructive; the blocks are available for further testing.

Lack of fluency in German hindered the literature review.

6.2   Recommendations for further research

The performance of hemp-clay and hemp-lime can be predicted from the capillarity, hygroscopicity and vapour permeability of their components, but empirical research similar to that done by Evrard and DeHerde on hemp-lime should be conducted to compare the two composite materials. Computer simulation of the behaviour of both materials using software such as WUFI (which models transient hygrothermal behaviour) should be helpful. Physical strength properties (compressive and tensile strength, and shear resistance) also need to be fully investigated, as does its weather resistance and durability. Given that both hemp-lime and hemp-clay would probably have an external render there is reason to suppose that hemp-clay would be equally durable.

Efforts should be made to determine the optimum mix and density for different purposes. The best mix to minimise shrinkage is likely also to minimise mould. The roles of pH and nutrient content in mould growth should be investigated, as well as additives that are effective in preventing it. It would also be beneficial to determine whether the retting process itself contributes to excessive growth of mould.

Quicklime reduces the quantity of clay required to bind the hemp, but whether or not this is advantageous remains to be tested. It may be that using more clay is enough to prevent mould growth as well as giving sufficient compressive strength. It would be worth investigating the effect of lime on compressive strength.

Answers should be sought to the following questions. Is there any benefit to be derived from the addition of lime to clay-rich earth? Does lime make the hemp-clay significantly more resistant to weathering? What process is occurring in the stabilisation of clay soils with lime, and how does this translate to clay slip? How much lime can be added before the clay is saturated with lime? If lime is added beyond saturation point is there any benefit? Does the lime weaken the mixture in any way?

Is any benefit to be derived from compression of the mixture (tamping)? Can there be too much clay in the slip and what is the optimum percentage? Can clay slip be advantageously

blended with other things (eg paper-pulp, cellulose or starch paste, dung, urine, ash)?
Further research is needed to establish what difference the type of clay makes and which
types are most suitable.

It would be useful to know whether there are any advantages provided by straw over
hemp; straw may provide stronger fixing points into the walls for shelves, cupboards and
services. Consideration should also be given to the location of the timber frame, to
facilitate fixing. Additionally, what other aggregates or fibres might be effective, either
singly or in combination? Cork granules, paper pulp, wood pellets, expanded clay or
foamed glass beads may offer possibilities for some applications.

The use of roundpole timber (which requires little processing), and possibly bamboo (which
grows very quickly and is extremely strong), should be investigated for the framing. There
seems no reason why these materials should not be compatible with the method.

Support should be given to facilitate the construction of some experimental buildings
where rigorous post-occupancy monitoring can be conducted. A reusable shuttering
system needs to be designed that is quick and easy to fit and remove.

The impermeability of national and language boundaries is lamentable, and although the
internet is facilitating the dissemination of information around the world, very little of the
knowledge and experience gained in light-earth has filtered through to the UK because
most of the literature is in German. For a start, Franz Volhard's book "Leichtlehmbau: alter
Baustoff – neue Technik" should be translated into English!

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Pictures of earth buildings in figure 10 were taken from the following websites: (1) Devon, UK
http://www.cobcottage.com/node/115, (2) Shibam, Yemen http://archnet.org/library/images/one-
image.jsp?place_id=2716&image_id=75797, (3) Djenné, Mali
http://www.treehugger.com/files/2007/11/the_future_is_mud.php

Picture of Swallows on title page from http://www.unm.edu/~vscience/images/Barn-Swallow-Nest-(14).jpg

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Appendix Contents

1   Appendices to the introduction

1.1   Embodied energy, embodied carbon and carbon sequestration.

Embodied energy and embodied carbon (see glossary for definitions) correlate closely but cannot be directly converted. The carbon emissions associated with a unit of energy obviously depend on how it is generated. CSIRO [2008] estimate that, on average, 1 gigajoule of embodied energy represents 0.098 tonnes of CO_2. At the end of the day, even renewable energy production is associated with an amount of embodied carbon so cannot be considered completely benign. For the purposes of this study the term *embodied carbon* will be avoided as far as possible as the terminology can be confusing. It is sometimes quoted in units of tonnes of carbon and sometimes in tonnes of CO_2; it is also referred to as *embedded carbon* which muddies the water, especially when there is also the term sequestered carbon. Sequestered carbon is almost the reverse of embodied carbon, it is the carbon *removed* from the atmosphere.   Where possible, the term embodied energy will be used as a measure of the negative environmental impact of a given material, and carbon sequestration as a measure of environmental benefit.

2   Appendices to the Literature Review

2.1   Clay types

Clays are fundamentally built of sheets of tetrahedral molecules of silica layered with sheets of octahedral molecules of alumina. They are commonly referred to as 1:1 or 2:1 clays. Kaolinite is a 1:1 clay having one tetrahedral sheet and one octahedral sheet. Illite and montmorillonite are 2:1 clays, consisting of an octahedral sheet sandwiched between two tetrahedral sheets. [Houben & Guilland, 1994, 27]

Kaolinite ($Al_2Si_2O_5(OH)_4$) or $Al_2O_3 \cdot 2(SiO_2) \cdot 2(H_2O)$ (chemical water), aka china clay, has low shrink-swell capacity and a low cation exchange capacity.

Montmorillonite - $(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$. is the main constituent of the volcanic ash weathering product, bentonite.   It swells with the addition of water, some montmorillonites expand considerably more than other clays due to their structure and affinity for water penetrating the interlayer molecular spaces and concomitant adsorption. It has high bending and compressive strength.

Illite $(K, H)Al_2(Si, Al)_4O_{10}(OH)_2 \cdot nH_2O$ is a non-expanding, clay. The CEC of illite is smaller than that of montmorillionite but higher than that of kaolinite.

2.2   The effect of deflocculants on clay slip

In preference to lime, Volhard [1995, 47] suggests the addition of deflocculants[1] such as washing-soda (Na_2CO_3) and waterglass (Na_2SiO_3) to clay slip. These act as electrolytes causing the clay crystals to repel each other so that they slide over each other more easily.   Their use reduces the requirement for water and thereby accelerates drying and reduces shrinkage.

Figure 1 [ibid] shows the test results of two samples of clay slip with the same viscosity, but the one on the right included soda and therefore contained less water. The top pictures show paper strips immediately after being immersed in the slip, the middle row show the same strips 10 minutes later, and the bottom pictures show cylindrical samples after they have dried. On the paper strip on the left, the slip flowed together into drops on the edge whereas the one on the right was more uniformly and thickly covered. When dry, the slip with soda showed significantly less shrinkage. They should be used in the proportion 0.1-0.4% by weight of dry clay, or perhaps up to 2% by weight of dry earth. This equates to less than 4 grams per kg of plastic clay.

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[1] These are widely used in the ceramics industry for thinning clay slurries and permitting a reduction in water content, thereby reducing shrinkage.
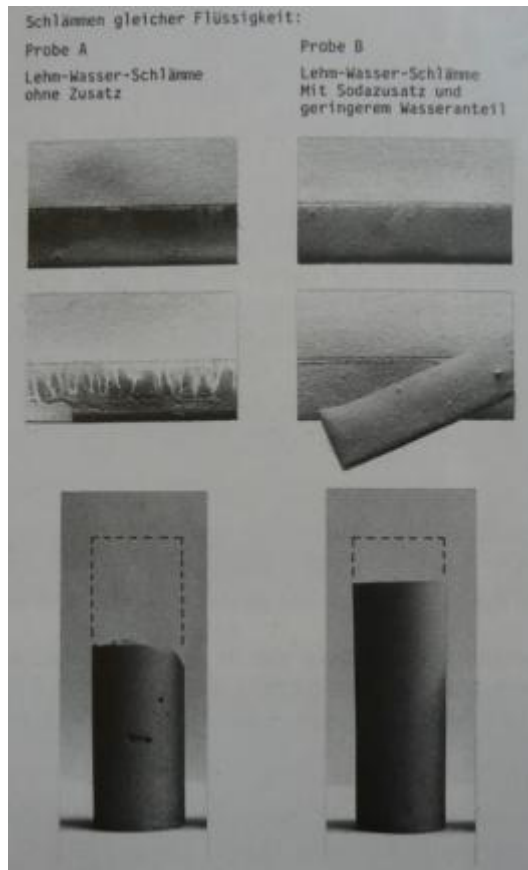
Figure 1: The effect of deflocculant on coverage and shrinkage [Volhard, 1995,46]

2.3   Embodied energy of construction materials

The embodied energy in the construction of buildings comes largely from the manufacturing processes of materials rather than the construction activities and transport; for medium and high EE materials such as steel and concrete, it is about 70%. Table 1 compares the energy required to produce a kilogram of various building materials, and shows that earth/soil requires less than 10% of the energy required for lime. [Der-Petrossian, 2000,7-8].

Material	Primary energy requirement (MJ/kg)
Cement	4-8
Lime	3-10
Concrete-in-situ	0.6-2
Concrete, blocks and tiles	0.9-1.6
Sand-lime bricks	0.7-1.2
Lime/cement mortar	0.5-1
Cement-stabilized earth blocks	0.3-0.8
Natural stone, sand, aggregate, soil	≤0.3

Table 1: Comparative energy requirements of building materials

3   Appendices to the methodology

3.1   Measuring clay content

One of the field tests for clay content is to shake up a sample of earth ($^1/_3$ of a jar) in water and see how long the particles take to sediment out. The heaviest particles sink to the bottom first and the clay last. Distinct layers can often be seen which indicate the relative proportions of gravel, sand, silt and clay making up the sample. This was done and after two days there was still virtually no clear water at the top of the jar and a barely discernable layer of larger particles at the bottom (marked with a line in Figure 2).   After two months it had still not fully settled out.

Figure 2: sedimentation test with clay sample (left) after 2 days and (right) after two weeks

3.2   Making clay slip

Various methods were tried for making slip from plastic clay. In previous experience as a hobby potter it was found easier to make a smooth slip by rehydrating perfectly dry clay than to try to make it from plastic clay. Comments from the manager at Coleford Brick did not allay doubts about the feasibility of making slip by simply soaking plastic clay in water, and the possibility of drying it in the sun first then breaking it up with a hammer or roller was considered.

Nevertheless, attempts were made to produce slip from plastic clay. Experiments with a potato masher (useless), hand tearing and mashing (effective but very slow), foot trampling (better, but still slow), a paint mixer on a 500W domestic electric drill (reasonable but at risk of motor burn-out), lead eventually to the purchase of a Makita paddle mixer for cement and mortar. If the plastic clay was first torn into apple-sized lumps (Figure 3) before adding water, this tool produced an acceptably smooth slip with the consistency of thick cream and without any tangible lumps in about 10 minutes. If the clay was left to soak for 24 hours (or better, several days) then it produced a

smooth slip within about 5 minutes (Figure 4). There was always a little sediment of sand and grit at the bottom of the bucket and some build up on the paddle where the larger particles of grit had accumulated in the grooves on the paddle (Figure 5). Perhaps a different shaped paddle might avoid this, but these lumps were easily dislodged and broken down by hand at the end. The slip was stirred thoroughly just before use to distribute the sediment evenly. Throughout, the water used was rainwater from a water butt.

Figure 3: clay torn into lumps and soaking in water

Figure 4: clay lumps after soaking overnight

Figure 5: buildup of grit on paddle

3.3   Measuring Viscosity

A simple equipment setup for measuring the viscosity of slip was devised. A kitchen
cooling rack with legs about 12cm high was placed on a narrow glass window lying
horizontally in its frame. A large yoghurt pot with its base removed was placed upside
down on the cooling rack and in this was suspended a plastic kitchen funnel so that the
end of the funnel fitted between the wires on the rack. The yogurt pot was trimmed in
height so that the end of the funnel was exactly 10cm above the surface of the glass.
The exit diameter of the funnel was 12mm (Figure 6). Holding the funnel vertically and
with a finger blocking the hole at the bottom, 100ml water was poured into the funnel
and the level was marked for future reference.

Figure 6: Equipment setup for measuring viscosity

The height of the meniscus of the liquid above the 100ml line was not the same for slip
as for water and depended on the thickness of the slip. For thicker slips, wobbling the

funnel from side to side a little levelled out the meniscus a little, but this was done as it obtained a horizontal slip level around the funnel. The thicker slips also left more residue on the sides of the funnel. These factors obviously introduced some variability in the exact volume of slip being measured, but this was ignored.

The diameter of the circle of slip was measured using a right angled strip of clear plastic which had been marked at 0.5cm intervals on its two perpendicular sides (Figure 7). The accuracy of this home made ruler was probably only +-1mm but, with an additional straight line, it allowed easy measurement of the circle of slip (see pictures) and was easily and quickly washed.

Figure 7: Measuring viscosity

The diameters resulting from the various slip mixes are listed in the table below. Repeated tests of the same slip mix resulted in measurements that were consistent to +- 2mm.

Figure 8: setup for viscosity testing

Water:Clay	Diameter of circle for 100ml slip
1:1	18.5
1:1½	14.9
1:2	9.5
1:0 (ie pure water)	No circle, water flows all over the glass.

Table 2: viscosity results for slip mixes

A device called a '**viscosity cup**' (aka 'flow cup') was subsequently discovered (Figure 9). This is used to measure the viscosity of glazes, paints, plasters etc. There are various

designs depending on the purpose, but it is essentially a gravity device comprising a cup with a hole in the bottom, usually with a long vertical handle so that it can be dipped into the liquid in question. The time for a full cup of liquid to run through the hole is measured. The cup is always filled to the top so the volume is constant and repeat tests can be reliably conducted. This testing method seems a lot simpler and could be easily conducted on site. Once initial tests were completed satisfactorily the ratios of clay, lime and water could be translated into set volumes for use in the mixing apparatus with reasonable reassurance of getting a consistent binder mix. Testing should then only be required occasionally to check the mix still meets requirements.

Figure 9: viscosity cup[2]

3.4   Methods of mixing hemp with slip

Various methods of mixing were tried. The tarpaulin method involved two people rolling and throwing the mix around on a tarpaulin by alternately lifting and dropping the sides of the tarp. This worked reasonably well but tended to produce a bit of balling-up of the mix which had to be broken down by hand (Figure 10). This effect is also noticed when mixing hemp-lime on a tarp and in a cement mixer, and it is important to break the balls down to get a consistent mix.

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[2] Picture retrieved from http://en.wikipedia.org/wiki/Ford_viscosity_cup

Figure 10: mixing hemp and slip on tarp

In a couple of cases quicklime was added after the hemp and slip had been combined by sprinkling it on top of the mix before further mixing on a tarpaulin (Figure 11), but it proved easier to mix the quicklime into the slip in a bucket before adding it all to the hemp. Gloves, goggles and a mask were worn when handling quicklime.

Figure 11: adding quicklime to hemp-clay on tarp

Another manual method, the one adopted, was to mix by hand wearing elbow-length rubber washing-up gloves in a very large plastic builder's trug. This was simplest as it could be done by one person, avoided balling-up and didn't take any longer than the tarp method

There was no access to a cement mixer other than the paddle mixer and because the mix was so dry it proved easier to mix by hand.

3.5 Making the hemp-clay samples

3.5.1 Blocks - first series

The material proportions in the blocks are shown in Table 4 below. Insufficient hemp was used in block 2 so only 1½ blocks were made; the next row in the table ('block 2 adjusted') shows the proportions that would have been used if the mix were scaled up to 3 blocks.

After six sets of blocks became apparent that there were too many variables (clay, hemp, lime, water) and it was necessary to restrict them. Making each set was quite time consuming and used up a large volume of materials so some further small test samples were made first.

Mixes of clay slip were prepared using different proportions of water:1kg water to 1kg plastic clay (hereafter called 1:1 slip), 1kg water to1.5kg plastic clay (1:1.5 slip), and 1kg water to 2kg plastic clay (1:2 slip). The first had a consistency of double cream, the last more like a very thick custard.

Figure 12: Consistency of 1:1 and 1:2 slip

A series of samples were made in identical yogurt pots with hemp/clay/lime in different proportions.

3.5.2 Sample pots

To narrow down the variables after the first blocks had been made, a series of smaller samples were made. Identical yogurt pots were filled with hemp/clay/lime mixes in different proportions. Each sample used 90g hemp which was the volume of dry hemp without any slip that when compressed filled the yogurt pot to the brim, see Figure 13.

Figure 13: 90g of hemp in yogurt pot (uncompressed)

The volume of slip was varied and also the quantity of lime. Slip was weighed out in proportion to the weight of hemp: 1.5, 3, 4.5 and 6 times the weight of hemp. Six times the weight, ie 540g slip, corresponded to roughly ¾ of the volume of the pot, see Figure 14.

Figure 14: 270g, 405g & 540g pots of slip weighed out in preparation

Initially 1:1 slip[3] was used, followed by mixes using 1:2 slip. Table 3 shows labels given to the sample pots along with the proportion of lime in each pot as a percentage by weight of plastic clay. So for example, sample 2b contained 270g 1:1 slip (which contains 135g plastic clay) and 27g lime (which is 20% of the weight of plastic clay). Pictures of the results are shown in Figure 15 (on the samples 'a,b,c,d' are represented by dots).

Weight of Slip (g)	135	270	405	540
1:1 Slip				
Weight of plastic clay in slip(g)➔	67.5	135	202.5	270
Weight of Lime(g) ↓ 0	0a (0%)	0b (0%)	0c (0%)	0d (0%)
13.5		1b (10%)	1c (7%)	1d (5%)
27		2b (20%)	2c (13%)	2d (10%)
40.5		3b (30%)	3c (20%)	3d (15%)
54		4b (40%)	4c (27%)	4d (20%)
1:2 Slip				
Weight of plastic clay in slip(g) ➔		180	270	360
Weight of Lime (g) ↓ 0		5b (0%)	5c (0%)	5d (0%)
27		6b (15%)	6c (10%)	6d (8%)
54			7c (20%)	7d (15%)

Table 3: Labels of sample pots, also showing percentage of lime

[3] '1:1 slip' = 1kg water to 1kg plastic clay, and '1:2 slip' = 1kg water to 2kg plastic clay

Figure 15: sample pots when dry (1:1 slip in left picture, 1:2 slip on right)

The conclusions drawn from these tests are described in more detail in the methodology.

- insufficient slip means the hemp is not bound together well enough, after sample 0a the idea of using 135g slip was abandoned.
- too much slip (eg as in 1d) – very slow to dry (and very difficult to remove from the yogurt pot as the suction was so high).
- rows 0,1,2,3 all showed signs of mould in the samples with higher volumes of slip, the worst mould being on sample 1d, followed by 1c then 0d.
- Samples 4b, 4c, 7c, 7d all contained grains of undissolved lime, mainly because the viscosity of the slip was so high once the lime had been added that it was impossible to blend it in completely.

3.5.3   Blocks - second series

In making the second series of blocks the plan was to keep the viscosity constant. It was time consuming to adjust each mix to the correct viscosity; it is an iterative process involving the addition of water in stages, followed each time by viscosity testing.   An attempt was made to speed up the process by making two large batches of slip, one with no lime and the other with 10% lime (as a proportion of plastic clay). These two batches were adjusted with water until the viscosity fell within the acceptable limits of 15.0cm ±2.5cm. For simplicity, as far as possible quantities of water and clay were measured in whole kilograms. For the pure clay slip the 100ml slip circle measured 14.5cm, for the 10% lime slip it was 13.25cm.

It was assumed that the two batches of slip could be mixed in varying proportions to make up blends of slip containing 0% 2% 4% 6% 8% and 10% lime as a proportion of plastic clay. In fact, closer consideration of the figures showed that this was not true since the 10% lime slip had to have a higher water content to maintain the viscosity and the slip was measured into the mixing trug in litres but by then the blocks had been made. This method held a further surprise regarding viscosity, reported in the results.

The proportions in the second series of blocks are shown in Table 4 below. Each set of blocks used 9 litres slip and the calculation of the proportions of lime, clay and water is shown in the appendix.

Mix	Plastic Clay (kg)	Water (kg)	Hemp (kg)	Lime (kg)	Total weight of 3 wet blocks (kg)	Total weight of 3 dry blocks (kg)	Lime:Clay (% by weight)	Average weight per dry block (kg)	Comments
minibrick	0.6	1	0.2	0	1.8	1.19	0.00%		v.successful
First series									
blocks 1	6.3	3.7	2.1	0	12.1	6.16	0.00%	2.05	very crumbly and loose, like muesli bar
blocks 2	5.7	3.3	1	0.057	10.06	6.72	1.00%	4.48	Only 1½ blocks made
blocks 2 adjusted	11.4	6.6	2	0.114	20.12	13.44	1.00%	4.48	Only 1½ blocks made – quantities scaled up
blocks 3	8	3.5	2.1	0	13.60	8.50	0.00%	2.83	crumbly, not well bound, but better than 1
blocks 4	8	7	2.1	0.8	17.90	9.83	10.00%	3.28	
blocks 5	8	6	2.4	0.4	15.28	8.67	5.00%	2.89	
blocks 6	9	6	2.4	0.45	16.48	9.35	5.00%	3.12	
blocks 7	9	9	2.25	0.45	20.70	10.13	5.00%	3.38	very smooth sides, well bound
Second series									
blocks 8: "pure"	7.36	4.91	2.2	0	14.47	7.62	0.00%	2.54	
blocks 9: "10%"	4.05	6.75	2.2	0.405	13.41	5.87	10.00%	1.96	
blocks 10: "10%"	4.05	6.75	2.2	0.405	13.41	5.91	10.00%	1.97	lime left soaking in slip overnight
blocks 11: "8%"	4.71	6.38	2.2	0.324	13.62	6.19	6.88%	2.06	4 parts 10% slip, 1 part pure clay slip
blocks 12: "6%"	5.38	6.01	2.2	0.243	13.83	6.51	4.52%	2.17	3 parts 10%, 2 parts pure clay
blocks 13: "4%"	6.04	5.65	2.2	0.162	14.05	7.00	2.68%	2.33	2 parts 10%, 3 parts pure clay
blocks 14: "2%"	6.70	5.28	2.2	0.081	14.26	7.50	1.21%	2.50	1 part 10%, 4 pure clay
blocks 15: "2%" + added water	3.78	6.39	2.2	0.058	12.43	5.82	1.52%	1.94	As above + extra water. Smooth sides, v. well bound

Table 4: Proportions of water, clay, hemp and lime in the blocks

3.5.4   Calculation of proportions of clay, water and lime in batch method

Table 5 shows the calculation of the proportions of clay, water and lime used in the second series of blocks. These were made using two batches of slip, one with no lime and the other with 10% lime. The last line shows the proportions for mix 15; this included 2.75 litres of additional water which was added to bring the viscosity back to within acceptable limits.

slip used in second series of blocks (8 to 14)	clay (kg)	water (kg)	lime (kg)	volume to nearest 100ml	weight	weight of clay per litre of slip	weight of water per litre of slip	total weight per litre	weight of lime per litre
pure clay slip	9	6	0	11	15	0.82	0.55	1.36	0
clay slip + 10% lime	9	15	0.9	20	24.9	0.45	0.75	1.25	0.045
mix 15: 5.4 litres pure slip, + 1.35 litres 10% slip + 2.75 litres water to match viscosity => 9.5 litres slip in total	3.96	6.71	0.06	9.5	10.73	0.42	0.71	1.13	0.006

Table 5: calculation of weight per litre of clay, water and lime in second series blocks

3.5.5   Weights of dry blocks

Table 6 shows the weights of the blocks after drying for between 1½ and 2½ months (the blocks were made over the period of a month). Despite the manual method of distributing the material for each set of blocks between the forms, in all cases[95] the 3 blocks were within 5% of the average weight for the set and in most cases within 2%.

Batch number	Block a (kg)	Block b (kg)	Block c (kg)	average	Comments
1	2.032	2.038	2.087	2.052	
2	4.271	2.444		(4.477)	only 1 ½ blocks made
3	2.884	2.766	2.852	2.834	
4	3.318	3.300	3.215	3.278	
5	2.856	2.88	2.931	2.889	
6	3.046	3.104	3.204	3.118	
7	3.335	3.398	3.397	3.377	
8	2.527	2.56	2.528	2.538	
9	1.965	1.955	1.946	1.955	
10	1.978	2.000	1.934	1.971	
11	2.092	2.048	2.052	2.064	

---

[95] With the exception of batch 2 which had only 1 ½ blocks

Batch number	Block a (kg)	Block b (kg)	Block c (kg)	average	Comments
12	2.200	2.155	2.157	2.171	
13	2.308	2.244	2.443	2.332	
14	2.534	2.523	2.443	2.500	
15	1.963	1.919		1.941	one block crumbled

Table 6: distribution of weight between blocks in each set (after 1½ to 2½ months drying)

3.5.6 Measuring Scales

Two sets of kitchen scales were used initially. Unfortunately on subsequent cross-checking they proved to be fairly inaccurate and mutually inconsistent. They were also limited to quantities under 3kg. Bathroom scales were trialed for larger quantities but these proved to be completely ineffective for anything under 10 kilos, so a SuperSamson Hand Held Spring Balance (Capacity 25 kg x Graduation 100 g) was purchased from ScalesExpress.com (Figure 16).

Figure 16: SuperSamson Hand Held Spring Balance used to measure slip ingredients

3.6   Conductivity testing with the Isomet Heat Transfer Analyzer

The Isomet Heat Transfer Analyzer is a portable device for dynamically measuring
thermal. Similar devices are also known as transient needle-probes, transient thermal
conductivity probes, transient heat flow or heat transfer probes. All work in basically
the same way.

Two types of probe are available (Figure 23): needle probes for porous or soft materials,
and surface probes for materials which cannot easily be penetrated with a needle
probe. Probes of each type are available in a range of sensitivities. The surface probe
was tried but was too 'leaky', light could be seen under it because of the rough surface
texture.

Figure 17: Isomet heat transfer analyzer probes: (left) surface and (right) needle

The needle probes (3mm diameter) consist of a linear heat source running internally along the axis of the needle with a thermo-junction to measure the temperature response of the material being tested. This is a dynamic conductivity measurement and the samples do not need to be fully dry as they would in a hot-box. The sensor part of the needle probe is 50 mm long beginning 15 mm from the tip of the needle. The probe is inserted at least 80mm into the sample, switched on and left for a few minutes until a baseline thermal equilibrium is reached; the probe then emits a series of heat flow impulses and measures the temperature response of the material over time.

3.6.1   Calibration of the Needle Probe

The probe is calibrated in the factory and calibration was checked by taking multiple measurements on a commercially produced hemp fibre insulation batt which has a published thermal conductivity value of 0.04 W/m.K. The readings were all very close and slightly higher than the published value, possibly due to moisture content; the average was 0.047 W/m.K.   The calibration was deemed acceptable. An attempt was made to improve the thermal contact between the probe and the batt with toothpaste [following Goodhew & Griffiths, 2005, 452] but it made no difference to the results.

Needle probe 0.035-0.2 with hemp Batt

						toothpaste	
Conductivity	0.0474	0.0467	0.0477	0.0497	0.0464	0.0474	0.0467
Spec. heat	0.104	0.087	0.102	0.097	0.11	didn't record these	
Diffusivity	0.497	0.538	0.464	0.514	0.421	as conductivities so close.	

Reported level 0.04 on sample.

Figure 18: calibration of the Needle probe (completed by Ranyl Rhydwen , 2007)

3.7   Moisture testing probe

The Protimeter Surveymaster moisture probe consists of two electrode probes and works on the basis that the electrical conductivity of a material increases with free moisture content. This is because the moisture dissolves small amounts of the material,

forming ions which move towards one or other of the two electrodes. Moisture content (MC) can be very variable for different samples of the same material, except for timber; moisture content for most timbers is fairly standard for a given RH. For this reason, moisture content is often given as %WME; this is the amount of moisture that would be contained by timber if it were in moisture equilibrium with material being measured.

Conversion tables are available for converting RH to MC for timber (Table 7). Wood with 20% moisture content is considered damp; 18-20% is borderline, and below 18% is safe. With a minor adjustment for temperature, timber will have 18% moisture content at around 85% RH and anything above this is likely to be at risk. Other materials are considered damp if they are in equilibrium with this humidity, however their actual moisture content may be very different. In essence, %WME can be interpreted to give the ambient relative humidity at the tips of the probe.

Relative Humidity %	Wood Moisture Content %	Condition of timber
0	0	Extremely dry
30	6	Dry
40	8	Dry
60	11	Dry
65	12	Dry
80	16	Dry
85	18	Borderline
89	20	Wet
99	28	Saturated
100	29	Saturated

Table 7: Conversion between Relative Humidity and Moisture Content for timber at 20°C

4   Appendices to the Results

4.1   pH

The pH tests were completed on a sample batch of slip comprising 1.5kg clay in 1 kg water. Quicklime was added in 15g quantities. The 15g (1%) of quicklime dramatically affected not only the pH but also the viscosity so that it was not possible to stir in further quicklime without first adding water. For each 15g of lime a further 150g water was added to maintain the viscosity.

The pH of the slip without lime was 8.2, but as soon as even 1% lime was added then the pH rose to around 12.8, and remained fairly constant from this point on. Subsequent additions of quicklime increased the viscosity less and less, but they did

cause the temperature to increase and steam to be released. The pH was measured after each addition of quicklime and of water. The results are in Table 8.

Total % quicklime (additional weight added)	pH after quicklime added	Additional water added	pH after additional water added	Comments – viscosity tested by eye and feel only
0	(8.19)		N/A	Initial pH without quicklime
1% (15g)	12.71	150g	12.73	Very thick, had to add more water No obvious temperature increase.
2% (15g)	12.79	150g	12.82	Not much thicker. Warmer
3% (15g)	12.82	150g	12.82	Little change to viscosity. Steam and heat.
4% (15g)	12.81	150g	12.82	Viscosity same, slightly thinner after water. Steam and heat.
5% (15g)	12.80	150g	12.80	Viscosity same, slightly thinner after water. Steam and heat.
7% (30g)	12.77	300g	12.79	Viscosity same, slightly thinner after water. Steam and heat.
10% (45g)	12.76	450g	12.78	Viscosity same, slightly thinner after water. Steam and heat.

Table 8: The effect on pH of adding quicklime to clay slip

4.2   Mould rating compared with raw material quantities and proportions

The following charts map the mould rating against the weight of various ingredients in the mix and the ratio of various pairs of ingredients.   It is acknowledged that the mould rating is highly subjective, but for the sake of interest a trendline was added to each chart in Excel. There is no obvious correlation on any of the graphs, though it does look as if increasing water generally increases mould which is to be expected. Interestingly, increasing the lime content did not appear to reduce the mould which is surprising given that the pH is around 12 when lime is added.
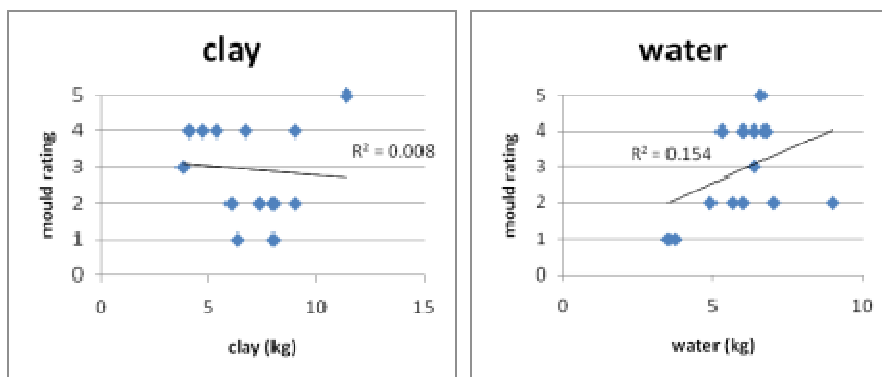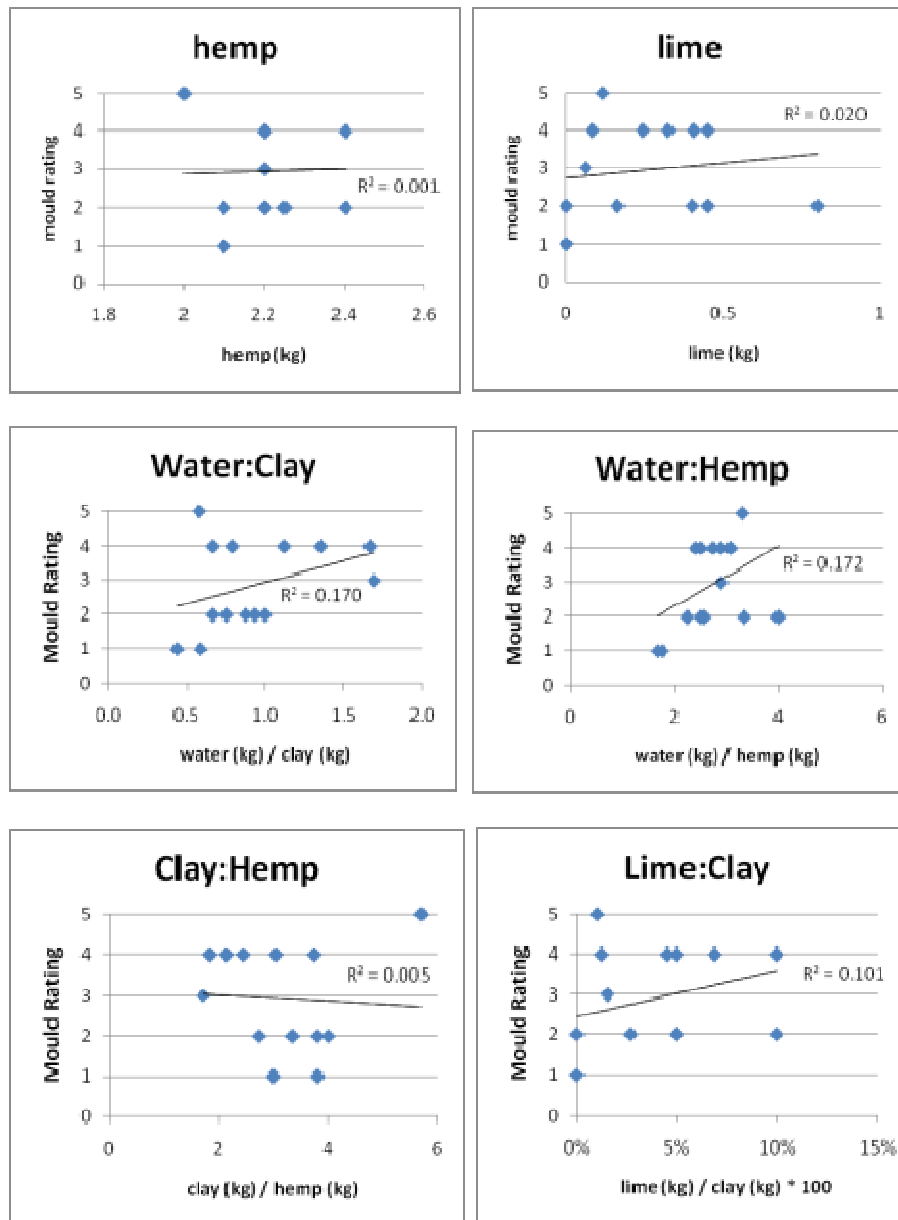
4.3   Thermal conductivity against density for test blocks

For the sake of interest the chart was redrawn excluding block 2 which was very damp and only had half the hemp content. It made little difference to the results (see section 4.5 in the main thesis).
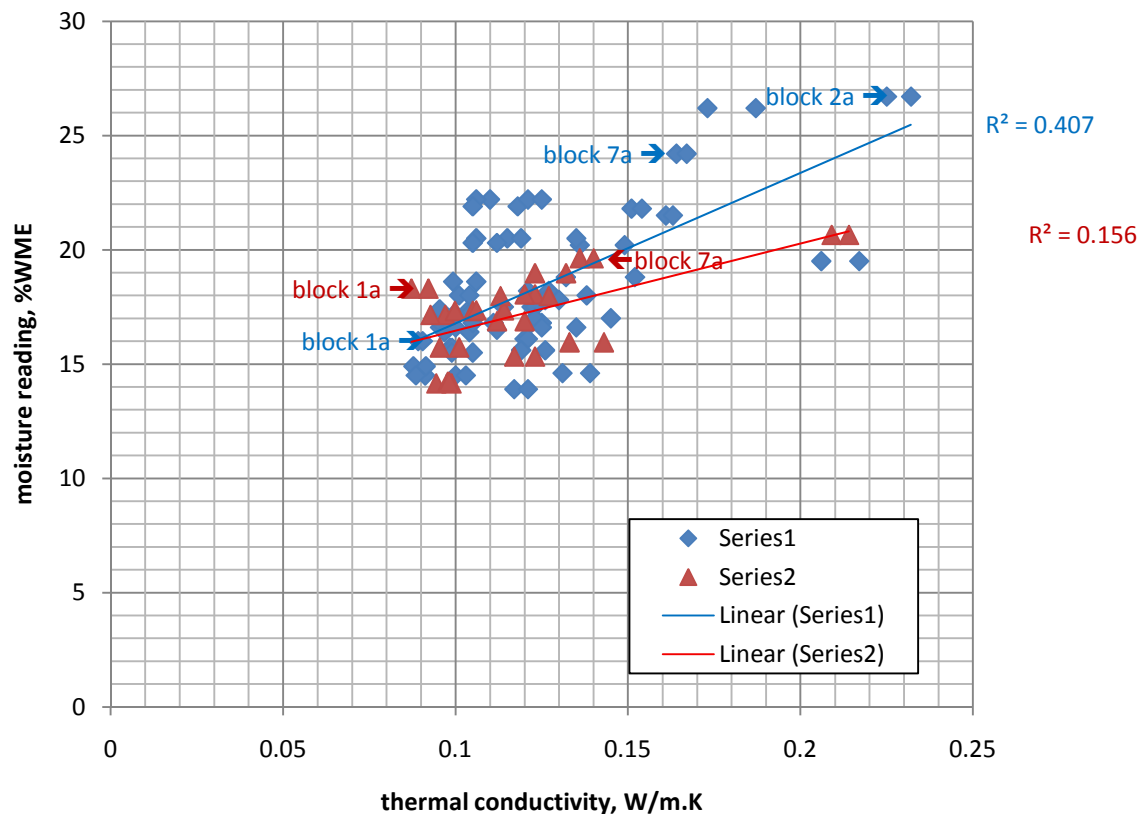
5   Appendices to the Discussion

5.1   Mould

Various cellular components of moulds have been identified as responsible for health effects, as well as secondary metabolites such as mycotoxins; moulds produce mycotoxins in response to environmental stress, such as other competing fungi and bacteria or changes in pH [KnowMycotoxins, 2008]. Not all mycotoxins are harmful to humans (penicillin is a mycotoxin) but some are blamed for a range of health problems. Since moulds occur throughout our environment, so do mycotoxins.

There have been successful lawsuits over exposure to "toxic mould" with substantial compensation payouts particularly in the US and Canada, but the degree to which moulds and mycotoxins are a risk to health is an area requiring further research.

Cleanup methods recommended by USEPA (2007, 85) for mould in buildings (and depending on the affected material) include steam cleaning, wiping or scrubbing surfaces with water or detergent solution before drying thoroughly; vacuuming with a high-efficiency particulate air (HEPA) vacuum after the material has been thoroughly dried (and disposing of the contents in well-sealed plastic bags); discarding water-damaged materials in sealed plastic bags. They recommend the use of goggles, gloves

and masks to minimise contact with mould. In normal circumstances, they don't recommend the use of biocides such as chlorine bleach.

6   New Mexico Clay-Straw Guidelines

Downloaded from **http://www.buildwise.org/library/construction/earth-adobe/straw-clay-guidelines.pdf**

6.1   New Mexico Guidelines

STATE OF NEW MEXICO

CONSTRUCTION INDUSTRIES DIVISION

CLAY STRAW GUIDELINES

REGULATION & LICENSING DEPARTMENT

CONSTRUCTION INDUSTRIES DIVISION

725 ST. MICHAEL's DRIVE

P.O. Box 25101

SANTA FE, NM 87504

PHONE: (505) 827-7030

1. DEFINITIONS:

     1.A CLAY SLIP: A suspension of clay particles in a water solution.

     1.B CLAY SOIL: Soil containing 50% more clay content by volume.

     1.C INFILL: Straw clay which is placed between the structural members of a building.

     1.D LIGHT CLAY: A mixture of clay and straw compacted to form an insulating wall.

     1.E MONOLITHIC: A continuous wall without seams.

     1.F NON-LOAD BEARING: Not bearing any of the weight of the building beyond the weight of light clay itself.

     1.G PROTECTIVE WRAP: Kraft waterproof building paper or asphalt-saturated rag felt used to wrap structural members.

     1.H STRAW: The stalk or stem of grain from wheat, rye, oats, rice or barley left after threshing or when the seed head has been removed.

     1.I TREATED WOOD: Wood treated with an approved preservative under the treating and quality control requirements specified in the UBC standard No. 25-12 or an ICBO approved coating.

     1.J WOOD OF NATURAL RESISTANCE TO DECAY: The heartwood of baldcypress, black locust, black walnut, the cedars and redwood.

     1.K VOID: Any space in the light clay wall that will allow a 2" sphere to be inserted into it.

2. STANDARDS FOR NON-LOAD BEARING LIGHT CLAY CONSTRUCTION:

2.1 GENERAL.

2.1.A Light clay shall not be used to support the weight of the building beyond the weight of the light clay material. The light clay will act as wall in-fill between the structural members or surrounding them.

2.1.B The structural support of the building shall be designed according to the Provisions of the Uniform Building Code (UBC). All loadings shall be as required by Chapter 23 of the UBC for vertical and lateral loads.

2.1.C The general construction of the building shall comply with all provisions of the Uniform Building Code (UBC).

2.1.D For the purposes of placement of perimeter foundation insulation, the light clay may overhang the bearing surface of the foundation up to the thickness of the perimeter insulation, but in no case greater than 4" inches.

2.1.E Unless otherwise provided for in the Standard, the following codes are minimum requirements:

a. Uniform Building Code (ICBO);

b. Uniform Mechanical Code (ICBO);

c. Uniform Plumbing Code (ICBO);

d. National Electrical Code (NFPA);

e. State of New Mexico Electrical Code;

f. L.P. Gas Codes;

g. ANSI;

h. Current Energy Conservation Code;

i. New Mexico Building Code;

j. Any additional codes and standards as may be adopted by the Construction Industries Division.

NOTE: The current edition of the above codes adopted in the State of New Mexico with applicable New Mexico changes shall apply. Copies of these codes are on file at the Construction Industries Division.

3. MATERIAL SPECIFICATIONS:

3.1.A STRAW: Straw shall be wheat, rye, oats, rice or barley, and shall be free of mold, decay and insects.

3.1.B CLAY SOIL: Dry soil mixture may contain a mixture of clay, silt and sand. The clay content shall be 50% or more of the total mixture by volume.

3.1.C STRAW/SLIP MIXTURE: All straw stalks shall be mixed with the clay slip until they are thoroughly and evenly coated so as to avoid pockets of dry straw.

4. WALL CONSTRUCTION:

4.1.A The exterior walls shall be a minimum of 12" inches thick unless otherwise approved by the certifying architect or engineer.

4.1.B Light clay shall not be used below grade. The foundation shall be constructed so that the bottom of the light clay wall is at least six (6') inches above final exterior grade.

4.1.C A moisture barrier shall extent across the full width of the stem wall between the light clay wall and the stem wall. The moisture barrier shall consist of an ICBO approved moisture barrier. All penetrations through the moisture barrier, as well as all joints in the barrier, must be sealed with asphalt, caulking or and ICBO approved sealant.

4.1.D All wood structural members embedded in exterior light clay walls shall be of wood of natural resistance to decay, or shall be treated wood or wood protected with approved coatings, or protective wrap. All non wood structural members shall be resistant to corrosion or coated to prevent corrosion with an approved coating.

4.1.E A moisture barrier shall be installed at all window sills prior to installing windows.

4.1.F A decay resistant sill plate shall be used over the moisture barrier and stem wall.

5. WALL REINFORCING:

5.1.A Vertical wall reinforcing shall be a minimum, of 2x4's, 32" on center, secured to sills and plate or gable rafters. This reinforcing shall be blocked every 8' feet vertically with 2x4 blocks placed horizontally.

5.1.B Nonstructural horizontal stabilizing bars shall be installed at 24" on center vertically and secured to vertical members. Nonstructural stabilizing bars may be one of the following: V2" bamboo, V4" fiberglass reinforcing rod, 3/8" steel reinforcing rod, 1/4" wood doweling, I x I hardwood, I x2 softwood.

6. MONOLITHIC WALLS:

6.1.A Formwork shall be strong enough to resist bowing when the light clay materials is compacted into the forms.

6.1.B Forms shall be uniformly loaded with light clay materials and be evenly tamped to achieve strong, stable, monolithic walls that are free of voids. Light clay material shall be loaded in lifts of no more than 6" inches and shall be thoroughly tamped before additional lifts or materials are added.

6.1.C Formwork shall be removed from walls within 24 hours after tamping, and walls shall remain exposed until dry. Any voids present once forms are stripped should be patched with straw clay mixture prior to plastering.

6.1.D Whenever a wall in not continuously built, the following procedure shall be used to prevent cold joints: The top of the wall shall be thoroughly coated with clay slip prior to the application of a new layer of light clay material.

7. OPENINGS:

7.1.A Rough bucks and/or door and window frames shall be imbedded in the light clay walls at the perimeter of the openings and fastened securely to wooden structural members.

8. WALL SURFACING:

8.1.A All exterior wall surfacing material shall allow, for the diffusion of moisture through the wall.

8.1.B Bridging shall be required at the juncture of dissimilar materials prior to the application of plaster. Acceptable bridging materials include: expanded metal lath, fiberglass mesh, tape or burlap. Bridging shall extend a minimum of 2" on either side of the juncture.

8.1.C Exterior wood wall siding shall be spaced a minimum of 3/4" inches from the light clay wall to allow for moisture diffusion. The siding shall be fastened to wood furring strips. Furring strips shall be securely fastened to the 2x4 vertical wall reinforcing.

9. ELECTRICAL:

9.1.A All wiring within light clay walls in residential construction shall be Type UF or approved conduit systems.

9.1.B All wiring within light clay walls may be channeled or embedded in the walls, maintaining a minimum depth of one and one-fourth inches (1-1/4") from the surface of the interior of the light clay wall surface.

9.1.C All cable, conduit systems, electrical and junction boxes, shall be securely attached to the light clay wall or wall framing.

9.1.D All electrical wiring methods and materials in light clay walls shall meet the provisions of the National Electrical Code, and any other applicable State codes or standards currently in effect within the State of New Mexico.

10. PLUMBING:

10.1.A All plumbing shall meet all provisions of the Uniform Plumbing Code, Uniform Mechanical Code and New Mexico Plumbing and Mechanical Code, and any other applicable State codes or standards, currently in effect within the State of New Mexico.

11. PROFESSIONAL SEAL REQUIREMENT AND CERTIFICATE OF OCCUPANCY:

11.1.A Construction documents detailing the structural design of the structure shall be prepared by a licensed New Mexico architect or structural engineer. The architect or engineer stamp must be affixed to each page of the plans detailing construction of the structure with the design professionals signature and date affixed over each stamp.

11.1.B Prior to issuance of a Certificate of Occupancy by the Construction Industries Division, an inspection report must be proved to the General Construction Inspector by the licensed New Mexico architect or structural engineer. The report shall attest to the building's structural integrity and conformance with the permitted drawings.