DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY COLLEGE DUBLIN

An Investigation of Hemp and Lime as a Building Material

A project submitted in part fulfilment of the requirements for the degree of

Bachelor of Engineering

by

John O'Dowd & David Quinn

March 2005

Supervisor: Dr. Mark Richardson

In this project, the use of hemp and lime as a construction material was investigated. The historical background of the materials was briefly reviewed and the current methods of production for each material were discussed. The compressive and tensile strengths were measured for a variety of mixes and a theoretical value of the thermal conductivity was estimated.

Based on this information, an analysis of a dwelling built solely with hemp and lime was conducted. It was concluded that a combination of hemp hurds and lime is a viable structural and insulating material for dwellings.

Acknowledgements

The authors would like to thank:

- Dr. Richardson for his helpful guidance and assistance
- Mr. Marcus McCabe of Ecoflo Reedbeds, for supplying hemp in several forms
- Mr. Edward Byrne of The Traditional Lime Company, for supplying lime and sand
- Dr. Peter Walker, Department of Architecture and Civil Engineering, University of Bath, for his advice on this project
- Mr. Terry Mangan, Mr. Thomas Webster, Mr. Paddy Donovan, Mr. Derek Holmes, Mr. Frank Dillion and Mr. George Cosgrave, of the Civil Engineering Laboratory, UCD, for their helpful assistance during our experiments

TABLE OF CONTENTS

1 INTRODUCTION

In this project, the two materials being investigated are hemp and lime. The combination of these materials is considered as an alternative structural building material to other conventional materials. In addition to considering the historical background of these materials, this project examines the individual properties of the materials, and considers the advantages and disadvantages of using them in combination.

The materials used in this project are ‘environmentally friendly’ and have, overall, a low level of embodied energy. Hemp is a plant and thus utilizes carbon dioxide (CO_2) during its growth. Natural hydraulic lime [$Ca(OH)_2$] produces less CO_2 in its production than cement and also absorbs CO_2 as it sets. As well as being of benefit to the environment, this feature is beneficial economically if carbon taxes or CO_2 production limits are introduced in the future.

In this experiment, hemp was used for two main roles. Firstly, hemp hurds were mixed with a hydraulic lime binder as an aggregate; secondly, fibres were added as a tensile reinforcement in a lime/hemp hurd mix. This investigation was designed to examine the strength of a typical lime/hemp hurd mix and to determine if hemp fibres can strengthen it.

By conducting experiments to measure the compressive and tensile strength of various mixes, the aim of this investigation was to find a mix which has an optimum balance between compressive strength and thermal conductivity – two important properties for a building material.

2 CONSTITUENTS: BACKGROUND REVIEW

2.1 Historical Background

The first documented use of organic materials in construction dates as far back as the Mesopotamian civilisation (2000 BC), where buildings were discovered made from mud bricks reinforced with reeds (Lloyd et al. 1972). This tradition has continued down through the ages and is now being revitalised in the 21st century through the increased building with cob (monolithic mud and straw, Figure 1), straw-bale houses (Figure 2) and adobe (mud and straw bricks, Figure 3).

Figure 1: Cob house in England (www.ecodesign.co.uk)

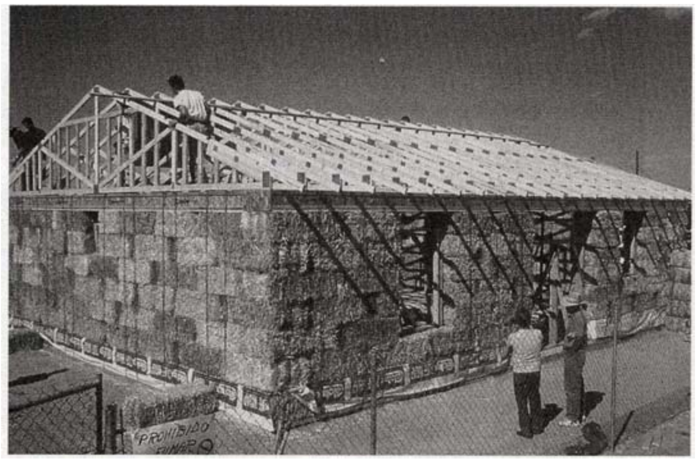


Figure 2: Straw bale house (Elizabeth and Adams 2000)

Figure 3: Adobe house in Mexico (Elizabeth and Adams 2000)

2.1.1 Hemp

Building with hemp hurds and lime mortar is a relatively new idea and there is little technical information available on this topic. There is much interest amongst both engineers and architects in using these hurds (Figure 4) as an aggregate with hydraulic lime binders, as they are both strong and light. Throughout the world, hemp is cultivated commercially for its strong, valuable fibres and oil. These hurds are a natural by-product after the plant has been used for other purposes.

Figure 4: Sample of hurds

2.1.2 Lime

Lime comes from limestone rock and has been used in building for thousands of years (Holmes and Wingate 2002). It is widely accepted that lime has been used since the beginning of human habitats (Hill et al. 1992). It was used in ancient times and in the Roman Empire. The earliest traces of lime use in construction have been found in early Egyptian buildings. According to Vicat (1997) the blocks of the Pyramids, especially those at Cheops, were bound using a lime mortar.

Masks made of "fibrous plaster" dating from 4400 BC have been discovered by archaeologists (Cowper 1998). The palace of Knossos in Crete was plastered with lime. Some fragments of decorative modelled stucco are still preserved in Rome and Pompeii dating to AD 79. Pliny the Younger, a Roman lawyer and senator, who lived circa 80 AD, stated that 'no builder should employ lime which had not been slaked at least three years'. The famous architect and engineer, Vitruvius, gives guidelines for lime production and uses of lime in *The Ten Books on Architecture*. He also described in detail pozzolanic additives and mentioned the powder around Mt. Vesuvius as one '…which from natural causes produces astonishing results…' (Morgan, 1914, p.46). In his description of slaking he explains how the '…best lime, taken in lumps, is slaked…' giving the term 'best hand-picked lump lime' in building specifications as described by Holmes and Wingate (2002). Another example of lime use is in the Pantheon in Rome, which has a lime concrete dome (Figure 5).

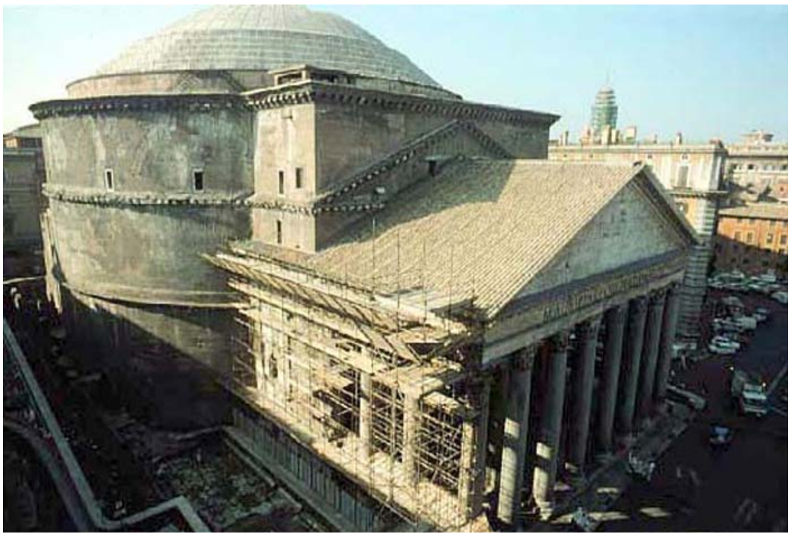


Figure 5: The Pantheon (www.erusd.k12.ca.us)

After the fall of the Roman Empire, the secrets of building with lime were lost. It was Smeaton's experiments, first published in 1791 that truly explained the way hydraulic limes develop strength. Until then, it was commonly accepted that durable mortars came from the hardest limestones and that chalk only produced soft mortars. Smeaton showed that hydraulic limes came from limestones or chalks which contained clay (Pasley 1997). Lime mortar was commonly used in the construction of older houses until the 1900s with many advantages over today's modern artificial cements. It is flexible and allows small amounts of distortion without cracking as well as being permeable to vapour, allowing moisture to travel through it and escape. Currently, lime in mortar has been largely replaced by Portland cement, which is stronger and harder, but neither porous nor flexible.

In this investigation hydraulic lime (NHL 3.5) was used, as it is considered more suitable by hemp/lime builders than modern cements. Its flexibility allows small movements without cracking, and it also provides a moisture permeable binder around the hemp hurds which is necessary for an organic material. Environmentally, it requires less energy and is less polluting to produce than Portland cement both in terms of energy and CO_2 emissions.

Hydraulic lime hardens and sets in the presence of water; it subsequently gains strength as it absorbs CO_2 from the air.

2.1.3 Composite Materials

A composite building material consists of at least two different materials, neither of which is suitable for constructing buildings on its own, but when combined, result in a strong and suitable material (Pultron 2004).

Composite materials have been used in buildings for thousands of years. Adobe mud huts made from a mixture of straw and clay have existed since the Stone Age. Archaeologists have discovered '…heavy mud brick reinforced with matting and three-inch cables of twisted reeds…' in buildings which were constructed over 4000 years ago in Mesopotamia (Lloyd et al., 1972, p. 25). Use of hemp has been discovered in the mortar of a bridge from the Merovingian Dynasty (AD 476 – 750), which is still standing (Isochanvre 2004).

According to Vitruvius, a mortar made up of a mixture involving sand and hair was used to plaster curved ceilings. Until as recently as 1850, clay and chopped straw were used in plaster floor construction. This mixture was plastered over bunches of reeds which spanned across timber joists. Plastering, using 'plaster of Paris' and hair (horse or human), over timber laths was used for ceilings and hollow partition walls until the twentieth century. Composite load-bearing materials, such as concrete reinforced with steel are used to transfer loads and resist forces in the majority of large buildings constructed today.

Advanced Composites

In the last 40 years, advanced polymer composite materials have been developed. Polymer composites (or advanced composite materials) can be described as materials, which are manufactured using modern synthetic glues and fibre reinforcement. The fibre reinforcement provides strength and stiffness, while the glue matrix binds the fibres together. In reinforced glass fibre composite material, the fibre is held in place by a polymer matrix, and the fibres are orientated in defined directions to provide maximum strength (Figure 6).

As well as being extremely resistant to corrosion, polymer composites can also be manufactured in unique, specific shapes.

Figure 6: Example of glass fibre mats for an advanced composite material

Modern polymer composite materials consist of high-strength fibres in a polymer matrix. Currently, the most common artificial fibres used are aramid, carbon and glass, which are extremely strong. However, to produce these fibres, significant amounts of energy are used, which usually results in large amounts of CO_2 being produced. Production of one ton of glass fibres requires 27.0 GJ (Roaf 2001). Glass fibres are most commonly used, due to their low cost and good mechanical properties. Currently, concrete reinforced with steel fibres is being used in floor screeds to prevent shrinkage cracking as the steel fibres provide tensile strength.

Natural Fibres

In the past, natural fibres were of major importance. However, with the development of artificial fibres they have become less important and only recently are being used as reinforcement in high-strength composites. Growing natural fibres does not release CO_2 and the only energy needed is provided by the sun. This is particularly important today, both environmentally and financially, as there is an urgent need to reduce pollution and the cost of energy production is increasing steadily.

There is renewed interest in discovering possible uses of natural fibres to replace fibres from the petrochemical industry. Interest in hemp developed in Europe in the 1980s when, whilst searching for an alternative non-food crop, hemp was chosen as a suitable plant as it grows quickly and is a high-yielding crop (Crowley, quoting Werf 1994).

Many plants produce fibres, which are useful to society. Applications of sisal, flax and ramie are all currently being explored. Hemp however has certain distinct advantages. It is stronger than sisal and ramie, and it is much cheaper to grow and process than flax. Hemp also grows with a much higher yield per acre than flax (Ranalli 1999).

As its physical properties are being recognised, hemp is being used increasingly in more mainstream products. Researchers at the Daimler-Benz car company have found that hemp fibres can be used instead of glass fibres for reinforcing plastic components in vehicles (Figure 7).

Figure 7: Example of inner car door made using hemp fibres (Nova Research Institute 2003)

These researchers state that hemp fibre is more economical than flax, and matches or surpasses flax in terms of performance potential as hemp fibres are stiffer than flax fibres (Ranalli 1999). This is verified by Herrmann et al. (1997). The use of natural fibres is preferred to synthetic fibres, as they are more environmentally friendly to produce, and are not hazardous to dispose of, unlike glass fibres which cause harmful dust when ground up.

2.2 Environmental Assessment of Materials

2.2.1 Hemp

As hemp is a plant, it is an ecologically sustainable method of producing a material. It does not require pesticides and requires little fertilising (Rannalli 1999). A hemp crop can be grown in Ireland in roughly 100 days. One hectare of hemp produces 3.5 tons of hurds (Bertucelli, S., 2004, pers. comm., 6 October). The current decortication process of separating hemp into its separate parts of long fibres and woody hurds results in the hurds as a by-product. The only direct energy required for processing is inspection of the material, packaging and transportation. Hurds are now available from a large hemp producer in England (Hemcore), and there are several suppliers throughout Ireland. This material has little negative impact on the environment in terms of CO_2 production.

2.2.2 Lime

Lime is an 'environmentally friendly material'; Although CO_2 is emitted during its manufacture, CO_2 is also absorbed in its curing process. The construction industry is responsible for producing large amounts of CO_2 emissions, which are contributing to global warming. Many of these problems are caused by cement production, which is responsible for producing 10% of the world's CO_2 emissions (Elizabeth and Adams 2000). It is estimated that the main source of CO_2 production today is from buildings, from both their construction and their heating. This is thought to be as high as 50% of the annual CO_2 production worldwide (Roaf 2001). Environmental awareness and consideration is not only affecting civil engineering, it is influencing business decisions based on economics. It is hoped that in this area, this project will be most influential. For these reasons, investigating environmentally friendly building materials is becoming more important.

2.2.3 Combination

Hemp hurds can be used as an aggregate in the lime mix to form a durable and lightweight building material. Currently, this is being used as an infill in timber-frame houses, and has being used occasionally for buildings in Ireland (Figure 8), England and France. The timber frame is the main structural element, and the hemp is a non-structural infill which insulates the building. When hemp and lime buildings are constructed, air trapped in the internal voids of the material provides good insulation properties. A thermal conductivity of 0.12 W/mK has

Figure 8: Infill of timber frame structure with hemp hurds and lime (www.oldbuilders.com)

been measured by the Centre Nationale de Technicale Bureau (CSTB), France (Isochanvre 2004) for a mix of hemp and hydraulic lime. Hemp and lime form a porous material, which allows moisture vapour to escape from an enclosed space. This prevents the accumulation of condensation, and allows the building to 'breathe'. As the material has a certain amount of flexibility, small movements in timber-frame structures can be accommodated by the lime/hemp mix, which can move slightly without cracking. Due to the lighter weight of the overall structure there is a '…50% saving in the amount of soil disposal resulting from the construction of the foundations…' (BRE report of 2002). The alkaline nature of lime preserves the overall structure, protecting both the timber frame and the hurds. This prevents decomposition due to moisture and attack by rodents (Kennedy et al. 2003).

3 CONSTITUENTS: PRODUCTION METHODS

3.1 Hemp

3.1.1 Origin and History of *Cannabis sativa*

Hemp is a member of the *Cannabaceae* family and is a plant (Figure 9) which produces bast fibres. Bast fibres are soft woody fibres obtained from the stems of dicotyledonous plants. Hemp originated in Central Asia and was grown for its fibres since 2800 BC. It was cultivated in the Mediterranean countries during the Middle Ages (*Encyclopaedia Britannica* 1987). Hemp (also known as *Cannabis*) was one of the first plants to be cultivated by the human race and was previously considered to be one of the most important agricultural crops. The Celts considered hemp to be a mystical plant and Queen Elizabeth I decreed that all farmers were obliged to grow hemp on their farms (Bertucelli, S., 2004, pers. comm., 6 October). Until the 1800s, *Cannabis* was used to produce rope, cloth, food, lighting oil and medicine and was one of the main cultivated plants throughout the western world (Ranalli 1999). Guttenberg's first Bible was published upon hemp paper and currently hemp fibres are used to manufacture bank notes.

Figure 9: Field of hemp in Co. Down

Hemp is an extremely useful plant, as it provides fibres, oil and hardwood. Its fibres are very strong with a tensile strength of 550 – 900 MPa (Wambua 2003) and were valued hugely before the development of plastic fibres from petrochemicals. From the 1930s, *Cannabis sativa* disappeared from the world markets. With the increase of petrochemical fibres, the importance of natural fibres declined and as a result *Cannabis* became a less important crop. The banning of the plant in the US coincided with the release of the first plastic fibres from

Dupont Pharmaceuticals (Crowley 2001). At the time of the US banning of *Cannabis sativa*, a Dupont senator was a direct advisor to the president and advocated the ban, on grounds of drug misuse. In 1937, a US tax made growing hemp (the drug-free form of *Cannabis sativa)* prohibitively expensive preventing any further growth of the plant in America. Ranalli states that 'The prohibition of *Cannabis* drugs has led to the prohibition of *Cannabis* cultivation in general, and the historically important uses of *Cannabis* have been largely forgotten…' (1999, p.8).

3.1.2 Stem Structure and Composition

Industrial hemp (*Cannabis sativa*) is a fast growing plant; it takes 80 – 100 days for a crop to reach maturity in Ireland (Eason, L., 2004, pers. comm., 6 October). It can grow with little fertilizer and its rapid growth rate (6 – 8 feet at maturity) prevents weeds from growing between the plants (Ranalli, 1999, p.86). It grows in most temperate climates throughout the world, and is considered to be an indigenous plant in parts of Eastern Europe.

Figure 10: Sample of hemp fibres (cm scale)

The stem of the plant consists of an outer layer, inner fibres and a strong woody core. The inner bast fibres make up 35% of the inner stem and the woody core makes up 65%. The outer layer contains the valuable fibres, described as long bast fibres (5 to 50 mm) with an average fibre length of 16 mm shown in Figure 10. The inner woody core of the plant consists of fibres with a length of 0.5 to 0.6 mm (Ranalli 1999). Recently, as hemp was being reintroduced as an agricultural crop, the centre core was considered as waste material and discarded. However, this part of the plant is central to this investigation. The fibres are

Figure 11: Sample of hurds (cm scale)

strongly bonded together, and are extremely hard when dry. ‘Botanically as well as chemically, hemp woody core is comparable to hardwood’ (Ranalli, 1999, p.219). An example of the hurds is shown in Figure 11.

3.1.3 Current uses of Hemp

Hemp fibres are used mainly for ‘slim’ papers, e.g. banknotes and cigarette papers. The fibres are extremely strong and are used for reinforcement in some polymers in specialist applications. Currently, fibres are used for reinforcing plastics for some internal parts of cars (Ranalli 1999). Hemp is also cultivated for its valuable oil, which is consumed and used in toiletries (Bertucelli, S., 2004, pers. comm., 6 October). Hemp oil is extremely nutritious, containing the valuable Omega 3 oil which is rare in plants (Roulac 1997). Hurds are now available from a large hemp producer in England as a horse-bedding material, and there are several suppliers throughout Ireland.

3.2 Lime

3.2.1 Lime Production

Lime is produced by the burning of limestone in a kiln at a high temperature (≈ 900 °C). This allows CO_2 to be driven off. During this process the limestone or calcium carbonate ($CaCO_3$) is changed to calcium oxide (CaO). Calcium oxide is also known as lump-lime or quicklime. Slaking is the process of adding water to quicklime. The product of slaking is called hydrated lime, or calcium hydroxide [$Ca(OH)_2$]. When quicklime is slaked with an excess amount of water (i.e. more water than is needed for the reaction to take place) the heat caused by the reaction drives off the excess water and a dry powder remains. Care must be taken when water is added to quicklime. Quicklime reacts vigorously with cold water generating a lot of heat. The material may double in size as it swells (Wingate 1987). The remaining dry powder is called hydrated lime. If more water is subsequently added during the slaking process, the lime becomes a free flowing liquid, known as milk of lime. This is sieved to remove larger particles and discharged into a lime pit. In this pit, suspended solids are allowed to settle out and coalesce at the bottom to form lime putty. Putty requires time to mature properly. The time required varies depending on what product is required. For mortars it is one month, for plaster three months and for the repair of historic buildings it may be up to several years. In Denmark, for the repair of historic churches, lime putty must be at least five years old (Holmes and Wingate 2002).

When slaked lime is used (for mortar or plasterwork etc.), carbonation causes the lime to set. In this process the lime begins to absorb CO_2 and this carbonation forms the chemical compound, calcium carbonate. This is chemically the same material that the process started with (i.e. limestone) and hence the whole process is described as a cycle (Holmes and Wingate 2002).

3.2.2 The Lime Cycle

This cycle is shown simply and effectively in Figure 12. It is emphasised that lime comes

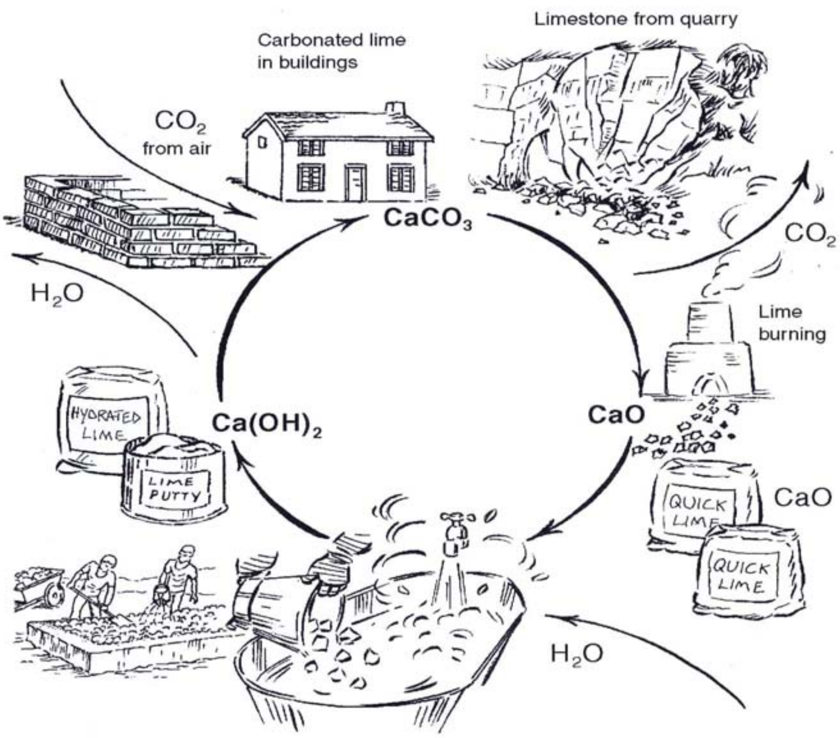


Figure 12: The Lime Cycle (Holmes and Wingate 2002)

from limestone and when it sets it has the same chemical composition as limestone. It should be noted that hydrated lime refers to both hydraulic lime and non-hydraulic lime that has been slaked with water (Byrne 2001).

3.2.3 Classification of Lime

The two main categories of lime are hydraulic lime and non-hydraulic lime. Hydraulic lime contains small quantities of silica, alumina and iron oxide, chemically combined with calcium oxide (Duggal 1998). Non-hydraulic lime is free of these impurities. Hydraulic limes were previously classified as feebly, moderately or eminently hydraulic. Now they are classified as NHL 2, NHL 3.5 and NHL 5 respectively. This classification refers to the ability of the lime to set with water, also referred to as its hydraulicity.

3.2.4 Hydraulic Lime

Hydraulic lime sets partly due to a chemical reaction with water and partly due to a chemical reaction with CO_2. In the past, hydraulic limes were manufactured by the addition of volcanic additives, known as pozzolans. The Romans used this method of hydraulic lime production in the building of aqueducts and wherever the lime was required to set in the presence of water, as described by Vitruvius (Morgan 1914). Today, it is understood that it is the nature of the impurities in the raw material that produces these hydraulic properties in limes. The raw material may contain fine clay materials such as silica (SiO_2) and/or alumina (AlO_3). These clay materials combine with lime in the kiln to form active compounds (Holmes and Wingate 2002).

Hydraulic lime has the ability to set under water. This is an important property for hydraulic engineering works such as dam and bridge construction. Hydraulic lime is usually sold in powder form. If there is no silica or other clays present in the lime to provide the hydraulic properties, pozzolans may be added (Keohane 2001).

4 THERMAL PROPERTIES OF POROUS SYSTEMS

4.1 Introduction to Porous Systems

According to research from several sources, thermal conductivity is proportional to density (Dewar 1991; Neville 1995). Density appears to be the main factor influencing thermal conductivity irrespective of the material matrix. By comparing several porous systems which rely on low densities for low thermal conductivities an approximate value is proposed for a hemp/lime mix for a specific dry density. Several porous systems which currently exist are briefly described and a comparison is made between relevant aspects of these systems. Light clay is one building technique which is similar to the material being examined in this project, while aspects of lightweight concrete are also considered.

4.2 Light Clay

Light earth (or light clay) is a composite building material consisting of straw or wood chips which are coated with clay, a binding agent (Figure 13). This can be used to produce blocks, panels or used as an *in-situ* fill (Figure 14). It is valued for its insulating properties due to its range of densities and is usually used as an infill in timber-frame housing. Its structural properties vary proportionally with density (Elizabeth and Adams 2000). Typical ranges

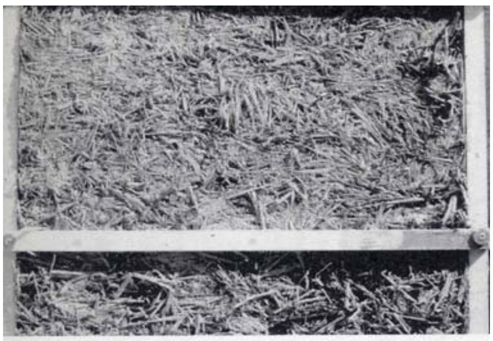


Figure 13: Infill of light clay, with straw (Minke 2000)

of density are 300 – 1200 kg/m^3. Traditionally, clay was mixed with straw, but currently other natural fibres are being substituted, such as wood chips, cork, sawdust, hemp and flax (Elizabeth and Adams 2000). The clay acts as both a binder and a preservative and also offers fire protection. This type of construction has been used widely across Europe, Africa and Asia, with examples of these buildings existing from the early 1900s. Light clay has been officially recognised in Germany and New Mexico, US where building regulations and standards exist for its use (Morgan and Scott 2003). It is important to use a moisture permeable render when sealing these surfaces, as the organic material can rot if the moisture content becomes high. This is particularly relevant with densities of less than 600 kg/m^3.

Figure 14: Light earth being placed *in-situ* (Minke 2000)

It is also necessary for the material to dry out after a reasonable time, so that fungi do not have time to grow (Minke 2000). Light earth blocks (Figure 15) can be used in climates where it is difficult to dry out walls in a reasonable period of time.

Figure 15: Light earth blocks (Elizabeth and Adams 2000)

4.3 Lightweight Concrete

Lightweight concrete is concrete which has a high air content and a density of less than 1850 kg/m^3. Lightweight concrete is produced either by the use of lightweight aggregate or by a foaming agent in a cement mortar. Lightweight aggregate usually has a large percentage of air voids trapped within the cellular structure of the material. As air is an excellent insulator with a thermal conductivity of 0.026 W/mK, air voids in a cement matrix reduce the rate of heat transfer (Newman 1993). If the material remains dry, the use of lightweight aggregate results in a better thermal insulator than normal-weight concrete. According to Newman, the thermal conductivity of lightweight aggregate cement depends primarily on density, aggregate type and moisture content. Dewar states that a decrease in density is accompanied by an increase in thermal insulation, although there is a decrease in strength. This is illustrated in Figure 16, where the relationship between thermal conductivity and density is shown. Dewar also states that high thermal efficiency is only achieved when lightweight concrete is kept dry. Controlling moisture content is an important factor for lightweight concrete to have good insulative properties. Particular care must be taken to avoid interstitial condensation as this causes a decrease in thermal efficiency.

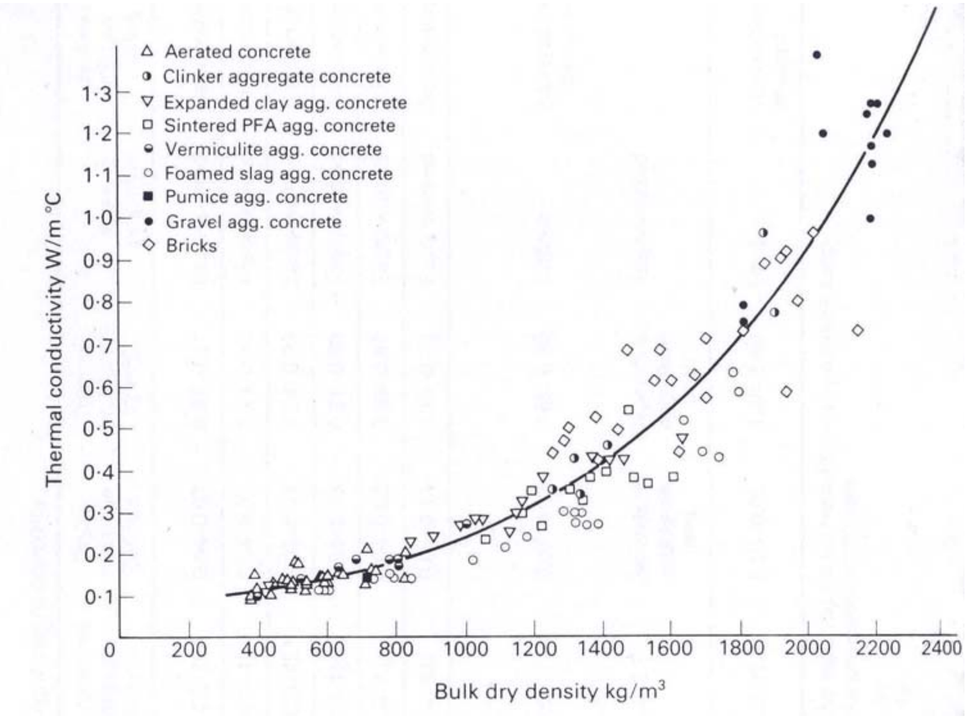


Figure 16: Graph showing thermal conductivity versus dry density (Dewar 1991)

There are two main types of lightweight concrete. One type is produced using a lightweight aggregate such as volcanic rock or expanded clay. The second is produced through the addition of a foaming agent in cement mortar. This creates a fine cement matrix which has air-voids throughout its structure. Aerated cement mortar is produced by the introduction of a gas into a cementitious slurry so that after hardening a cellular structure is formed (Dewar, 1991, p. 389). This type of block is currently produced by the Quinn Group (Quinnlite blocks) where powdered aluminium is added to a mix of fine sand, causing the production of hydrogen gas, which creates a lightweight concrete (Table 1).

Table 1: Thermal conductivity of Quinn-lite blocks

Compressive Strength	Thermal Conductivity
3 N/mm^2	0.12 W/mK
5 N/mm^2	0.17 W/mK
7 N/mm^2	0.19 W/mK

This, however is an extremely energy intensive procedure, as sand is ground to a fine powder before mixing with cement, lime and aluminium. After the initial reaction between these constituents, the blocks are autoclaved at a high temperature for 12 hours to increase the strength. They are also moisture impermeable, unlike lightweight materials constructed using lime or clay. They do have a much lower thermal conductivity than a typical concrete block, as shown in Table 2.

Table 2: Thermal conductivity of a typical concrete block

Compressive Strength	Thermal Conductivity
5 N/mm^2	1.33 W/mK

4.4 Uses of Lightweight Aggregate Concrete

Lightweight blocks have been used in multi-storey apartment buildings to reduce the dead load, and reduce the overall member sizes of the primary structure. They can also be used for fire protection, where they can shield structural steel from fire. They are also used as an insulating block which decreases the U-value of the structure. Lightweight concrete has been used to construct extremely large cantilevers, as the member can be narrower due to the decreased dead load. Using concrete of a lower density results in a lower dead load and can result in savings due to smaller member sizes. Occasionally this can allow construction on ground with a low load-bearing capacity (Neville 1995).

4.5 Types of Lightweight Aggregates

Lightweight Expanded Clay Aggregate (LECA)

This is produced by heating clay to a temperature of 1000 – 1200 ºC, which causes it too expand due to the internal generation of gases that are trapped inside. The porous structure which forms is retained on cooling so that the specific gravity is much lower than before heating (Neville 1995).

Natural Aggregates

Diatomite, pumice, scoria and volcanic cinders are natural, porous volcanic rocks with a bulk density of 500 – 800 kg/m^3 which make a good insulating concrete (Neville 1995). Concrete with pumice aggregate was used in ancient Rome to construct the dome of The Pantheon (Figure 5).

Organic Natural Aggregates

Wood chips and straw can be mixed with a binder to provide a lightweight natural aggregate. These are cellular materials which have air trapped within their structures once they have a low moisture content. This material has been used successfully as an infill in timber-frame houses in continental Europe (Elizabeth and Adams 2000).

4.6 Thermal Conductivity of Porous Systems

Based on data from Neville (Table 3), the following graph (Figure 17) was calculated for lightweight aggregate using expanded slag and expanded clay. For a similar density of hurds/lime with a 5:1 mix, the approximate thermal conductivity is estimated to lie between 0.11 and 0.17 W/mK (Table 4). Figure 18 shows the relationship between thermal conductivity and dry density for a range of concrete mix types and densities.

Table 3: Density and thermal conductivity values for concrete made with expanded slag and expanded clay

Dry Density [kg/m^3]	Expanded Slag [W/mK]	Expanded Clay [W/mK]
320	0.087	0.130
480	0.116	0.173
640	0.159	0.230
800	0.203	0.303
960	0.260	0.376
1120	0.315	0.462
1280	0.389	0.562
1440	0.462	0.678
1600	0.549	0.794
1760	0.649	0.952

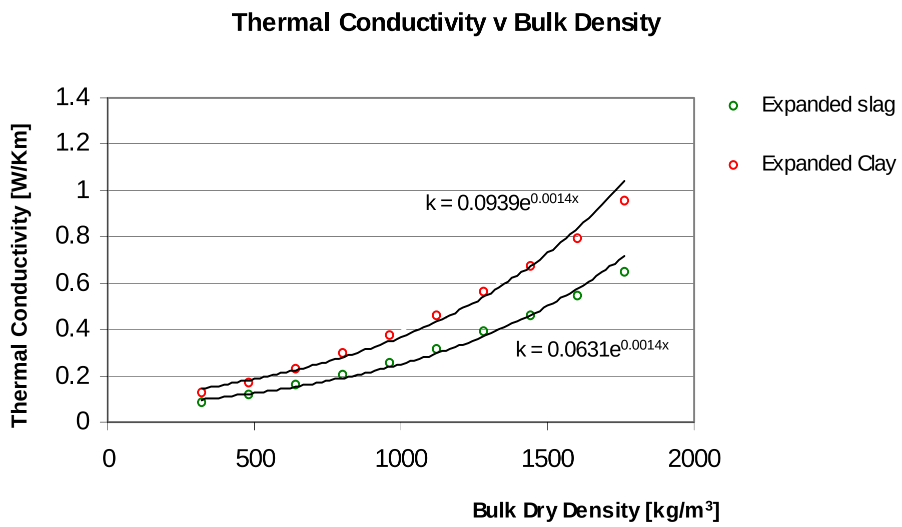


Figure 17: Graph based on data available from Neville (1995) relating the thermal conductivity of concrete to the bulk dry density

Table 4: Thermal conductivity values for concrete made with expanded slag and expanded clay

Density [kg/m^3]	k (expanded slag)	k (expanded clay)
425	0.11	0.17
550	0.14	0.20

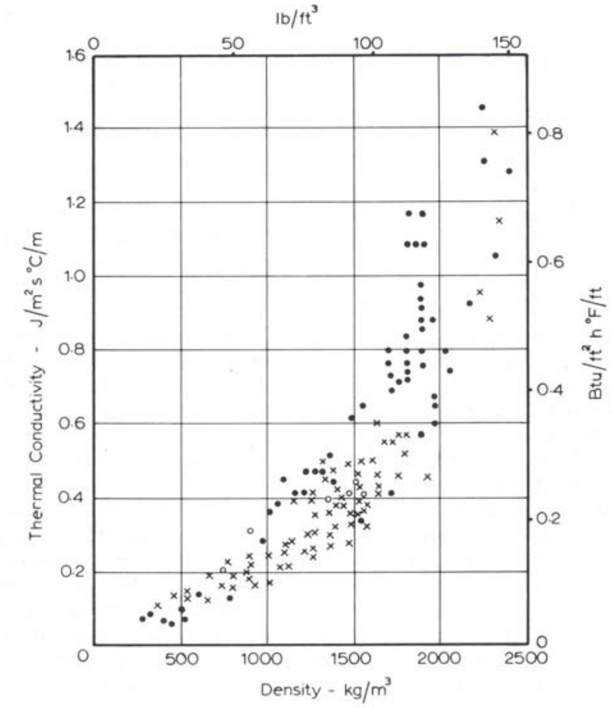


Figure 18: Thermal conductivity values for aerated concrete (Neville 1995)

As the hurds are botanically very similar to hardwood, it is unlikely that they would conduct heat as well as either expanded slag or expanded clay. This is due to their microstructure being less dense and being composed of individual cells. The fibrous nature of the matrix is shown in Figure 19 as well as an enlarged cross-section of a hurd (Figure 20). A value of *k* = 0.12 W/mK for a density of 550 kg/m^3 has been measured by the Centre Nationale de Technicale Bureau, in France (Isochanvre 2004) for a hemp/lime mix (ratio of mix not stated). This compares to a *k* value of 0.14 W/mK and 0.20 W/mK for expanded clay and earth at this density, respectively. The texture of each mix is shown in Appendix A.

Figure 19: Matrix of 5:1 lime/hurd mix

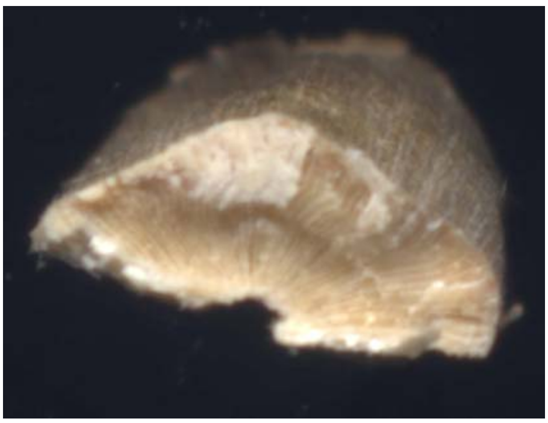


Figure 20: Enlargement of hurd

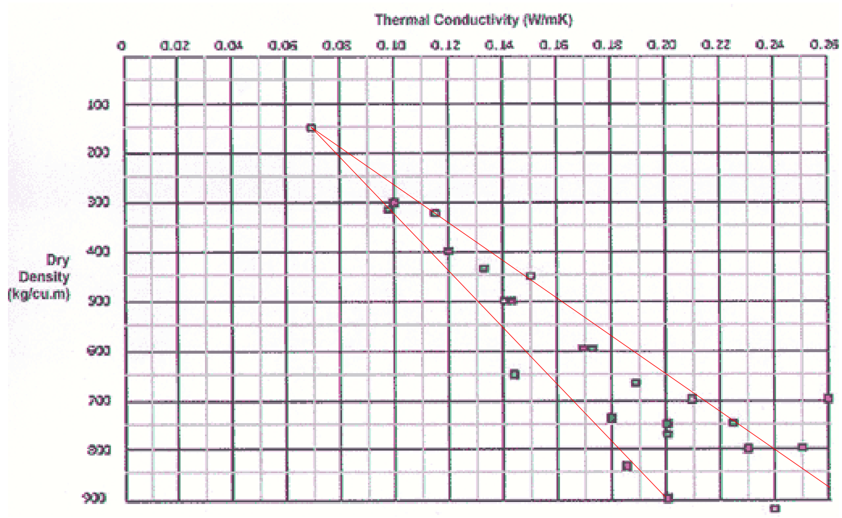


Figure 21: Thermal conductivity of light clay versus dry density (Morgan and Scott 2003)

Figure 21 shows the relationship between dry density and thermal conductivity for light clay (Morgan and Scott 2003). These data are spread over a small interval and no mathematical relationship is clear. However, from this graph, a light clay mix with a density of 425 kg/m^3 has a thermal conductivity of 0.12 – 0.14 W/mK.

Table 5: Summary of thermal conductivity values

Material	Density [kg/m^3]	Thermal Conductivity [W/mK]	Source of Information
Expanded Slag in Concrete	425	0.11	Neville (1995)
Expanded Clay in Concrete	425	0.17	Neville (1995)
Light Clay	425	0.12 – 0.14	Morgan and Scott (2003)
Expanded Slag in Concrete	550	0.14	Neville (1995)
Expanded Clay in Concrete	550	0.20	Neville (1995)
Light Clay	550	0.14 – 0.165	Morgan and Scott (2003)
Hemp/Lime Mix	550	0.12	Isochanvre [CSTB]

Table 5 summarises the values of thermal conductivities mentioned previously. Using this information a suitable thermal conductivity can be assumed for a chosen mix based on the dry density of the material.

5 EXPERIMENTAL RESULTS

5.1 Experimental Aims

The aim of this experimental program was to establish the compressive and tensile strength for a variety of mixes and to determine a balance between insulation and strength for a variety of mixes. The three mixes were:

1) hemp and lime
2) hemp fibres (and hurds) and lime
3) hemp, lime and sand

Table 6: Volume proportions of materials in mix

Hemp Hurds:Lime	Hemp fibres (and hurds):Lime	Hemp Hurds:Lime:Sand
0:1	0:1	3:1:0
1:1	1:1	3:1:1
2:1	2:1	3:1:2
3:1	3:1	3:1:3
4:1	No samples	3:1:4
5:1	5:1	No samples

In each variation one property of the mix was varied (Table 6). Three cubes and three cylinders were prepared so that an average strength could be calculated for each mix. The bulk density of each material was calculated (Table 7). This allowed the measurement of materials based on mass instead of volume resulting in greater accuracy.

Table 7: Bulk density of material

Hemp Hurds	Hemp fibres (and hurds):Lime	Lime	Sand
92 kg/m^3	106 kg/m^3	636 kg/m^3	1027 kg/m^3

The traditional mixing proportions when using lime as a binder are three volumes of aggregate to one volume of lime. Based on this information, mixes were chosen with 3:1 as the central mix in the series of mix compositions. Other mixes either side of this ratio were designed based on this information. In order to calculate an optimum mix within the time constraints the mixes that would be of most use in deriving the relationship between the various properties were estimated. A control mix of lime with no aggregate and a constant lime/water ratio was prepared and the strength of this material was used as a benchmark.

Figure 22: Samples in carbonation tank

Once the various samples were prepared, they were placed in a carbonation tank (Figure 22) to accelerate the carbonation of the lime.

5.2 Method of sample preparation

1) The dimensions of the cubes used were 100 mm × 100 mm × 100 mm. The cylinders had a diameter of 100 mm and were 200 mm high. The moulds were lined with 'cling film' instead of using a release agent as a permeable surface was desired to allow the evaporation of water from the material during curing and drying (Figure 23). The samples also had to be sufficiently porous to allow CO_2 to be absorbed. (It was decided that lining the moulds with cling film or greaseproof paper would be a suitable alternative to mould oil. After testing both of these methods, the cling film proved to be superior).

Figure 23: Mould lined with cling-film

2) A known volume of lime was mixed with water until a workable state was reached. This water/lime ratio was kept constant during the experiments. To prevent the hemp from absorbing water during mixing, it was soaked in water for 10 minutes in advance. This ensured a constant water/lime ratio throughout all samples.

Figure 24: Wet mix of Hemp and Lime

3) The materials were added gradually to a mixer. After mixing for an appropriate length of time the material (Figure 24) was removed from the mixer and a slump test was carried out. For mixes with a slump less than or equal to 40 millimetres a 2.5 kg Proctor hammer was used for compacting (Figure 25). A standard number of blows per volume was used for each cube and cylinder, so that the energy used to compact each sample was constant ($E = mgh = 2.5 \times 9.81 \times 0.3 = 7.4$ J per blow). For mixes with a slump greater than 40 millimetres, a vibrating table was used to expel air bubbles.

Figure 25: Proctor Hammer in use

4) The samples were de-moulded after 24 hours and allowed to dry at room temperature. They were then placed in a carbonation tank with a concentration ≈ 10%. They were allowed to cure for 30 days. As explained previously, hydraulic lime sets firstly with water and secondly with CO_2. The use of a carbonation tank accelerated this process, as the normal concentration of CO_2 in air is 0.03%.

5) After the samples had reached full carbonation in the CO_2 rich environment the samples were tested. Several trial cubes were cut in half to test for carbonation. The samples containing lime only were not fully carbonated when testing began so they were left in the CO_2 rich environment for 7 days longer. The centre of the lime cubes and cylinders were not fully carbonated (Figure 26) even after this additional period of one week and as a result had not reached their full potential strength.

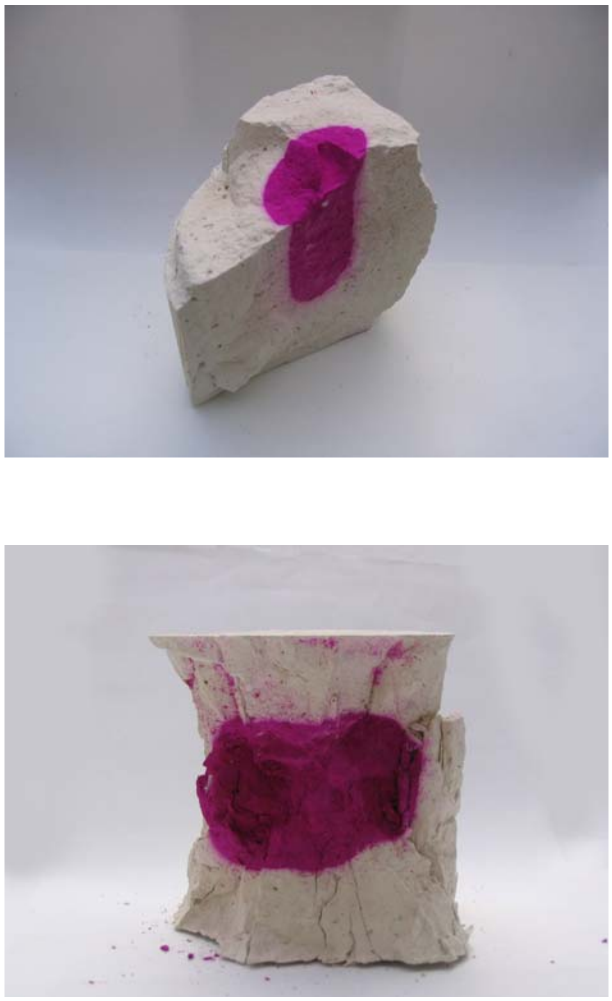


Figure 26: Lime cube and cylinder after testing

The samples were sprayed with phenolphthalein after testing. The purple colour in the above photographs (Figure 26) shows phenolphthalein reacting with the un-carbonated region.

5.3 Laboratory Tests

The compressive and tensile material strength of the different mixes was measured using cube compression tests and cylinder splitting tests. The tests were carried out using an INSTRON 1274 machine.

The cubes were subjected to a load applied at a constant rate. The cubes did not fracture but deformed slowly due to the fibrous nature of the material. The displacement was limited to 10 mm, and the maximum load was recorded.

The cylinders underwent tensile splitting tests. The cylinders were tested in the apparatus specified in BS 8110 for Structural Use of Concrete. A load was applied at a constant rate (3 mm/min) and the maximum force was recorded for each cylinder.

Cube Tests

The cubes were tested in accordance with BS ISO 844:2004 for Rigid Cellular Plastics. This international standard specifies a method of determining

a) the compressive strength and corresponding relative deformation

or

b) the compressive stress at 10% relative deformation

σ_m = maximum compressive strength [N/mm^2]

The maximum compressive strength is the maximum compressive force divided by the initial cross-sectional area of the test specimen when the relative deformation is ≤10%. If the value of the maximum stress corresponds to a relative deformation of less than 10 %, it is noted as the "compressive strength". If there is no clear maximum compressive force, the compressive strength of the material is calculated and its value noted as "compressive stress at a 10% relative deformation".

E= compressive modulus of elasticity (Young's Modulus)

The compressive modulus of elasticity is the compressive stress divided by the corresponding relative deformation below the proportional limit, when the relationship is linear.

ε = relative deformation (expressed as a percentage)

$$\varepsilon = \frac{\text{displacement}}{\text{initial thickness}} \times \frac{100}{1}$$

The data from each test is shown in Appendix A.

Cylinder Tests

A diagram of the apparatus used to test the tensile strength of cylinders is show in Figure 27. The cylinders were tested in accordance with BS 8110, using the apparatus shown in Figure 28.

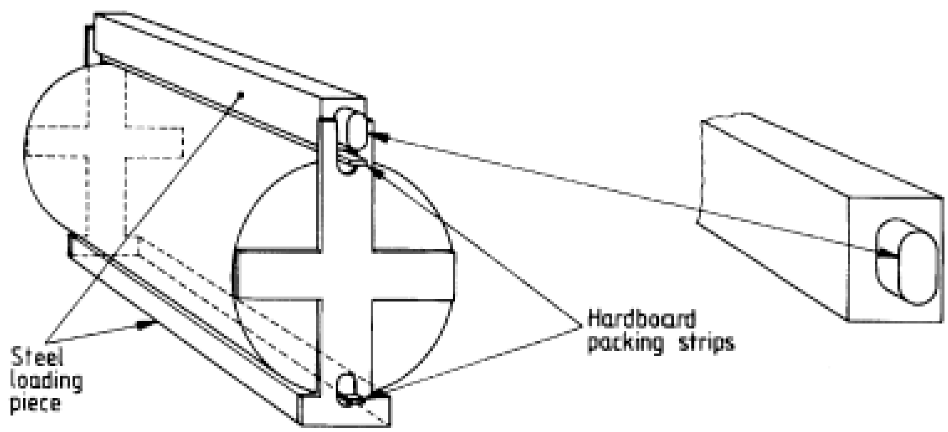


Figure 27: Diagram of layout for cylinder splitting (BS 8110)

Hardboard packing strips (Figure 29) were used so that the applied force was in contact with the cylinders' surface, in case of any imperfections. The load was applied at a constant rate of 3mm/min. The maximum force was recorded, and the tensile strength was calculated based on the following formula:

$$\sigma_{ct} = \frac{2 \times F}{\pi \times l \times d}$$

where: F is the maximum load [N]
l is the length of the specimen [mm]
d is the diameter of the specimen [mm]

Figure 28: Apparatus for cylinder splitting

Figure 29: Detail of packing strip

A clear maximum force was apparent in all of the specimens, and the data collected from each sample was recorded. This documents the failure of all of the cylinders tested.

5.4 Results of Strength Tests

The results from the compressive cube tests for each of the mixes are shown in Figures 30 – 57 and the results for the tensile testing is presented in Tables 9 – 11. The graphs are presented in the following order:

Figures 30 – 39: Hemp hurds: lime
Figures 40 – 47: Hemp (hurds + fibres) and lime
Figures 48 – 57: Hemp hurds: lime: sand

The stress/strain and load/displacement relationship for each mix is graphed, and a similar relationship exists for all cubes, showing consistency in experimental method and testing. Occasionally, a sample had a value which was significantly different, and this result was disregarded in the calculation of the average value. For the fibres/lime mix there was insufficient material to make 3 samples for each mix. Photographs of the tested cubes are shown in Figures 58 – 71.

In each of these three groups the graphs are arranged in order of increasing volume fraction of hurds, fibres and sand respectively. The data for these graphs is presented in Appendix B, C and D. Photographs of the tested cylinders are shown in Figures 72 – 84.

Hurds:Lime Mix

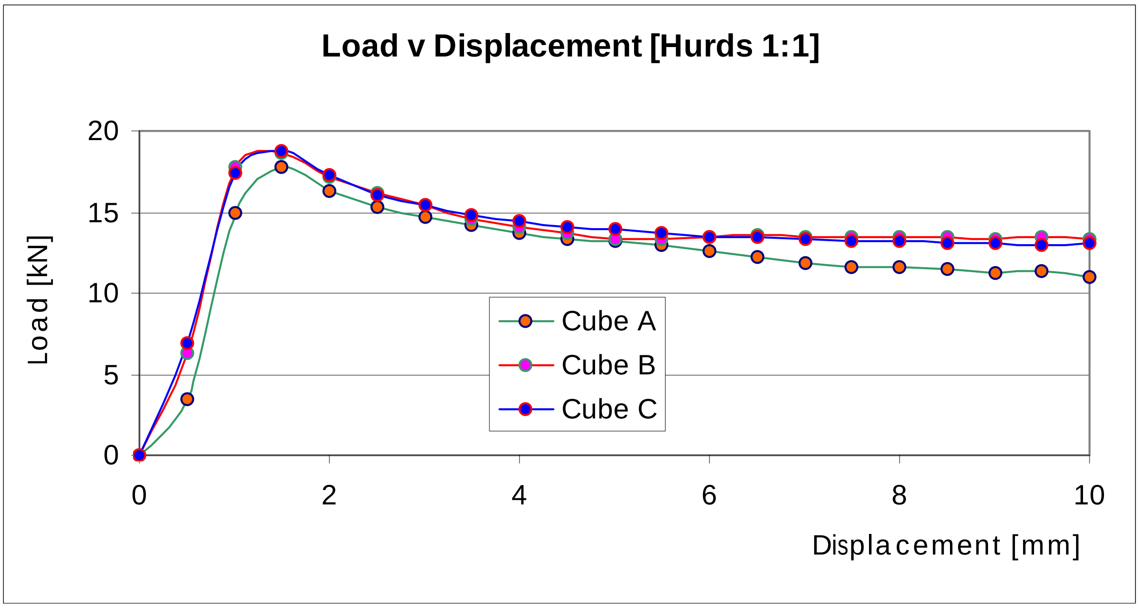


Figure 30: Graph of load versus displacement for hurds:lime, 1:1

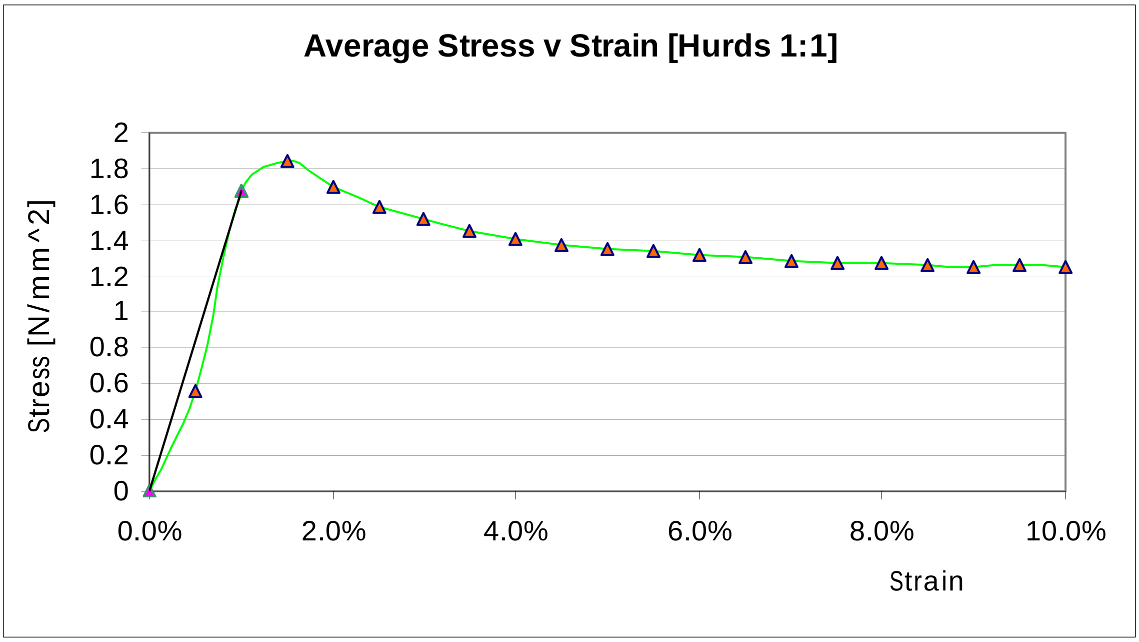


Figure 31: Graph of stress versus strain for hurds:lime, 1:1

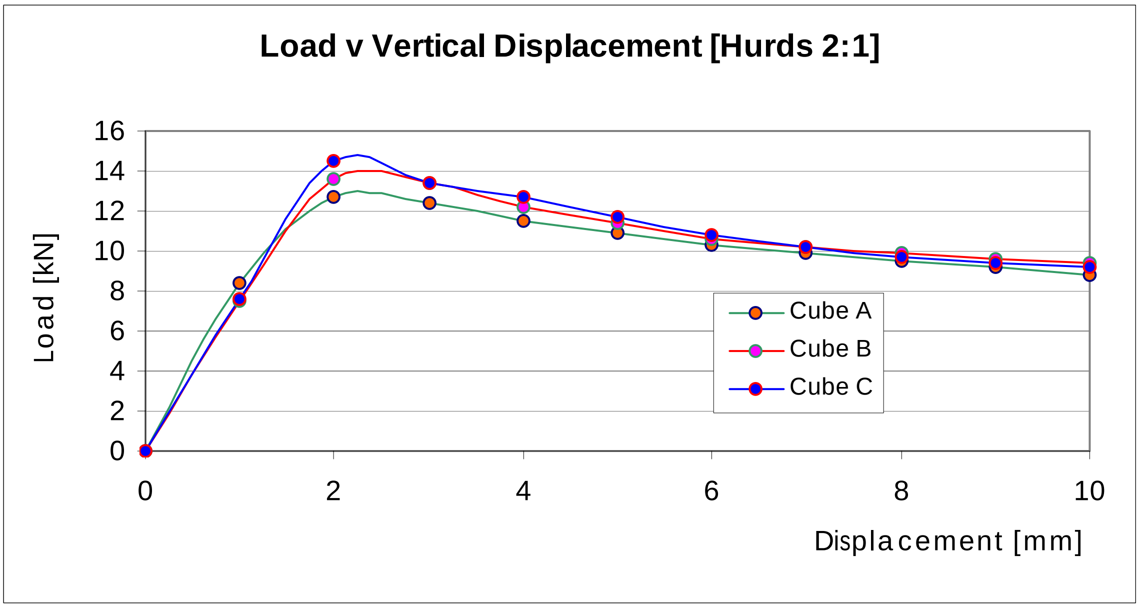


Figure 32: Graph of load versus displacement for hurds:lime, 2:1

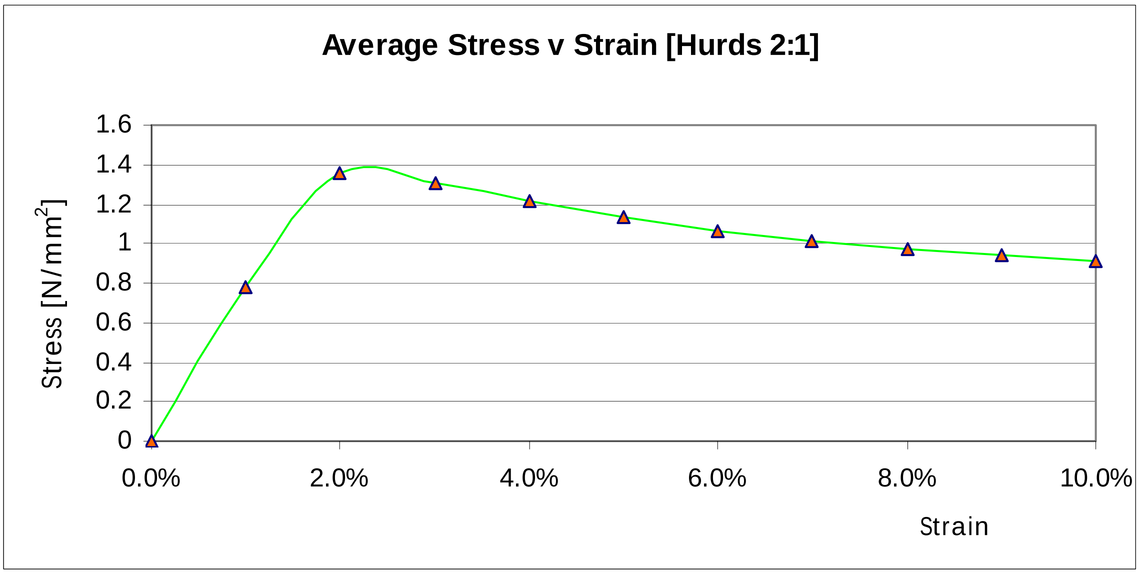


Figure 33: Graph of stress versus strain for hurds:lime, 2:1

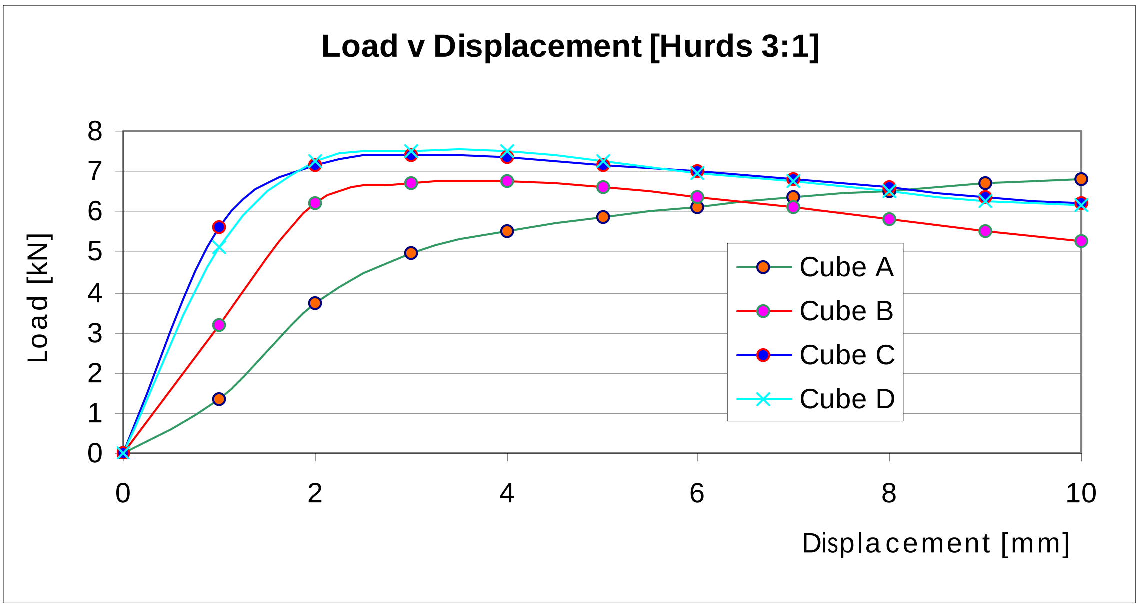


Figure 34: Graph of load versus displacement for hurds:lime, 3:1

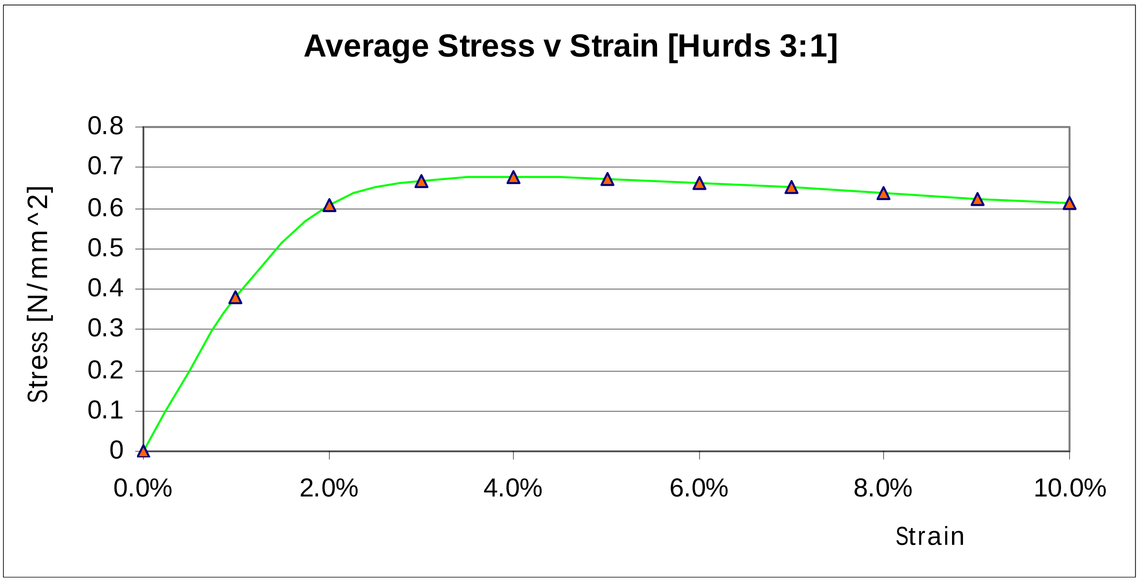


Figure 35: Graph of stress versus strain for hurds:lime, 3:1

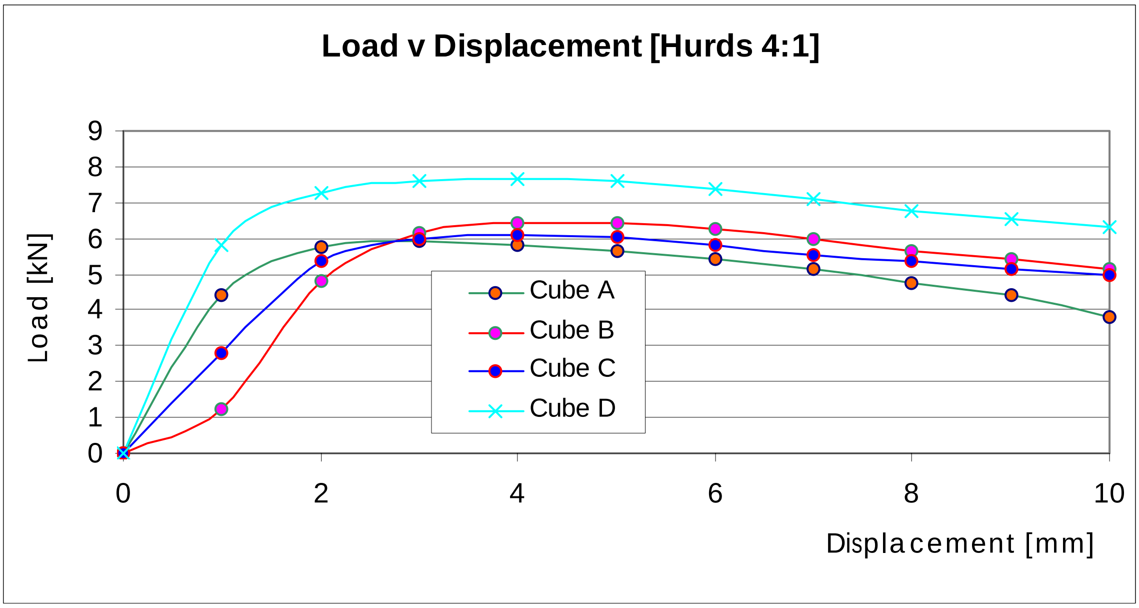


Figure 36: Graph of load versus displacement for hurds:lime, 4:1

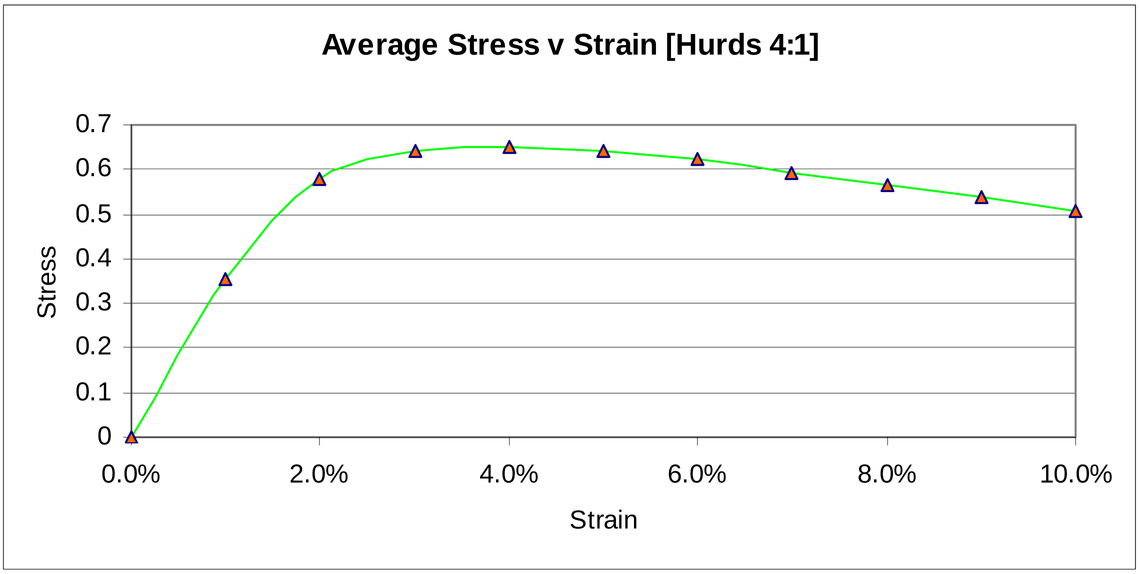


Figure 37: Graph of stress versus strain for hurds:lime, 4:1

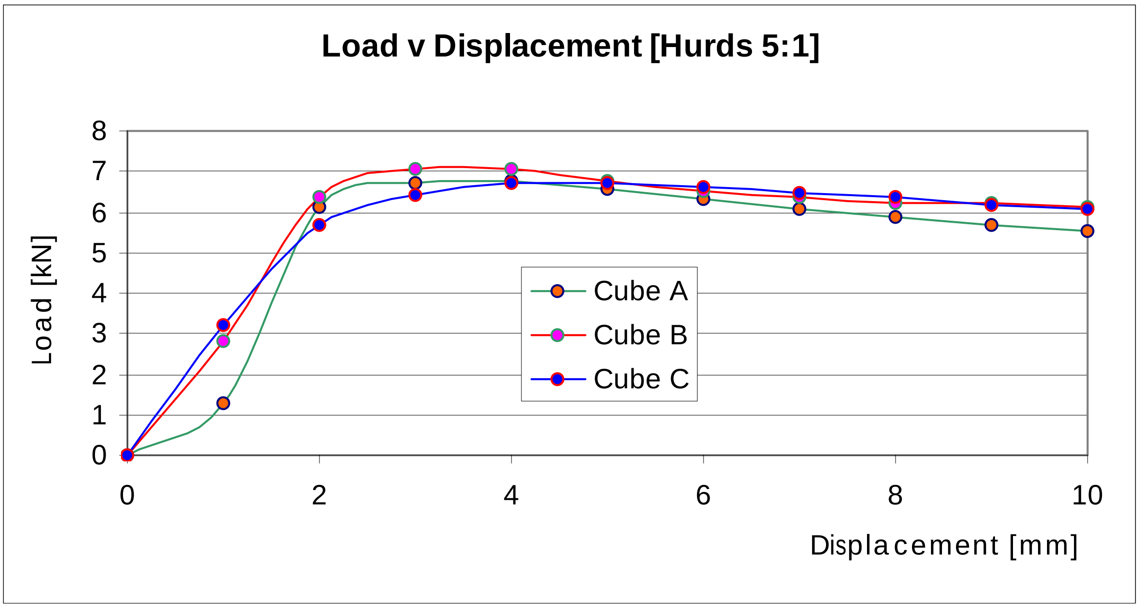


Figure 38: Graph of load versus displacement for hurds:lime, 5:1

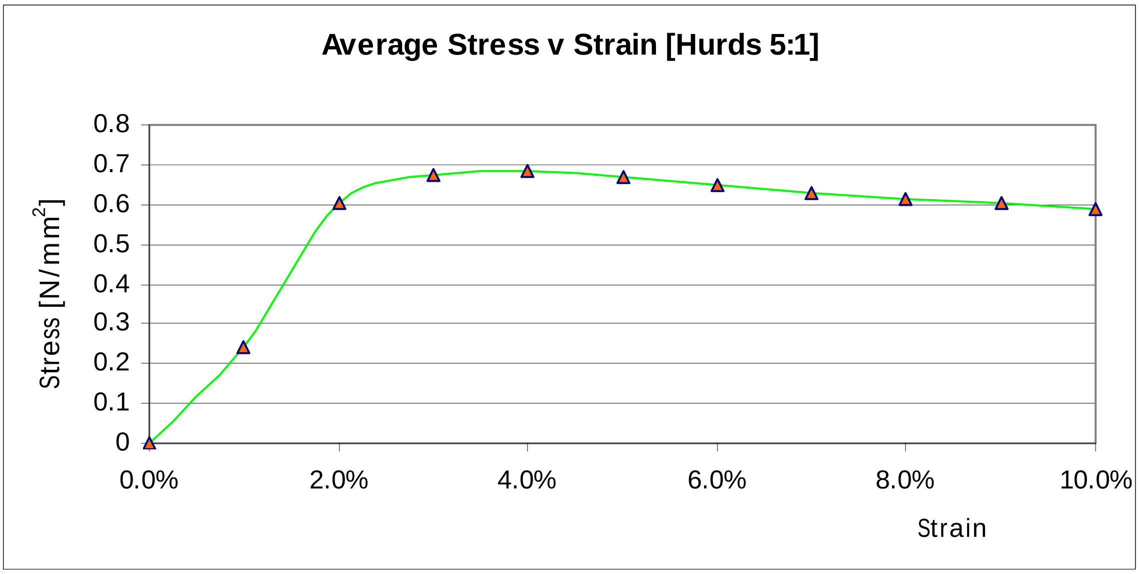


Figure 39: Graph of stress versus strain for hurds:lime, 5:1

Fibre:Lime Mix

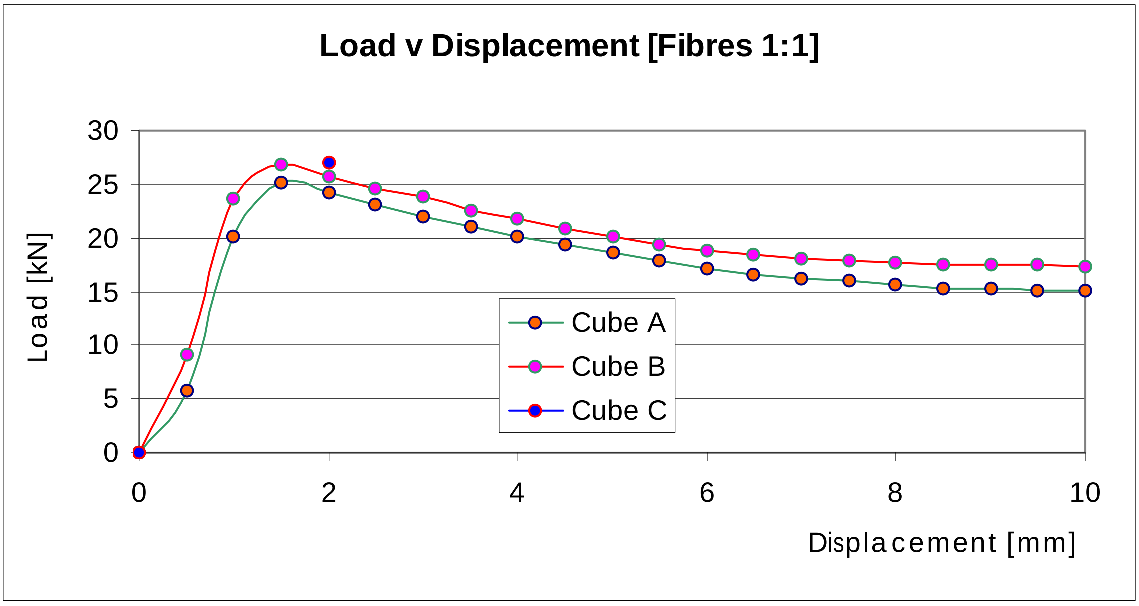


Figure 40: Graph of load versus displacement for fibres:lime, 1:1

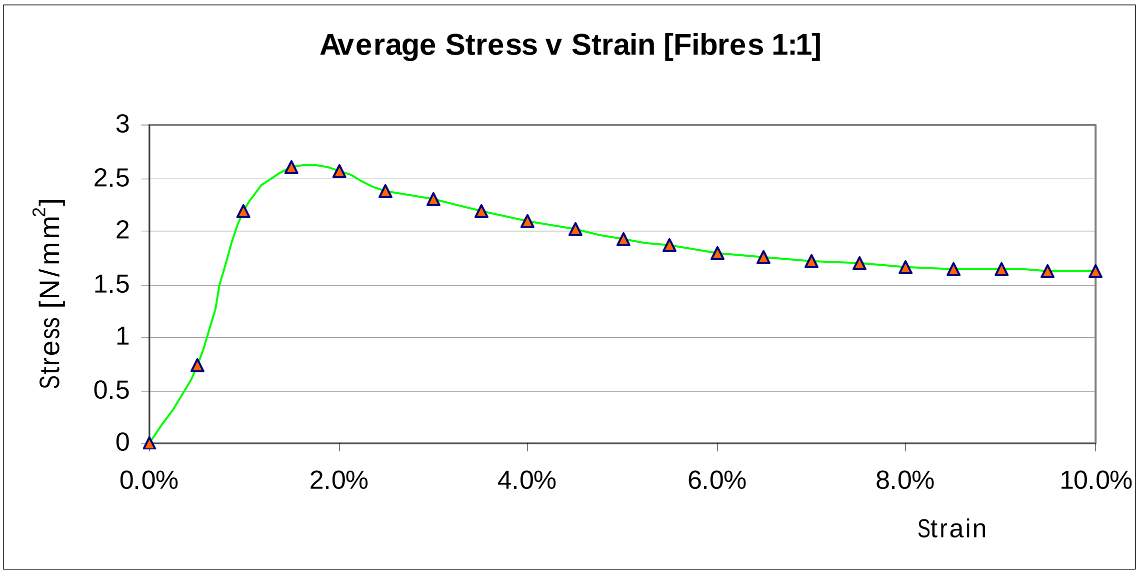


Figure 41: Graph of stress versus strain for fibres:lime, 1:1

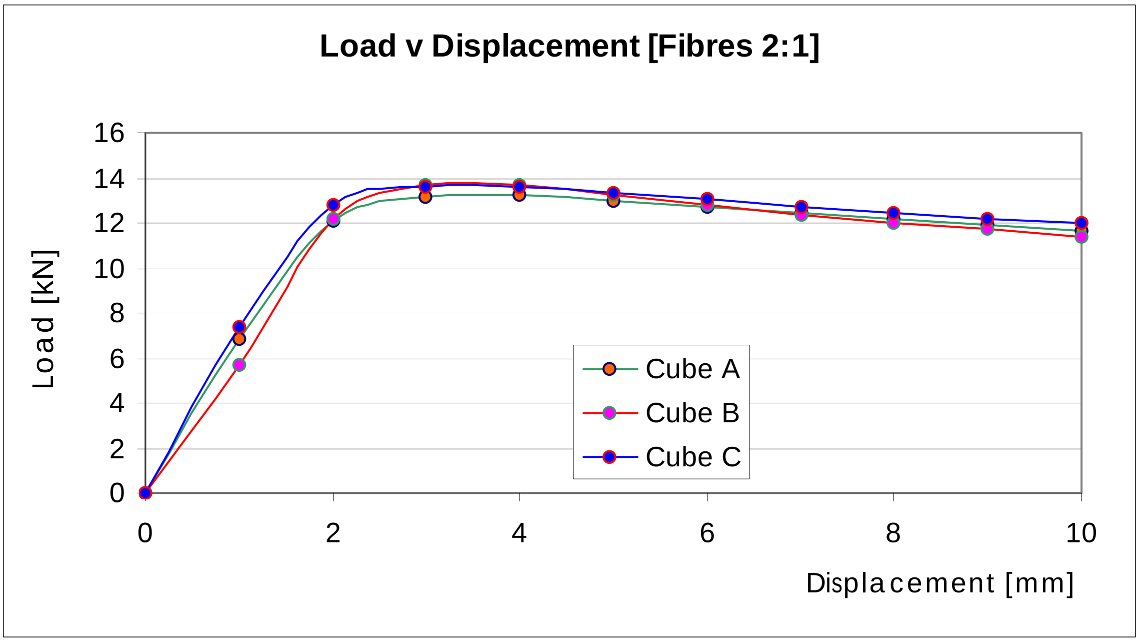


Figure 42: Graph of load versus displacement for fibres:lime, 2:1

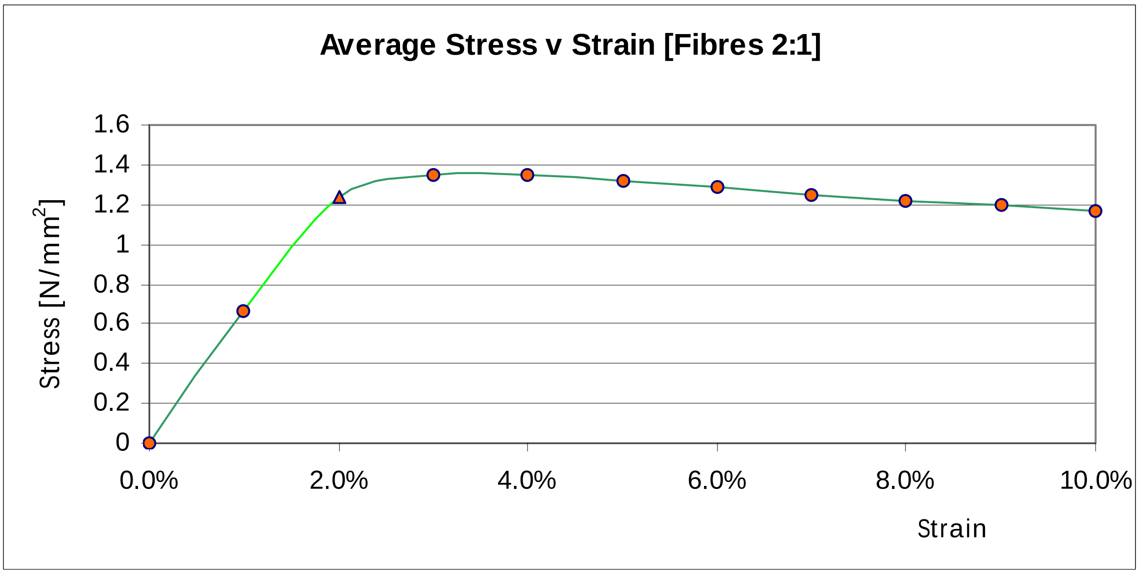


Figure 43: Graph of stress versus strain for fibres:lime, 2:1

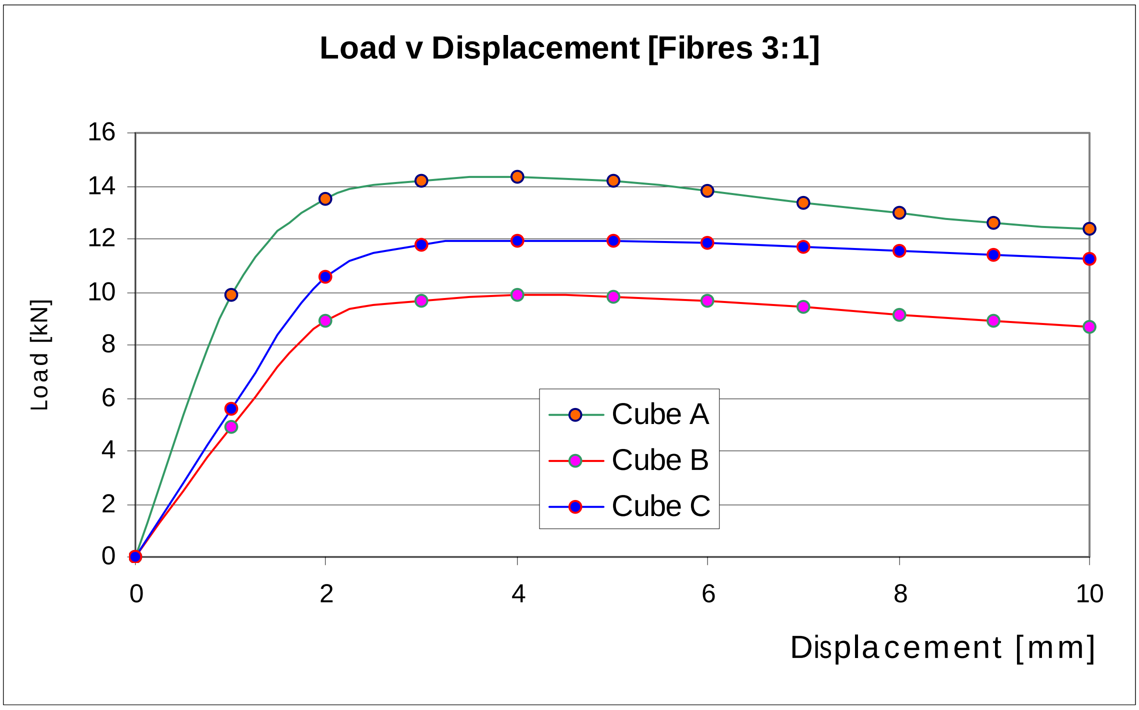


Figure 44: Graph of load versus displacement for fibres:lime, 3:1

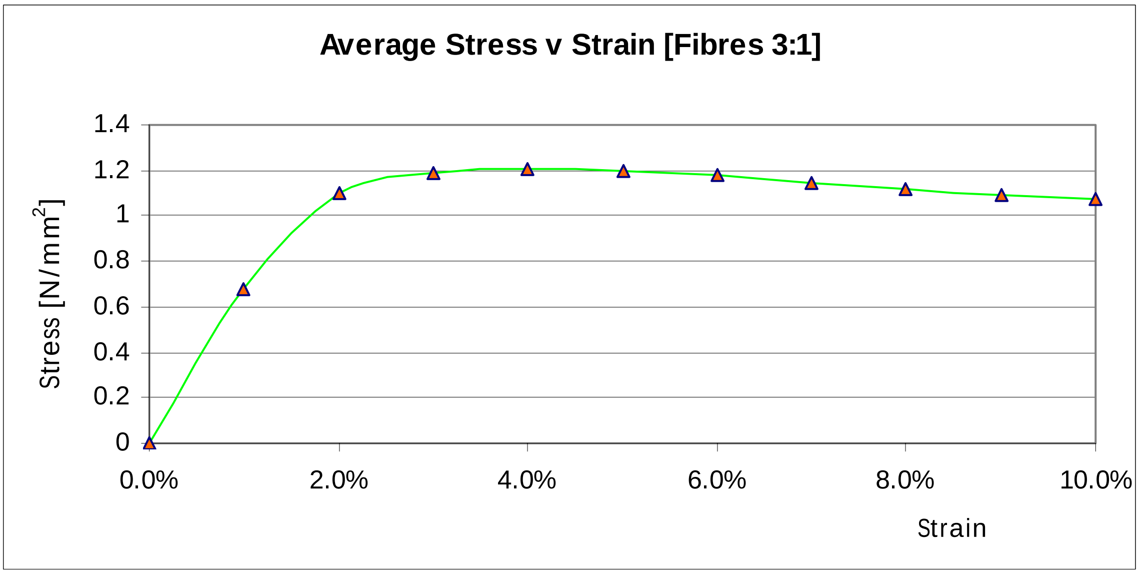


Figure 45: Graph of stress versus strain for fibres:lime, 3:1

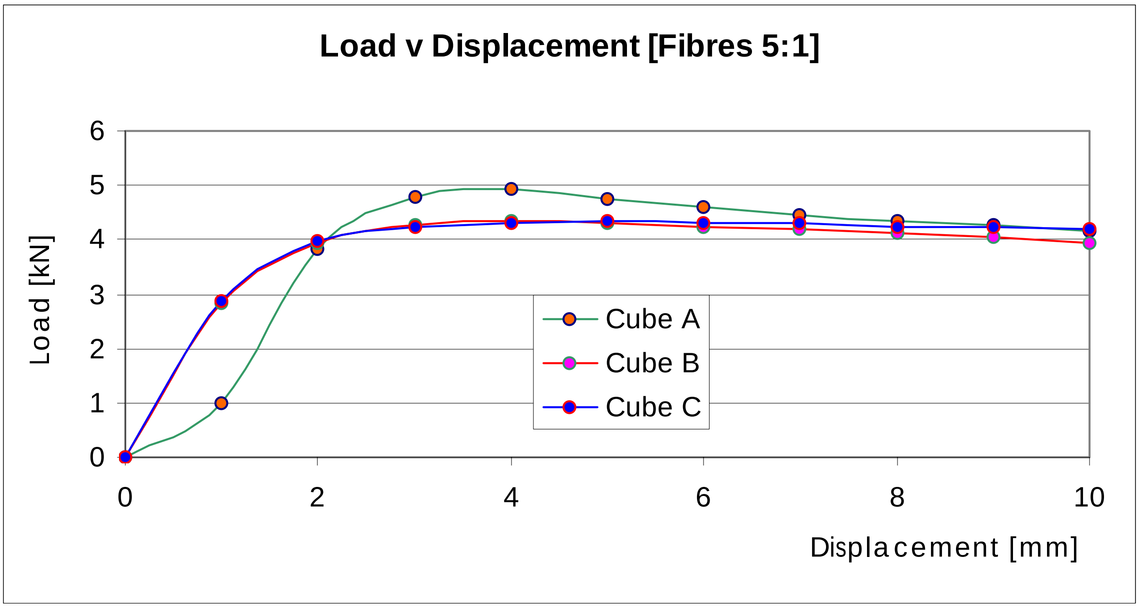


Figure 46: Graph of load versus displacement for fibres:lime, 5:1

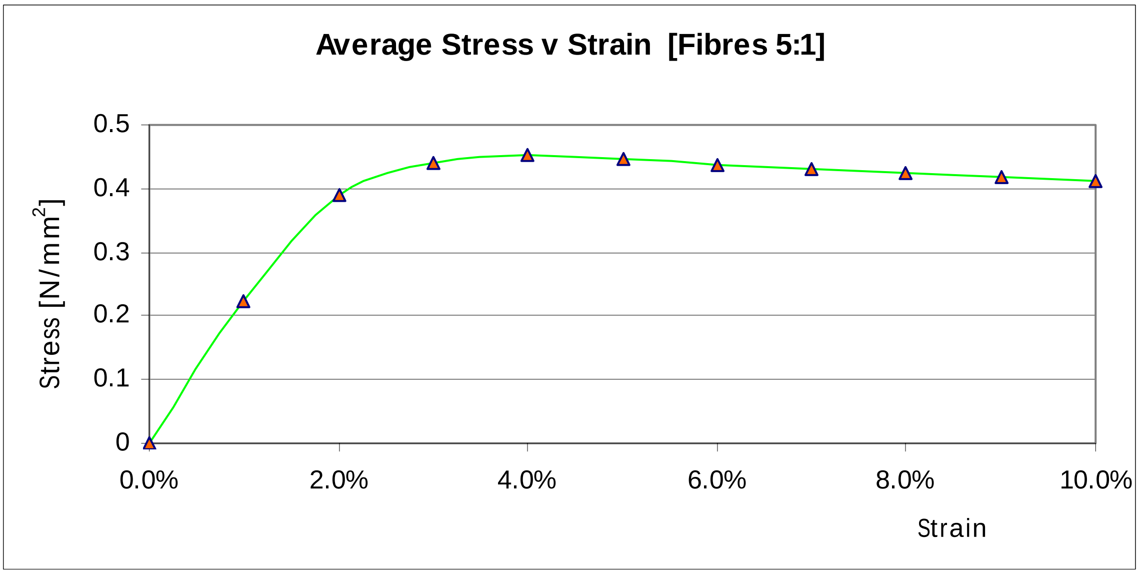


Figure 47: Graph of stress versus strain for fibres:lime, 5:1

Hurds:Lime:Sand

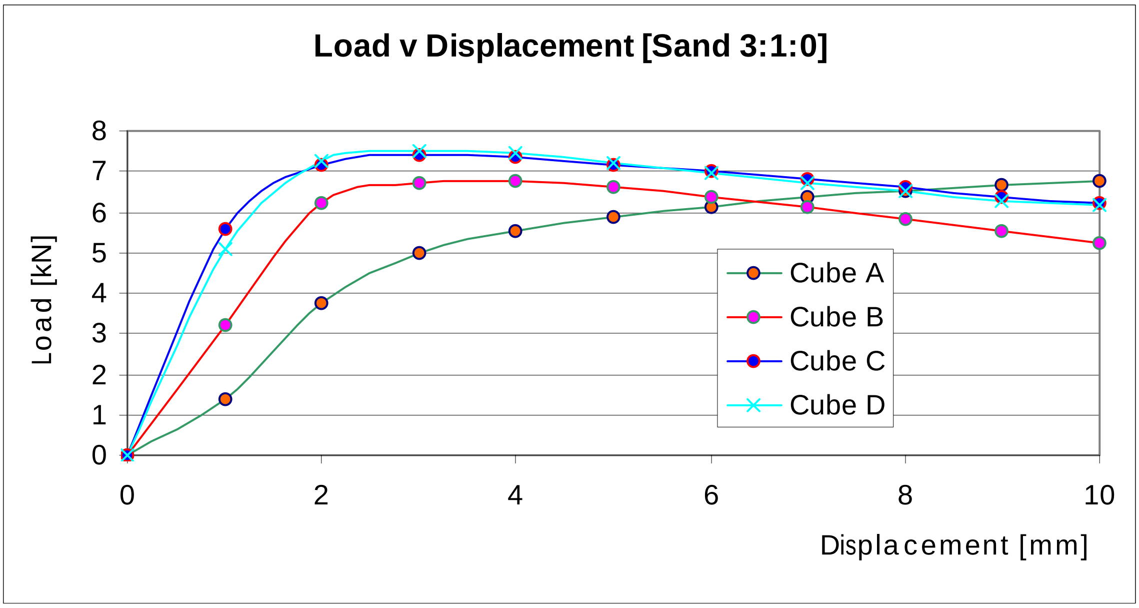


Figure 48: Graph of load versus displacement for hemp:lime:sand, 3:1:0

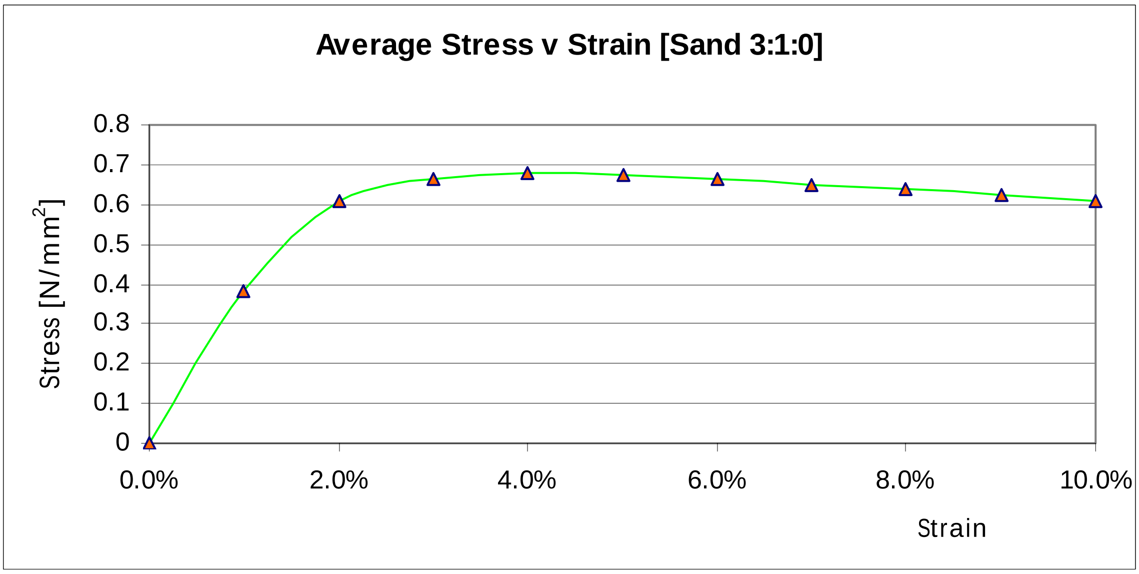


Figure 49: Graph of stress versus strain for hemp:lime:sand, 3:1:0

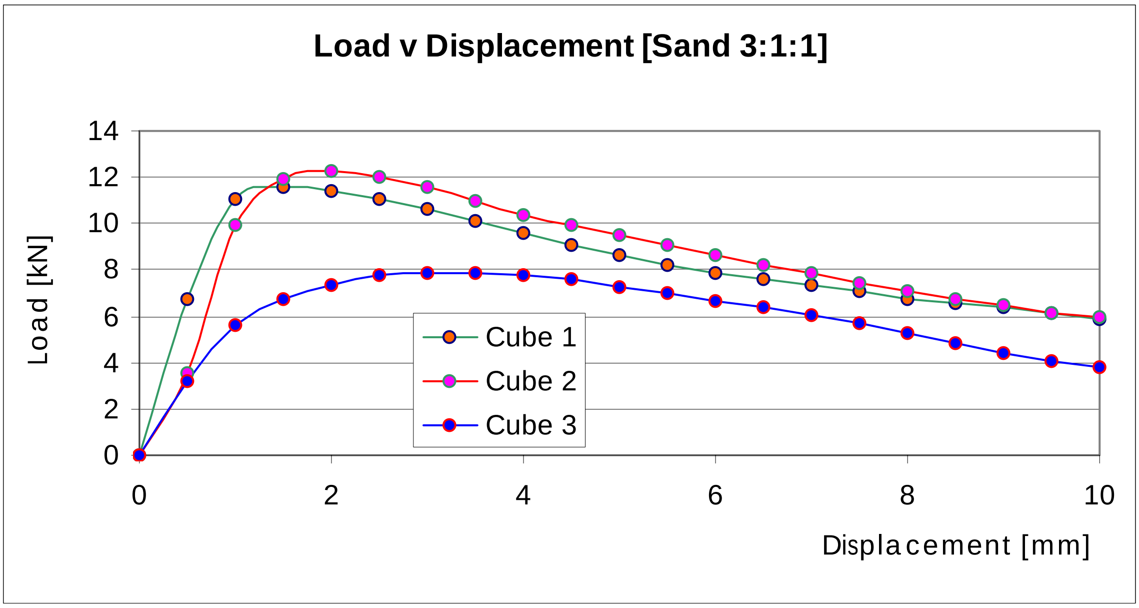


Figure 50: Graph of load versus displacement for hemp:lime:sand, 3:1:1

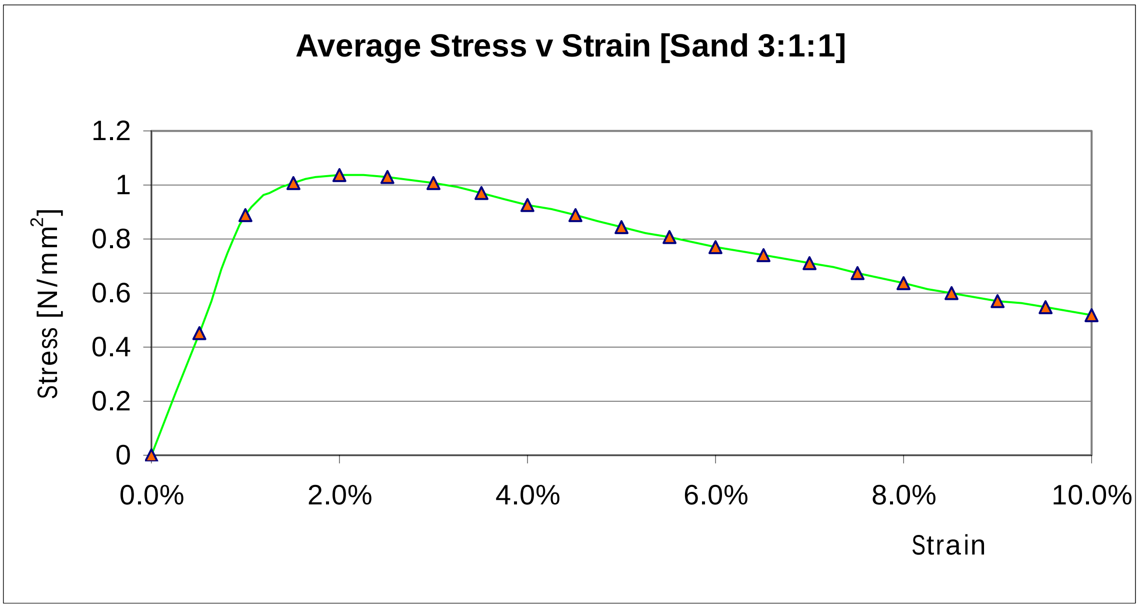


Figure 51: Graph of stress versus strain for hemp:lime:sand, 3:1:1

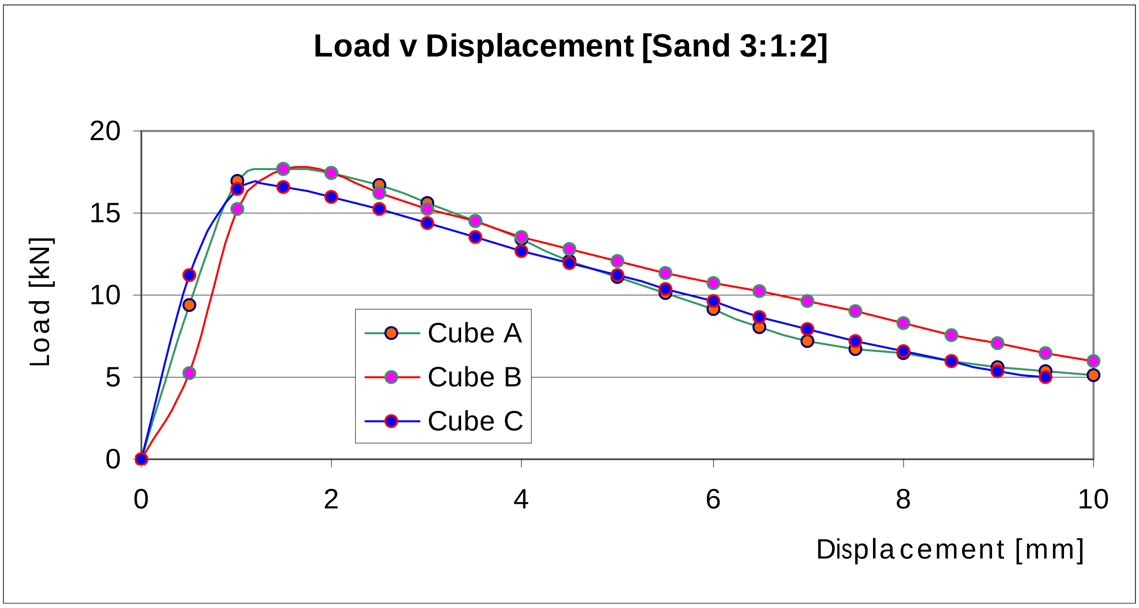


Figure 52: Graph of load versus displacement for hemp:lime:sand, 3:1:2

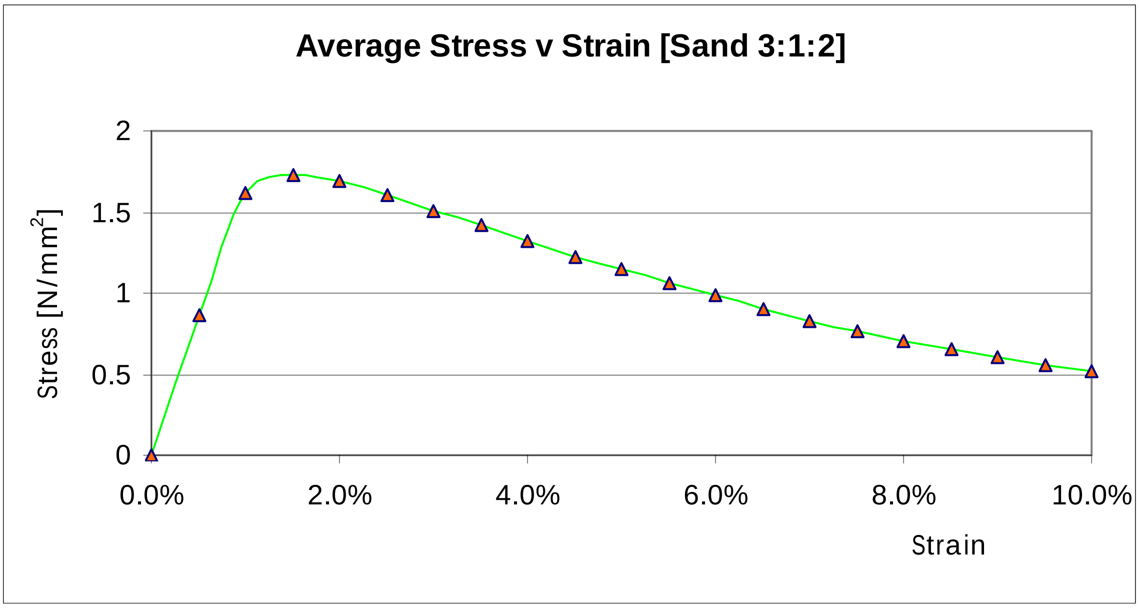


Figure 53: Graph of stress versus strain for hemp:lime:sand, 3:1:2

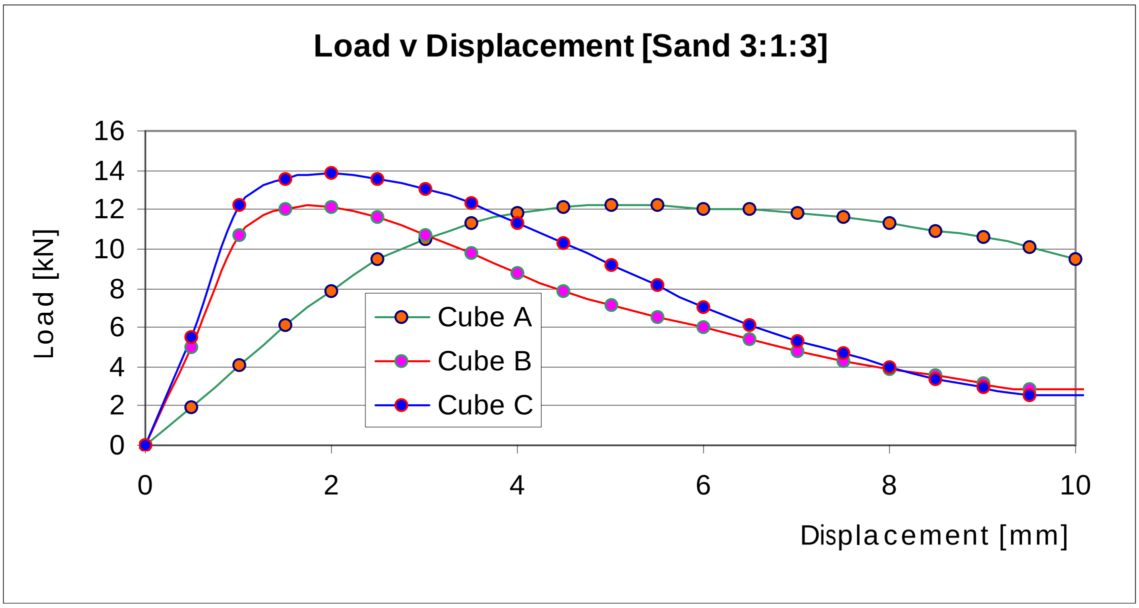


Figure 54: Graph of load versus displacement for hemp:lime:sand, 3:1:3

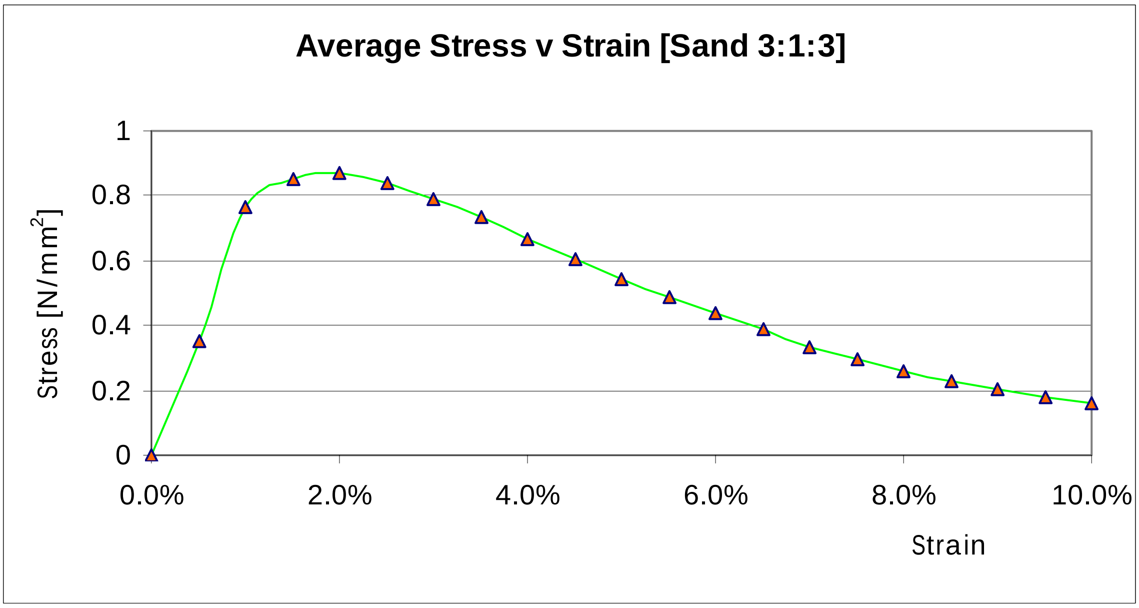


Figure 55: Graph of stress versus strain for hemp:lime:sand, 3:1:3

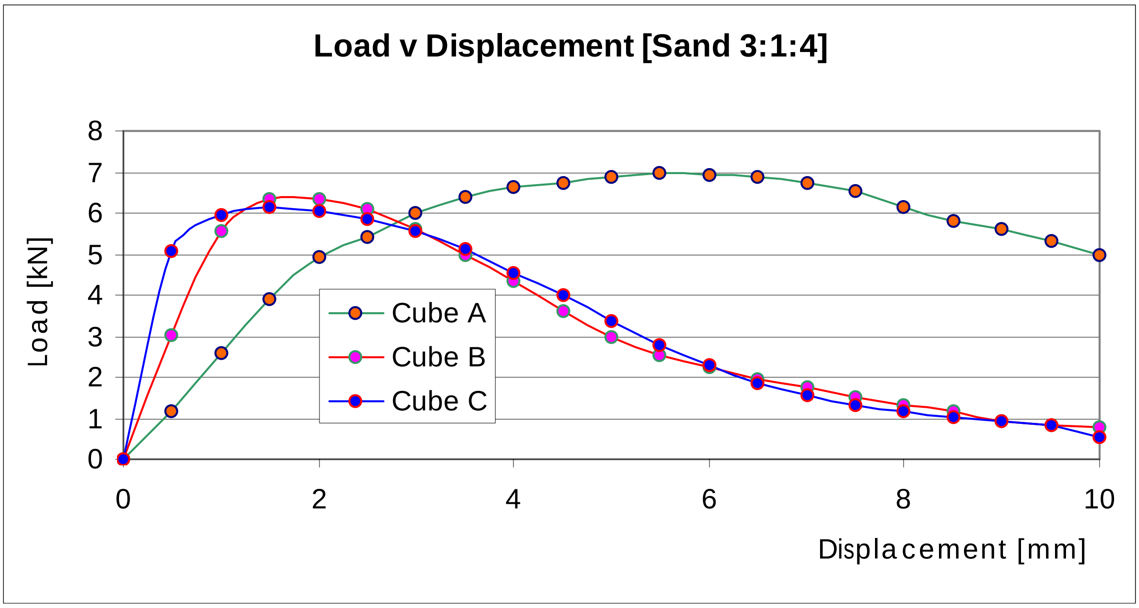


Figure 56: Graph of load versus displacement for hemp:lime:sand, 3:1:4

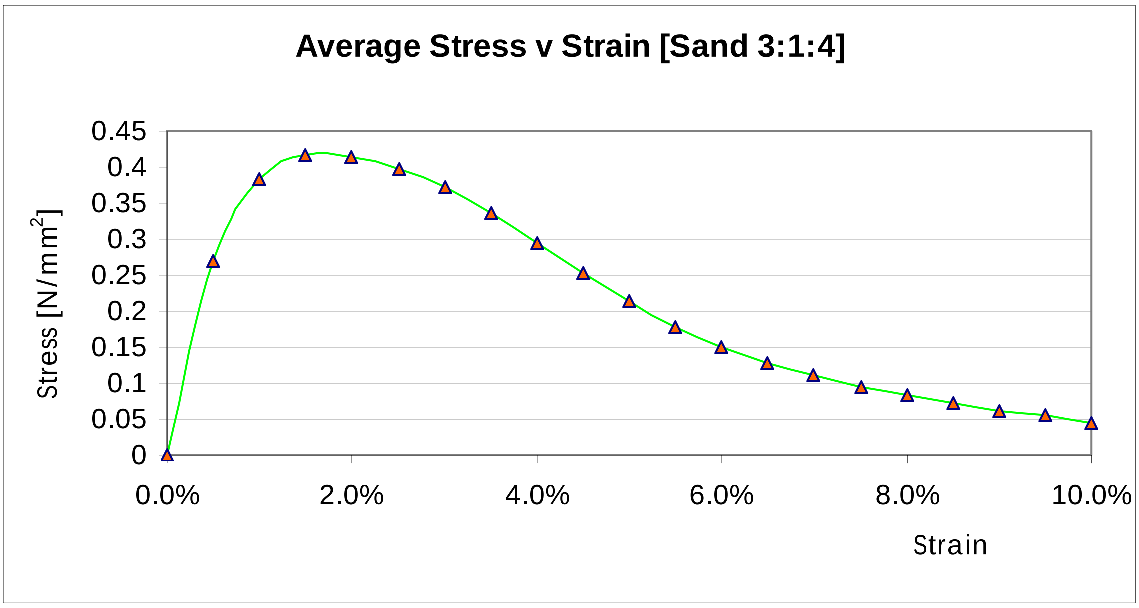


Figure 57: Graph of stress versus strain for hemp:lime:sand, 3:1:4

Figure 58: Hurds 1:1

Figure 59: Hurds 2:1

Figure 60: Hurds 3:1

Figure 61: Hurds 4:1

Figure 62: Hurds 5:1

Figure 63: Fibres 1:1

Figure 64: Fibres 2:1

Figure 65: Fibres 3:1

Figure 66: Fibres 5:1

Figure 67: Sand 3:1:1

Figure 68: Sand 3:1:2

Figure 69: Sand 3:1:3

Figure 70: Sand 3:1:4

Figure 71: Pure lime

Table 8: Results of tensile tests for hurd/lime mixes

Hurd Mix	Cylinder No.	Density [kg/m^3]	Force [kN]	Tensile Strength [N/mm^2]
1:1	1	1266.30	10.79	0.23
	2	1260.70	10.62	0.23
	3	1280.80	9.92	0.21
	Average	***1269.27***	***10.44***	***0.22***
2:1	4	1101.10	11.19	0.24
	5	1099.40	11.70	0.25
	6	1082.20	9.20	0.20
	Average	***1094.23***	***10.70***	***0.23***
3:1	7	871.00	6.15	0.13
	8	863.00	7.09	0.15
	9	862.70	8.07	0.17
	Average	***865.57***	***7.10***	***0.15***
4:1	10	719.50	5.36	0.11
	11	702.10	5.80	0.12
	12	720.90	6.08	0.13
	Average	***714.17***	***5.75***	***0.12***
5:1	16	640.50	4.52	0.10
	17	644.80	6.17	0.13
	18	671.70	6.35	0.13
	Average	***652.33***	***5.68***	***0.12***

Table 9: Results of tensile tests for fibre/lime mixes

Mix	Cylinder No.	Density [kg/m^3]	Force [kN]	Tensile Strength [N/mm^2]
1:1	29	1353.20	11.41	0.24
	30	1345.80	12.53	0.27
	31	1296.70	12.00	0.25
	Average	**1331.90**	**11.98**	**0.25**
2:1	28	1118.00	8.66	0.18
	-	-	-	-
	-	-	-	-
	Average	***1118.00***	***8.66***	***0.18***
3:1	32	941.10	7.95	0.17
	33	889.50	5.27	0.11
	34	912.80	6.06	0.13
	Average	***914.47***	***6.43***	***0.14***
5:1	35	692.00	4.30	0.09
	36	697.90	3.70	0.08
	37	684.90	3.56	0.08
	Average	***691.60***	***3.85***	***0.08***

Table 10: Results of tensile tests for hurd/lime/sand mixes

Mix	Cylinder No.	Density [kg/m^3]	Force [kN]	Tensile Strength [N/mm^2]
3:1:1	13	1267.70	5.60	0.12
	14	1273.80	5.71	0.12
	15	1282.30	5.60	0.12
	Average	***1274.60***	***5.64***	***0.12***
3:1:2	19	1719.00	7.68	0.16
	20	1701.50	8.90	0.19
	21	1706.00	6.88	0.15
	Average	***1708.83***	***7.82***	***0.17***
3:1:3	22	1933.50	8.33	0.18
	23	1870.00	8.00	0.17
	24	1831.70	8.30	0.18
	Average	***1878.40***	***8.21***	***0.17***
3:1:4	25	1836.00	5.00	0.11
	26	1912.10	3.00	0.06
	27	1884.00	1.41	0.09
	Average	***1877.37***	***4.71***	***0.10***

Table 11: Results of tensile tests for lime mix

Mix	Cylinder No.	Density [kg/m^3]	Force [kN]	Tensile Strength [N/mm^2]
1:0	1	2321.00	13.95	0.30
	2	2451.00	14.38	0.31
	3	2204.00	11.63	0.25
Average		***2325.33***	***13.32***	***0.28***




Figure 72: Hurds 1:1




Figure 73: Hurds 2:1

Figure 74: Hurds 3:1

Figure 75: Hurds 4:1

Figure 76: Hurds 5:1

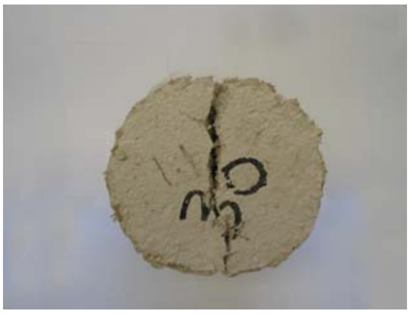


Figure 77: Fibres 1:1

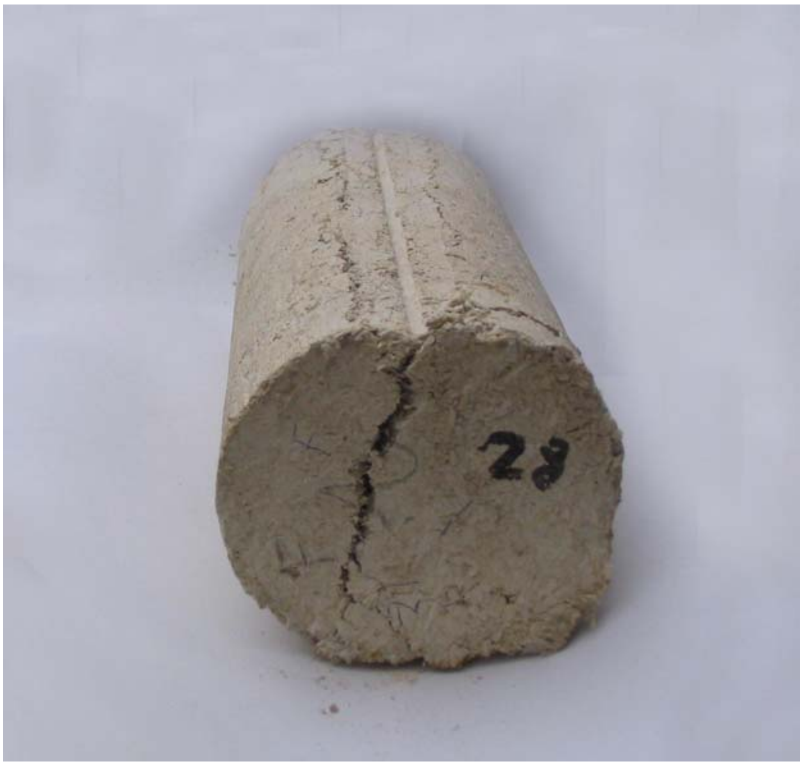


Figure 78: Fibres 2:1

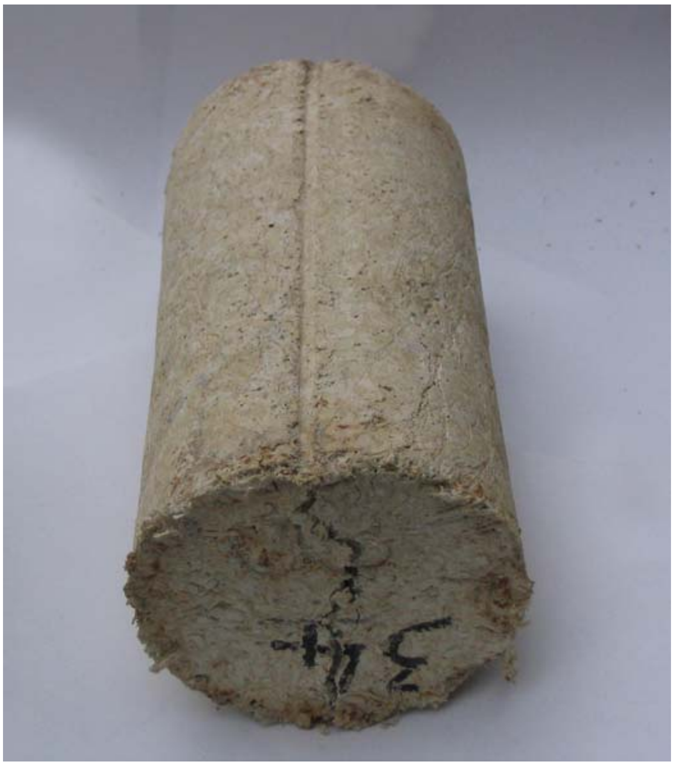


Figure 79: Fibres 3:1

Figure 80: Fibres 5:1

Figure 81: Sand 3:1:1

Figure 82: Sand 3:1:2




Figure 83: Sand 3:1:3




Figure 84: Sand 3:1:4

6 DISCUSSION OF RESULTS

6.1 Introduction to Analysis

The properties of the compressive and tensile strength of the material are analysed in the following sections. For a specific mix, the thermal conductivity is estimated and the elemental U-value is calculated. Based on this mix the typical loads for a dwelling are calculated and examined. The energy required to process this material for construction is also considered.

6.2 Analysis of Graphs

A pure lime mix has the highest compressive strength of 11.2 N/mm^2 (Figure 85 and Figure 87). The strength of the material decreases with the addition of hemp hurds and/or fibres. Figure 85 illustrates the relationship of the compressive strength plotted against the volume fraction of hemp hurds. This demonstrates that a 3:1 hemp/lime mix is similar in strength to a 4:1 and 5:1 mix, with a compressive strength of 0.7 N/mm^2. This is of interest as the higher the volume fraction of hurds used, the lower the density of the material and correspondingly the lower the thermal conductivity. This mix also uses less lime which is beneficial for the

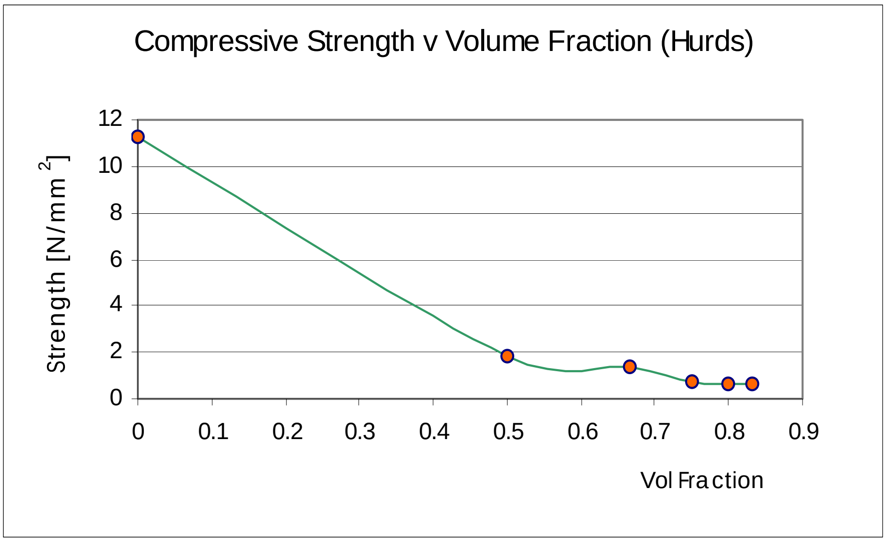


Figure 85: Graph showing compressive strength of cube versus volume fraction of hurds

environment in terms of pollution reduction, energy conservation and cost, as it has a high embodied energy. An enlarged section of the graph (Figure 86) illustrates the strength of the 3:1, 4:1 and 5:1 hurd/lime mixes. Based on this result, a 5:1 mix uses the material in the most efficient way, as it has the strength of a 3:1 mix, but the lower thermal conductivity of a 5:1 mix.

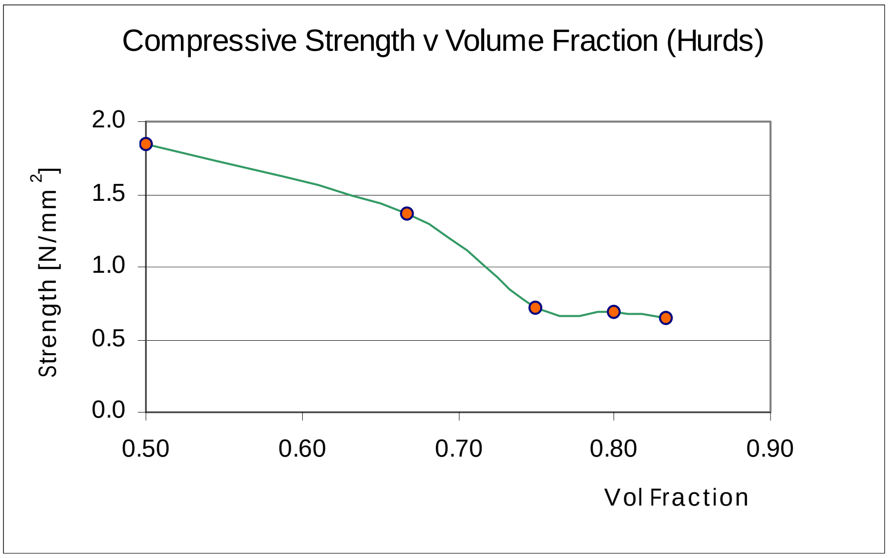


Figure 86: Graph showing enlarged section of Figure 85

Figure 87 shows the relationship between the compressive strength and the volume fraction of fibres (enlarged section is shown in Figure 88). The material decreases in strength with the addition of fibres. A mix of 3:1 has a compressive strength of 1.35 N/mm^2 with a density of

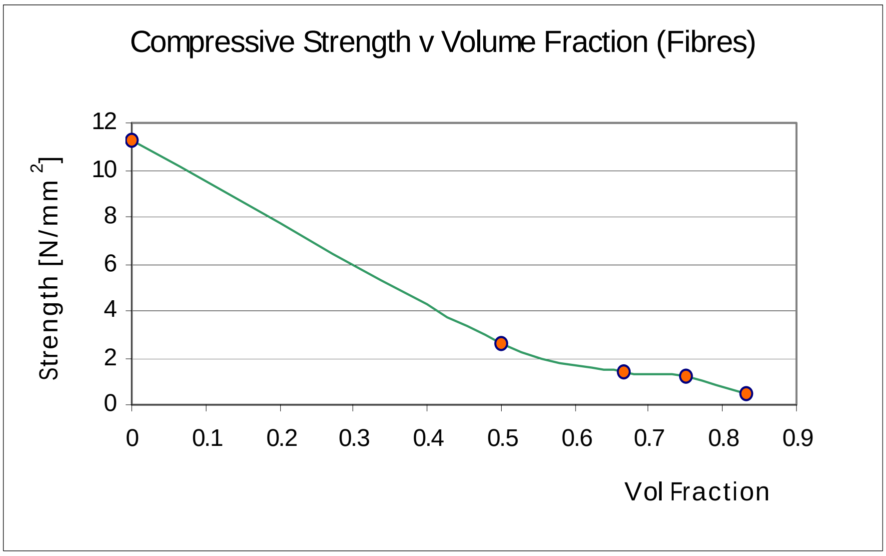


Figure 87: Graph showing compressive strength of cube versus volume fraction of hemp fibres

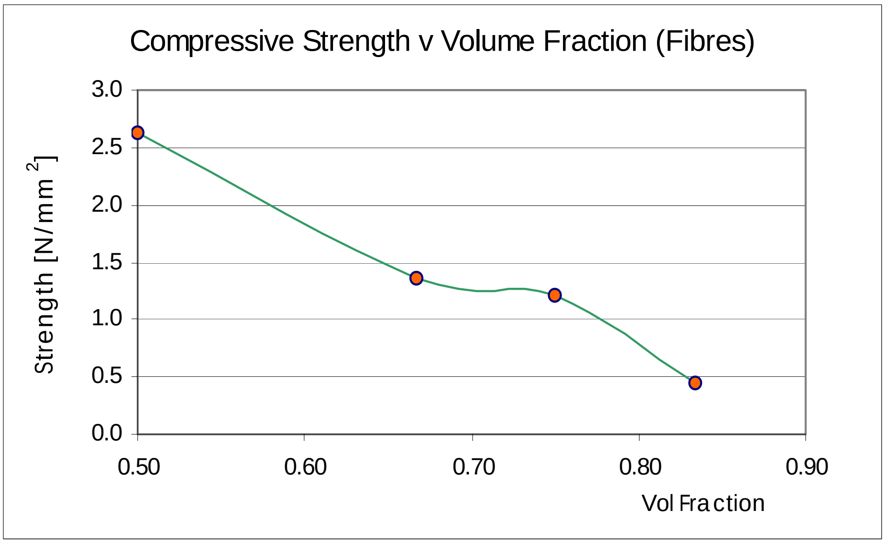


Figure 88: Graph showing enlarged section of Figure 87

914 kg/m^3. A 3:1 hurd/lime mix has a strength 0.71 N/mm^2 and density of 567 kg/m^3. However, the fibre mix has 54% more lime in the sample than the hurd mix. This explains the difference in compressive strengths of the mixes. Overall the lime/fibre mix is weaker when compared with the hurd mix, as for similar densities the fibre mix is weaker. This is probably due to the dust from the plant occupying a large volume of the hemp hurd and fibre mix. This dust does not have any compressive strength and makes up 15% of the volume of the processed material (Nova- Istitut 2003). Also, the 5:1 fibre mix is more dense than its respective hurd mix (465 and 425 kg/m^3 – a difference of 40 kg/m^3). Figure 89 illustrates that a 5:1 hurds/lime mix gives a greater maximum compressive strength than a 5:1 fibres/lime mix. For equivalent densities, the hemp fibre mix is weaker. It is thought that this is due to the fibre mix not having the same type of cellular void space as the hurds, which allows air to be

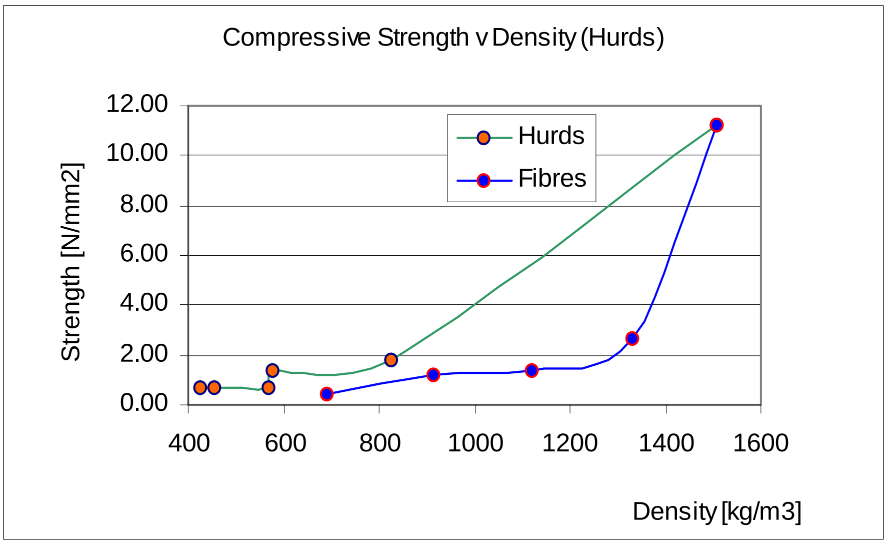


Figure 89: Compressive strength versus density of hurds and fibres

trapped within the cells, thus strengthening the material. Figure 90 shows the relationship between the compressive strength of the sand mix plotted against the volume fraction of sand. There is a clear optimum strength where the graph reaches a peak of 1.7 N/mm^2 for a 3:1:2 mix. A possible interpretation of this is that there is an optimum binder/aggregate ratio for lime of 1:5. It would be necessary to measure the strength of a 1:6 and 1:7 mix of hurds and

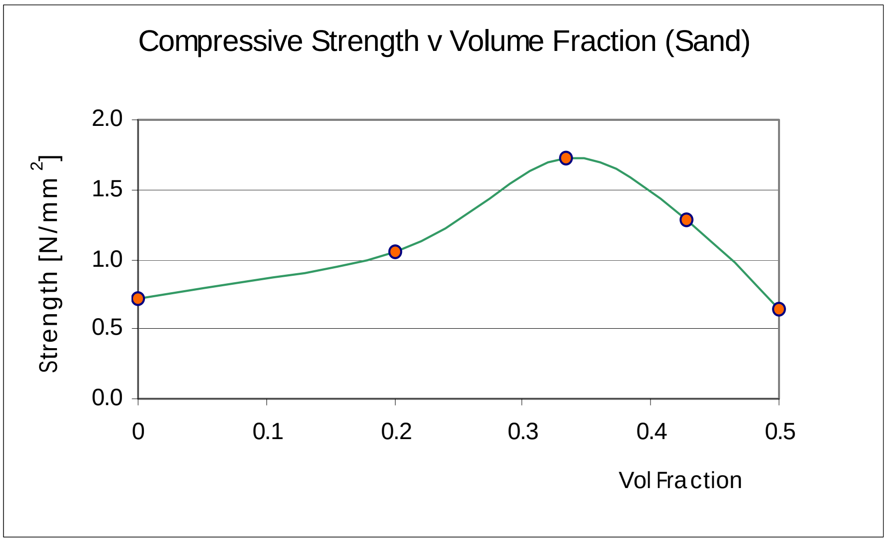


Figure 90: Compressive strength versus volume fraction of sand

lime to confirm this prediction. This strength is achieved at a density of 1088 kg/m^3 which gives a high estimated value of thermal conductivity. Figure 91, which shows the relationship between density and compressive strength, shows that a 3:1:2 mix has an optimum strength at a density of 1088 kg/m^3.

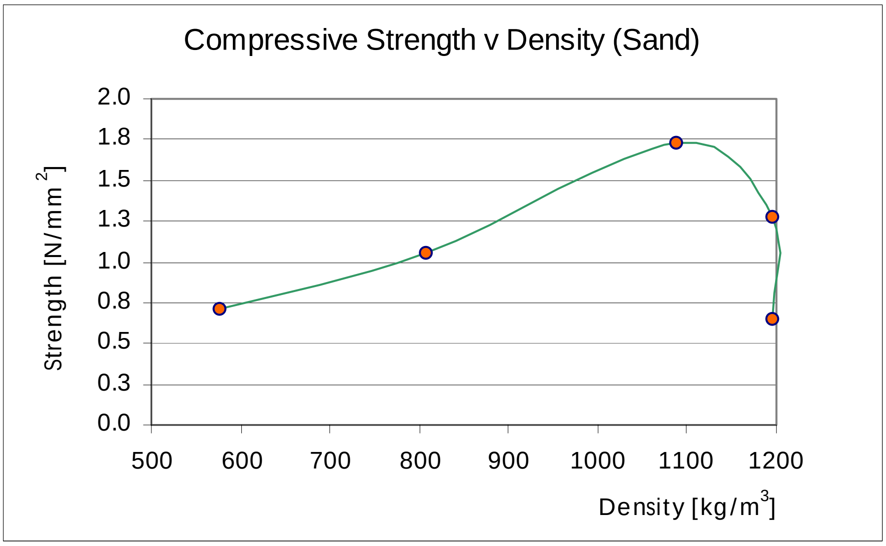


Figure 91: Compressive strength v density of sand mix

6.3 Tensile Strength

Figures 92 and 93 show that a pure lime mix has the strongest tensile strength of any of the above mixes. For a combination of materials, a 2:1 mix has an optimum tensile strength for a hurd/lime mix. It was thought that the addition of hurds and/or fibres would increase the tensile strength. This was not the case. It is possible that the lime did not bond well enough with the hemp to increase the tensile strength of the material. As the cylinders split, it appeared that the material was pulled from the lime binder and that the hemp material did not fail.

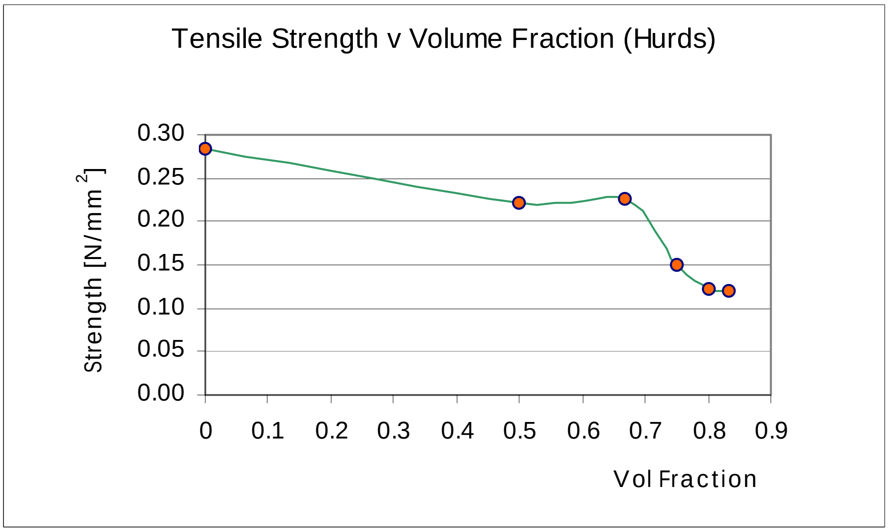


Figure 92: Tensile strength versus volume fraction of hurds

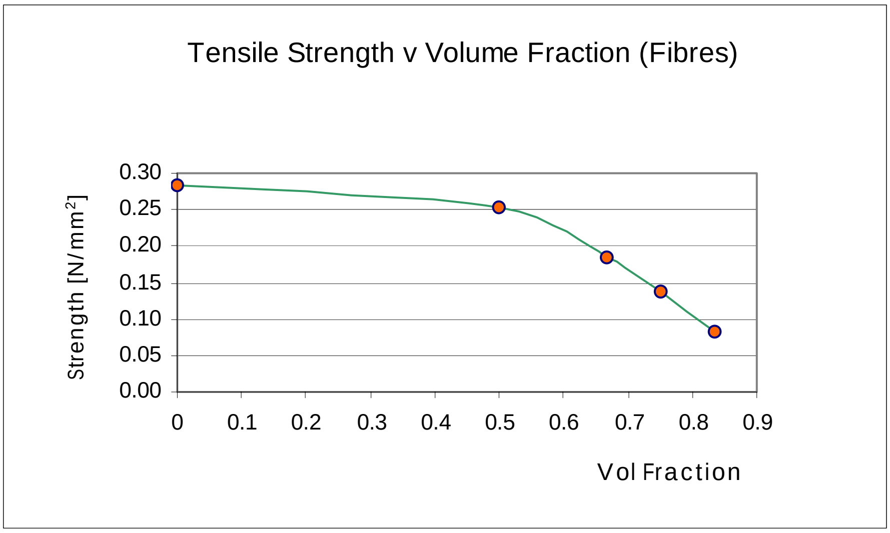


Figure 93: Tensile strength versus volume fraction of fibres

There is no clear optimum strength for the lime/fibre mix (Figure 93). During testing, for high volume fractions of hurds and fibres, the cylinders deformed significantly before failure (Figures 72 – 84). This may have led to slight inaccuracies in measuring the maximum value before failure, as the load was acting over a larger area than was initially applied.

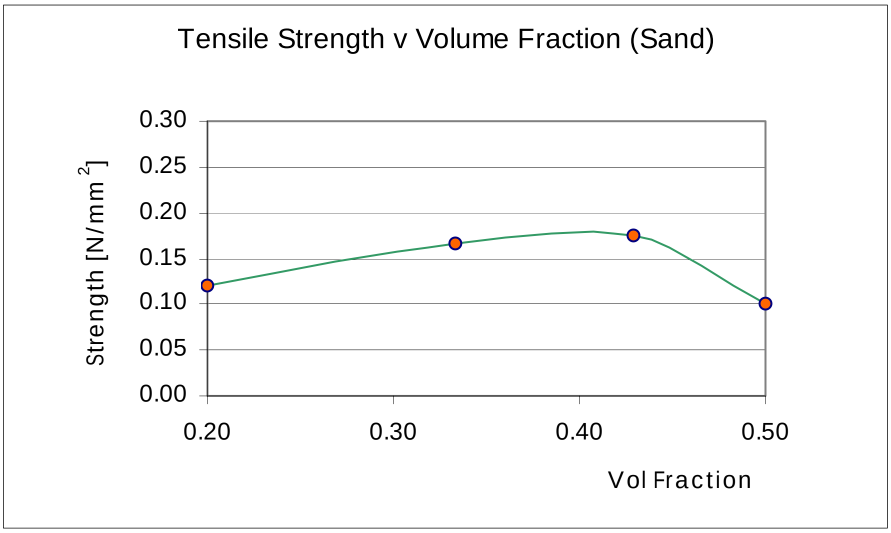


Figure 94: Tensile strength versus volume fraction of sand

A sand mix of 3:1:3 had the highest tensile strength (0.17 N/mm^2) for the mixes of hemp/lime/sand (Figure 94).

The overall tensile strength values are quite low for all of the mixes tested. The fibre/lime mix is not significantly stronger than the hurd mix, as was originally expected due to the strength of the fibres. This could be due to the lime not bonding well with the fibres, or the overall short length of the fibres (they were roughly 2.5 cm long). The strength of the material increases proportionally with density, with the exception of the sand mix. This may be due to the maximum binder/aggregate ratio being reached as previously mentioned in the compressive test results.

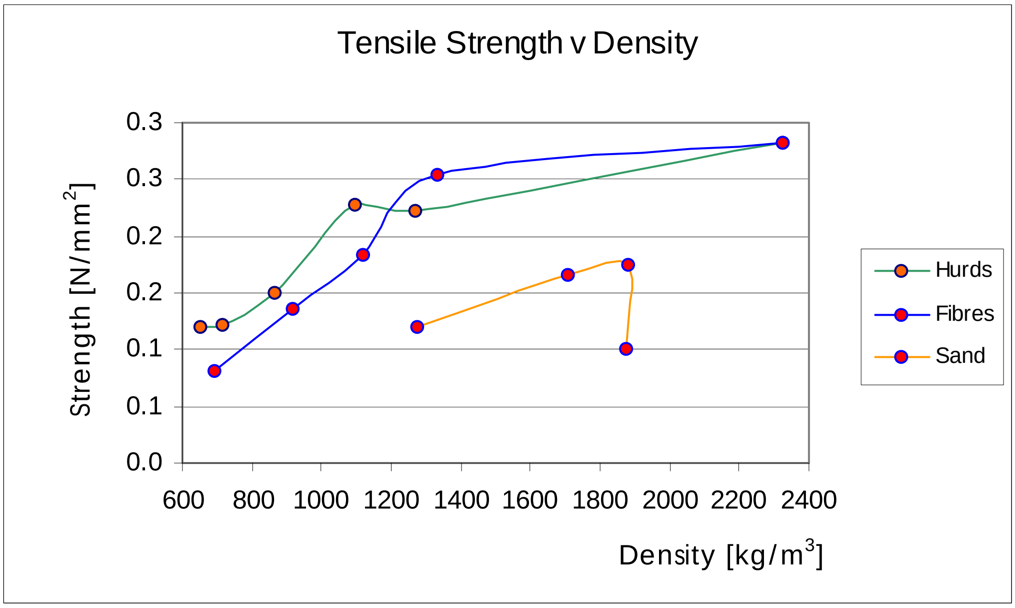


Figure 95: Tensile strength versus density of hurd, fibre and sand mixes

Figure 95 shows the relationship between tensile strength and density for the three tested variations i.e. hurds, fibres and sand. For both the hurd and fibre mixes, the strength increased proportionally with density (due to the addition of lime). The hurd/lime/sand mix reached a maximum strength at a density of 1088 kg/m^3 before a decrease in strength occurred.

Determination of Young's Modulus

Young's modulus of the material was calculated using the graph of average compressive stress versus strain, at 1%. The slope of the line between the stress at zero strain and the stress at 1% strain is plotted (Figure 31). Young's modulus is calculated from the slope of this line for each mix and these values are shown in Table 12.

Table 12: Value of Young's moduli for various mixes

Mix	Hurds [MPa]	Mix	Fibres [MPa]	Mix	Sand [MPa]
1:1	167	1:1	219	3:1:0	38
2:1	78	2:1	67	3:1:1	89
3:1	38	3:1	68	3:1:2	162
4:1	36	-	-	3:1:3	77
5:1	24	5:1	22	3:1:4	38

6.4 Optimum Mix

The data in Table 13 shows that an assumed *k* value of 0.11 W/mK is reasonable and, based on the *k* value measured by CSTB, it may be conservative. However, this is a theoretical estimation, and an actual measurement is necessary to verify this. This *k* value is being assumed for a 5:1 hemp/lime mix, with a density of 425 kg/m^3 for the calculations which follow in Section 6.5.

Table 13: Summary of Thermal Conductivity values

Material	Density [kg/m^3]	Thermal Conductivity [W/mK]	Source of Information
Expanded Slag in Concrete	425	0.11	Neville (1995)
Expanded Clay in Concrete	425	0.17	Neville (1995)
Light Clay	425	0.12 – 0.14	Scott (2003)
Expanded Slag in Concrete	550	0.14	Neville (1995)
Expanded Clay in Concrete	550	0.20	Neville (1995)
Light Clay	550	0.14 – 0.165	Scott (2003)
Hemp/Lime Mix	550	0.12	Isochanvre [CSTB]
Hemp/Lime Mix	425	0.11	Assumed

Properties of Mix: Mix Ratio: Hurds:Lime = 5:1 Experimental Strength = 0.7 N/mm^2 Theoretical Thermal Conductivity = 0.11 W/mK Density = 425 kg/m^3	
Data: Mass of Hemp required per cubic metre: 345 kg Cost: 48 euro Mass of Lime required per cubic metre: 80 kg Cost: 32 euro Total: 80 euro *Note: based on current prices for hemp and lime*	

Table 14: Properties of mix and current cost per cubic metre

6.5 U-Value of Wall

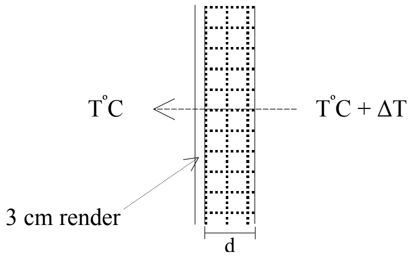
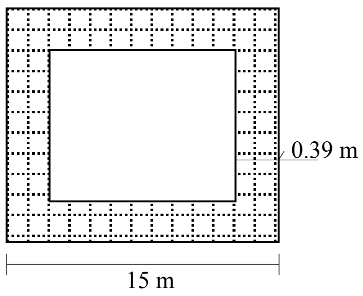
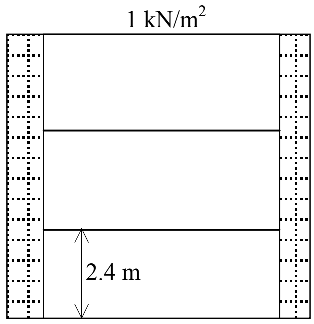
	
Data: Building Regulations (Part L): $U_{wall} = 0.27$ W/m²K External Surface Resistance : $R_{so} = 0.049$ m²K/W Internal Surface Resistance : $R_{si} = 0.123$ m²K/W External Rendering : $R_{render} = 0.053$ m²K/W	
Thermal Resistance Requirements: $U = \frac{1}{\Sigma R} = \quad \Rightarrow \quad \Sigma R = \frac{1}{U} = \frac{1}{0.27} = 3.704$	$\Sigma R = 3.704$
Wall Fabric Resistance: $\Sigma R = R_{so} + R_{wall} + R_{si} + R_{render}$ $R_{wall} = \Sigma R - R_{so} - R_{si} - R_{render}$ $R_{wall} = 3.704 - 0.049 - 0.123 - 0.053 = 3.479$	$R_{wall} = 3.479$
Wall Thickness: $R_{wall} = \frac{d}{k}$ $d = k \times R_{wall}$ $d = (0.11) \times (3.479) = 0.383$ m	$d = 0.383$ m

Table 15: Calculations to find thickness to meet U-value requirements of wall

6.6 Typical loads required for a dwelling

Schematic Diagram:  Plan  Elevation	
Data: Using a 5:1 Hemp/Lime Mix: Compressive Strength: $f = 0.7\ N/mm^2$ Unit Weight of Material: $\gamma = 0.425 \times 9.81 = 4.17\ kN/m^3$ Data (Chudley 2004) Dead Load of Floor: $0.226\ kN/m^2$ Live Load of Floor: $1.5\ kN/m^2$ Dead load of Roof: $1\ kN/m^2$	
For a house 15 x 15 m on plan, with walls 390 mm thick, placing material *in-situ*: Total cross-sectional wall area: $A_c = 15^2 - 14.22^2 = 22.79\ m^2 = 22.79 \times 10^6\ mm^2$ Total compressive force capacity: $F_c = 0.7 \times 22.79 \times 10^6 = 15\,954\,000\ N = 15\,954\ kN$	$F_c = 15\,954\ kN$
Dead Loads (G_k): Dead load: G_k = Vol. of Material x Unit Weight $G_k = (22.79 \times 2.4 \times 3) \times 4.17 = 684\ kN$ Dead load of roof: $1 \times 15^2 = 225\ kN$ Dead load of floor: $0.226 \times 15^2 = 51\ kN$ Total Dead Load: $G_k = 684 + 225 + (51 \times 2) = 1011\ kN$	$\Sigma G_k = 1011\ kN$
Live Loads (Q_k): Live load: L_L= Area x Load/Area $L_L = 1.5 \times 15^2 = 337.5\ kN$ Total Live Load: $(337.5 \times 2) = 675\ kN$	$\Sigma Q_k = 675\ kN$

Total Load: Total Load: $T_L = 1.4\ G_k + 1.6\ Q_k$ $T_L = 1.4\ (1011) + 1.6(675) = 2495$ kN $T_L < F_c$ 2495 kN < 15 954 kN Acceptable [Factor of Safety = 6]	Total load = 2495 kN
Actual Stress in Wall = $(2495 \times 10^3) / (22.79 \times 10^6) = 0.11$ N/mm^2 Strain for this stress (Figure 47) = 0.0045 Total Deflection of Wall: 0.0045 x 2.4 x 3 = 0.0327 m = 3.3 cm	Total Deflection = 3.3 cm

Table 16: Calculations for materials strength

According to BS 5628, for Masonry Design, there is no load capacity reduction factor necessary due to the effective height and thickness of the walls. These calculations are purely theoretical without any safety factors for the characteristic strength of the material. This assumes that the energy used to compact the material is the same as that used in the preparation of the samples for these experiments. It also assumes that there are no windows or doors in the building, giving a slightly heavier dead load than would realistically be present.

However, as the Young's modulus is so low for this mix (24 N/mm^2) there may be excessive deformation. Three possible options are available:

1) Use of a timber frame structure to support the building. In this case, the lowest density mix possible should be used. This may be of a higher ratio than 5:1, but should be at least 5:1 to minimise thermal conductivity.
2) Use of a pre-stressing mechanism, such as that used on load-bearing straw bale houses. The top wall plate could be pulled down to the foundation using either steel straps or threaded reinforcement bars to prevent deformation.
3) Design the structure taking into account this deformation initially, and allow the entire structure to come to static equilibrium. To do this, no finishes or renders could be applied until the initial settling of the structure had taken place due to the applied dead load (such as the walls, floors and roof).

6.7 Environmental and economic impact of building

The hemp and lime dwelling designed in Section 6.6, could be constructed without using conventional insulation, and as a result has an overall lower embodied energy. Most of the energy required is for the production of the hydraulic lime binder. 'Embodied energy' describes the amount of energy used to produce a product (Roaf 2001). This includes extracting raw materials, processing and manufacturing a product. As hurds are considered to be the by-product of a natural material, the embodied energy for the calculation below was assumed to be zero. Typical values of the physical properties of certain materials which are used to construct and insulate buildings are shown in Table 17 and compared with the materials in this project. Embodied energy is an important measurement tool for comparing building materials. Usually non-renewable energy is used in processing these materials and for overall energy conservation, a material should not need more energy for production than it can save within its lifetime. Artificial insulation materials are often the product of high energy exothermic reactions, hence they have high levels of embodied energy.

Table 17: Embodied energy for common building materials

Material	Thermal Conductivity [W/mK]	Compressive Strength [N/mm^2]	Embodied Energy [GJ/ton]
Cement[a]	-	-	7.8
Timber[a]	0.13 – 0.18	-	0.52 – 7.1
Steel[a]	17 – 50	-	24 – 59
Expanded Polystyrene[a]	0.033	0.11 – 0.15 @ 10% deformation	120.00
Rock Wool[a]	0.034 – 0.036	0.12 – 0.18	25.00
Phenolic Foam[a]	0.018	*unknown*	27.78
Lime	0.6	11.65	5.63[b]
Hemp/Lime 5:1 Mix	0.11	0.7	1.06

([a]Values for these materials based on Roaf 2001)
([b]Values for this material based on Reddy 2001)

6.8 Advantages and Disadvantages:

Hemp as a building material

Advantages	Disadvantages
• Natural, organic sustainable aggregate • Converts solar energy into a building material usable by man • Easy to produce and quick-growing requiring little fertilizer • Easy to grow in most soil conditions (good for soil and crop rotation) • Very fast growing (8 feet in 100 days) • Hurds are available as a by-product so using hurds prevents waste • No environmental damage • Renewable (as crops are harvested, more can be replanted)	• Difficult to process, unless equipment available • General confusion about legislation and licensing for growing

Lime as a building material

Advantages	Disadvantages
• Less energy required for production than for cement production • Absorbs CO_2 • Is a flexible and breathable binder • Preservative (prevents damage from rodents, fungi and micro-organisms) • Easily available	• Quarrying – environmental pollution • Burning uses energy • Caustic material – proper protection needed while working • Fine dust particles – care needed to avoid inhalation

Combination of Hemp and Lime as a building material

Advantages	Disadvantages
• Low embodied energy – an 'environmentally friendly' material • A structural and insulating building material • Durable and lightweight • Provides a 'breathable' and porous building membrane. This prevents moisture build-up and ensures a dry dwelling/building	• Low strength • No building codes/regulations available • Thick walls required for both structure and insulation. This may be significant on a small site • Low E-modulus resulting in significant compression of material under loading • May take a long period of time for walls to dry out. Fungal growth is possible in humid climates

7 CONCLUSIONS

7.1 Recommendations for further research

- The strength of a 6:1 and 7:1 hurd/lime mix should be investigated. This would have a lower value of thermal conductivity (as it is less dense than a 5:1 mix) hence its compressive strength would be of interest.
- The experimental measurement of thermal conductivity for hurd/lime mixes of various densities should be measured.
- The measurement of the strength gain over shorter time periods (such as 24 hours, 7 days, 28 days)
- The length of time before full carbonation and full strength is reached with various hydraulic binders (NHL 2, 3.5 and 5)
- Experiments with different sizes of hurds should be explored. If small cylindrical sections of the stem could be used the material may be stronger

7.2 Conclusions

Building with this material uses less energy than conventional construction methods and is a sustainable building solution for the future. It is a material which both insulates and provides structural strength as well as being low in embodied energy.

Adding hurds and fibres to a lime mortar reduces the material’s compressive and tensile strength. Based on these experiments and considering both compressive strength and thermal conductivity, a 5:1 hurd/lime mix was considered to be the optimum mix ratio with a compressive strength of 0.7 N/mm^2 and an estimated thermal conductivity of 0.11 W/mK.

The overall tensile strength values are quite low for all of the mixes tested, in comparison to concrete. The fibre/lime mix is not significantly stronger than the hurd mix, as was originally expected due to the strength of the fibres. This could be due to the lime not bonding well with the fibres, or the short length of the fibres (roughly 2.5 cm long).

A 3:1 hurd/lime mix has the same strength as a 5:1 hurd/lime mix. This is a significant result, as previously hurd/lime mixes used as infill in timber frames have been based on a 3:1 mix by volume which uses the lime binder less efficiently and has a higher thermal conductivity.

The constraint upon using this combination as a building material is the value of its thermal conductivity. To achieve a satisfactory U-value for a 5:1 hurd/lime mix, it is estimated that it is necessary to have walls 390 mm thick. This is a more than adequate value for the loads required to be resisted by the building’s walls (a factor of safety of six exists). The volume of material required for a building is extremely large. It may be more efficient to use a mix which has a lower thermal conductivity even if this caused a slight reduction in the strength of the material. Therefore, the required U-value could be achieved with narrower walls using less material.

The combination of hemp hurds and lime is a viable structural and insulating material for the construction of dwellings.

Appendix A

Sample of texture 1:1 hurd mix

Sample of texture 2:1 hurd mix

Sample of texture 3:1 hurd mix

Sample of texture 4:1 hurd mix

Sample of texture 5:1 hurd mix

Appendix B

Tested on Wed, 2nd Feb.		**Hemp Lime 1: 1**	
Displacement rate	**3 mm/min**		

Cube Number	**5**	**6**	**7**
Density [kg/m^3]	**812.9**	**821.2**	**841.6**

Cube	**A**	**B**	**C**
Displacement [mm]	**Force [kN]**	**Force [kN]**	**Force [kN]**
0	0	0	0
0.5	3.42	6.30	6.90
1.0	14.96	17.76	17.40
1.5	17.79	18.69	18.76
2.0	16.34	17.18	17.30
2.5	15.32	16.12	16.02
3.0	14.64	15.40	15.42
3.5	14.20	14.59	14.81
4.0	13.74	14.03	14.47
4.5	13.36	13.66	14.13
5.0	13.16	13.35	13.89
5.5	12.99	13.38	13.72
6.0	12.63	13.42	13.48
6.5	12.25	13.64	13.45
7.0	11.85	13.50	13.32
7.5	11.61	13.43	13.25
8.0	11.55	13.48	13.15
8.5	11.47	13.41	13.11
9.0	11.26	13.36	13.05
9.5	11.32	13.40	13.02
10.0	11.00	13.39	13.08

Average Force	**Stress**	**Strain (%)**
0	0	0.0%
5.54	0.55	0.5%
16.71	1.67	1.0%
18.41	1.84	1.5%
16.94	1.69	2.0%
15.82	1.58	2.5%
15.15	1.52	3.0%
14.53	1.45	3.5%
14.08	1.41	4.0%
13.72	1.37	4.5%
13.47	1.35	5.0%
13.36	1.34	5.5%
13.18	1.32	6.0%
13.11	1.31	6.5%
12.89	1.29	7.0%
12.76	1.28	7.5%
12.73	1.27	8.0%
12.66	1.27	8.5%
12.56	1.26	9.0%
12.58	1.26	9.5%
12.49	1.25	10.0%

Average Density	825.23	[kg/m^3]
Average Max. Force	18.41	[kN]
Average Max. Strength	1.84	[N/mm^2]

Tested on Feb 1st		**Hemp Lime 2:1**	
Displacement Rate	**6 mm/min**		

Cube Number	**8**	**9**	**10**
Density [kg/m^3]	**574.9**	**575.1**	**577.5**

Cube	**A**	**B**	**C**
Displacement [mm]	**Force [kN]**	**Force [kN]**	**Force [kN]**
0	0	0	0
1	8.4	7.5	7.6
2	12.72	13.61	14.49
3	12.37	13.4	13.39
4	11.5	12.19	12.68
5	10.89	11.36	11.73
6	10.35	10.65	10.82
7	9.9	10.22	10.19
8	9.51	9.88	9.7
9	9.18	9.57	9.41
10	8.8	9.43	9.25

Average Force [kN]	**Stress**	**Strain (%)**
0	0	0.0%
7.83	0.78	1.0%
13.61	1.36	2.0%
13.05	1.31	3.0%
12.12	1.21	4.0%
11.33	1.13	5.0%
10.61	1.06	6.0%
10.10	1.01	7.0%
9.70	0.97	8.0%
9.39	0.94	9.0%
9.16	0.92	10.0%

Average Density	576 [kg/m^3]
Average Max. Force	13.61 [kN]
Average Max. Strength	1.36 [N/mm^2]

Tested on Feb 1st		**Hemp Lime 3: 1**	
Displacement Rate	**6 mm/min**		

Cube Number	**11**	**12**	**13**	**14**
Density [kg/m^3]	**572.6**	**576.1**	**570.1**	**549.7**

Cube	**A**	**B**	**C**	**D**
Displacement [mm]	**Force [kN]**	**Force [kN]**	**Force [kN]**	**Force [kN]**
0	0	0	0	0
1	1.36	3.2	5.6	5.1
2	3.75	6.2	7.16	7.24
3	4.97	6.71	7.41	7.51
4	5.52	6.76	7.36	7.48
5	5.86	6.63	7.18	7.23
6	6.13	6.38	6.99	6.98
7	6.37	6.12	6.82	6.74
8	6.53	5.82	6.61	6.5
9	6.69	5.54	6.37	6.27
10	6.79	5.25	6.21	6.18

Average Force [kN]	**Stress**	**Strain (%)**
0	0	0.0%
3.82	0.38	1.0%
6.09	0.61	2.0%
6.65	0.67	3.0%
6.78	0.68	4.0%
6.73	0.67	5.0%
6.62	0.66	6.0%
6.51	0.65	7.0%
6.37	0.64	8.0%
6.22	0.62	9.0%
6.11	0.61	10.0%

Average Density	567	[kg/m^3]
Average Max. Force	7.12	[kN]
Average Max. Strength	0.71	[N/mm^2]

Tested on Feb 1st		Hemp Lime 4: 1	
Displacement Rate	6 mm/min		

Cube Number	15	16	17	18
Density [kg/m^3]	445.6	458.5	444	468

Cube	A	B	C	D
Displacement [mm]	Force [kN]	Force [kN]	Force [kN]	Force [kN]
0	0	0	0	0
1	4.43	1.23	2.8	5.8
2	5.76	4.8	5.38	7.27
3	5.94	6.14	6	7.62
4	5.84	6.41	6.12	7.68
5	5.66	6.41	6.03	7.59
6	5.4	6.26	5.83	7.38
7	5.12	6	5.56	7.08
8	4.74	5.66	5.39	6.79
9	4.41	5.43	5.17	6.56
10	3.8	5.17	4.97	6.33

Average Force [kN]	Stress	Strain (%)
0	0	0.0%
3.565	0.3565	1.0%
5.8025	0.58025	2.0%
6.425	0.6425	3.0%
6.5125	0.65125	4.0%
6.4225	0.64225	5.0%
6.2175	0.62175	6.0%
5.94	0.594	7.0%
5.645	0.5645	8.0%
5.3925	0.53925	9.0%
5.0675	0.50675	10.0%

Average Density	454	[kg/m^3]
Average Max. Force	6.54	[kN]
Average Max. Strength	0.65	[N/mm^2]

Tested on Feb 1st		**Hemp Lime 5: 1**	
Displacement Rate	**6 mm/min**		

Cube Number	**19**	**20**	**21**
Density [kg/m^3]	**431.4**	**422.7**	**420.3**

Cube	**A**	**B**	**C**
Displacement [mm]	**Force [kN]**	**Force [kN]**	**Force [kN]**
0	0	0	0
1	1.3	2.8	3.19
2	6.1	6.37	5.67
3	6.7	7.06	6.44
4	6.76	7.04	6.71
5	6.57	6.78	6.73
6	6.33	6.52	6.64
7	6.09	6.37	6.47
8	5.86	6.23	6.35
9	5.7	6.2	6.19
10	5.52	6.13	6.05

Average Force [kN]	**Stress**	**Strain (%)**
0	0	0.0%
2.4300	0.2430	1.0%
6.0467	0.6047	2.0%
6.7333	0.6733	3.0%
6.8367	0.6837	4.0%
6.6933	0.6693	5.0%
6.4967	0.6497	6.0%
6.3100	0.6310	7.0%
6.1467	0.6147	8.0%
6.0300	0.6030	9.0%
5.9000	0.5900	10.0%

Average Density	425 [kg/m^3]
Average Max. Force	6.85 [kN]
Average Max. Strength	0.69 [N/mm^2]

Appendix C

Tested on Wed, 2nd Feb.		Fibres 1:1
Displacement Rate	3 mm/min	

Cube Number	43	44	?
Density [kg/m^3]	887	867.8	?

Cube	A	B	C
Displacement [mm]	Force [kN]	Force [kN]	Force [kN]
0	0	0	0
0.5	5.70	9.10	
1.0	20.20	23.68	
1.5	25.15	26.75	
2.0	24.23	25.72	27.00
2.5	23.07	24.62	
3.0	22.03	23.82	
3.5	21.12	22.60	
4.0	20.15	21.72	
4.5	19.34	20.90	
5.0	18.57	20.06	
5.5	17.87	19.38	
6.0	17.16	18.84	
6.5	16.62	18.50	
7.0	16.22	18.15	
7.5	15.98	17.89	
8.0	15.68	17.70	
8.5	15.31	17.55	
9.0	15.22	17.47	
9.5	15.11	17.43	
10.0	15.04	17.42	

Average Force [kN]	Stress	Strain (%)
0	0	0.0%
7.4	0.74	0.5%
21.94	2.194	1.0%
25.95	2.595	1.5%
25.65	2.565	2.0%
23.845	2.3845	2.5%
22.925	2.2925	3.0%
21.86	2.186	3.5%
20.935	2.0935	4.0%
20.12	2.012	4.5%
19.315	1.9315	5.0%
18.625	1.8625	5.5%
18	1.8	6.0%
17.56	1.756	6.5%
17.185	1.7185	7.0%
16.935	1.6935	7.5%
16.69	1.669	8.0%
16.43	1.643	8.5%
16.345	1.6345	9.0%
16.27	1.627	9.5%
16.23	1.623	10.0%

Average Density	877 [kg/m^3]
Average Max. Force	26.30 [kN]
Average Max. Strength	2.63 [N/mm^2]

Tested on Feb 1st		**Fibres 2:1**	
Displacement Rate	**6 mm/min**		

Cube Number	**31**	**32**	**33**
Density [kg/m^3]	**732.4**	**735.7**	**737.9**

Cube	**A**	**B**	**C**
Displacement [mm]	**Force [kN]**	**Force [kN]**	**Force [kN]**
0	0	0	0
1	6.87	5.7	7.4
2	12.06	12.16	12.83
3	13.19	13.65	13.63
4	13.26	13.68	13.58
5	13.02	13.25	13.35
6	12.73	12.79	13.03
7	12.42	12.36	12.71
8	12.19	11.96	12.45
9	11.95	11.69	12.2
10	11.64	11.42	12.03

Average Force [kN]	**Stress**	**Strain (%)**
0	0	0.0%
6.657	0.666	1.0%
12.350	1.235	2.0%
13.490	1.349	3.0%
13.507	1.351	4.0%
13.207	1.321	5.0%
12.850	1.285	6.0%
12.497	1.250	7.0%
12.200	1.220	8.0%
11.947	1.195	9.0%
11.697	1.170	10.0%

Average Density	735	[kg/m^3]
Average Max. Force	13.52	[kN]
Average Max. Strength	1.35	[N/mm^2]

Tested on Feb 1st		**Fibres 3:1**
Displacement Rate	**6 mm/min**	

Cube Number	**34**	**35**	**36**
Density [kg/m^3]	**652.4**	**591.5**	**630**

Cube	**A**	**B**	**C**
Displacement [mm]	**Force [kN]**	**Force [kN]**	**Force [kN]**
0	0	0	0
1	9.9	4.9	5.6
2	13.5	8.93	10.56
3	14.22	9.68	11.75
4	14.31	9.86	11.94
5	14.18	9.83	11.95
6	13.83	9.67	11.82
7	13.34	9.4	11.72
8	12.96	9.11	11.55
9	12.58	8.89	11.38
10	12.35	8.71	11.23

Average Force [kN]	**Stress**	**Strain (%)**
0	0	0.0%
6.80	0.68	1.0%
11.00	1.10	2.0%
11.88	1.19	3.0%
12.04	1.20	4.0%
11.99	1.20	5.0%
11.77	1.18	6.0%
11.49	1.15	7.0%
11.21	1.12	8.0%
10.95	1.10	9.0%
10.76	1.08	10.0%

Average Density	625 [kg/m^3]
Average Max. Force	12.04 [kN]
Average Max. Strength	1.20 [N/mm^2]

Tested on Feb 1st (Cube A)		**Fibres 5:1**
Displacement Rate	**6 mm/min**	

Cube Number	**37**	**38**	**39**
Density [kg/m^3]	**460.2**	**468.7**	**466.5**

Cube	**A**	**B**	**C**
Displacement [mm]	**Force [kN]**	**Force [kN]**	**Force [kN]**
0	0	0	0
1	1.01	2.837	2.879
2	3.82	3.953	3.963
3	4.77	4.268	4.216
4	4.94	4.34	4.318
5	4.74	4.305	4.33
6	4.59	4.249	4.314
7	4.46	4.187	4.29
8	4.35	4.116	4.251
9	4.26	4.04	4.223
10	4.16	3.951	4.202

Average Force [kN]	**Stress**	**Strain (%)**
0	0	0.0%
2.24	0.22	1.0%
3.91	0.39	2.0%
4.42	0.44	3.0%
4.53	0.45	4.0%
4.46	0.45	5.0%
4.38	0.44	6.0%
4.31	0.43	7.0%
4.24	0.42	8.0%
4.17	0.42	9.0%
4.10	0.41	10.0%

Average Density	465 [kg/m^3]
Average Max. Force	4.54 [kN]
Average Max. Strength	0.45 [N/mm^2]

Appendix D

Tested on Feb 1st		Sand 3:1:0
Displacement Rate	6 mm/min	

Cube Number	11	12	13	14
Density [kg/m^3]	572.6	576.1	570.1	549.7

Cube	A	B	C	D
Displacement [mm]	Force [kN]	Force [kN]	Force [kN]	Force [kN]
0	0	0	0	0
1	1.36	3.2	5.6	5.1
2	3.75	6.2	7.16	7.24
3	4.97	6.71	7.41	7.51
4	5.52	6.76	7.36	7.48
5	5.86	6.63	7.18	7.23
6	6.13	6.38	6.99	6.98
7	6.37	6.12	6.82	6.74
8	6.53	5.82	6.61	6.5
9	6.69	5.54	6.37	6.27
10	6.79	5.25	6.21	6.18

Average Force [kN]	Stress	Strain (%)
0	0	0.0%
3.815	0.3815	1.00%
6.0875	0.60875	2.00%
6.65	0.665	3.00%
6.78	0.678	4.00%
6.725	0.6725	5.00%
6.62	0.662	6.00%
6.5125	0.65125	7.00%
6.365	0.6365	8.00%
6.2175	0.62175	9.00%
6.1075	0.61075	10.00%

Average Density	567 [kg/m^3]
Average Max. Force	7.12 [kN]
Average Max. Strength	0.71 [N/mm^2]

Tested on Wed, 2nd Feb.		**Sand 3:1:1**
Displacement Rate	**3 mm/min**	

Cube Number	**22**	**23**	**24**
Density [kg/m^3]	**813.1**	**809.1**	**798.7**

Cube	**A**	**B**	**C**
Displacement [mm]	**Force [kN]**	**Force [kN]**	**Force [kN]**
0	0	0	0
0.5	6.70	3.56	3.20
1.0	11.06	9.94	5.61
1.5	11.61	11.89	6.72
2.0	11.44	12.30	7.32
2.5	11.08	12.04	7.78
3.0	10.64	11.62	7.86
3.5	10.14	10.99	7.89
4.0	9.61	10.41	7.80
4.5	9.11	9.90	7.60
5.0	8.66	9.47	7.30
5.5	8.21	9.06	6.99
6.0	7.85	8.66	6.68
6.5	7.59	8.25	6.39
7.0	7.38	7.89	6.05
7.5	7.13	7.42	5.66
8.0	6.71	7.05	5.25
8.5	6.55	6.74	4.82
9.0	6.36	6.45	4.37
9.5	6.12	6.17	4.09
10.0	5.86	5.92	3.79

Average Force [kN]	**Stress**	**Strain (%)**
0	0	0.0%
4.49	0.45	0.5%
8.87	0.89	1.0%
10.07	1.01	1.5%
10.35	1.04	2.0%
10.30	1.03	2.5%
10.04	1.00	3.0%
9.67	0.97	3.5%
9.27	0.93	4.0%
8.87	0.89	4.5%
8.48	0.85	5.0%
8.09	0.81	5.5%
7.73	0.77	6.0%
7.41	0.74	6.5%
7.11	0.71	7.0%
6.74	0.67	7.5%
6.34	0.63	8.0%
6.04	0.60	8.5%
5.73	0.57	9.0%
5.46	0.55	9.5%
5.19	0.52	10.0%

Average Density	807	[kg/m^3]
Average Max. Force	10.60	[kN]
Average Max. Strength	1.06	[N/mm^2]

Tested on Wed, 2nd Feb.		**Sand 3:1:2**
Displacement Rate:	**3 mm/min**	

Cube Number	**25**	**26**	**27**
Density [kg/m^3]	**1088.6**	**1078**	**1096**

Cube	**A**	**B**	**C**
Displacement [mm]	**Force [kN]**	**Force [kN]**	**Force [kN]**
0	0	0	0
0.5	9.38	5.20	11.22
1.0	16.97	15.20	16.50
1.5	17.74	17.64	16.54
2.0	17.40	17.47	15.98
2.5	16.67	16.25	15.21
3.0	15.63	15.24	14.39
3.5	14.51	14.56	13.53
4.0	13.36	13.52	12.63
4.5	12.12	12.77	11.96
5.0	11.08	12.10	11.20
5.5	10.10	11.29	10.38
6.0	9.13	10.68	9.66
6.5	8.05	10.20	8.68
7.0	7.18	9.65	7.88
7.5	6.71	9.05	7.25
8.0	6.42	8.25	6.54
8.5	6.03	7.60	5.93
9.0	5.66	7.02	5.39
9.5	5.38	6.42	4.94
10.0	5.13	6.00	4.55

Average Force [kN]	**Stress**	**Strain (%)**
0	0	0.0%
8.60	0.86	0.5%
16.22	1.62	1.0%
17.31	1.73	1.5%
16.95	1.70	2.0%
16.04	1.60	2.5%
15.09	1.51	3.0%
14.20	1.42	3.5%
13.17	1.32	4.0%
12.28	1.23	4.5%
11.46	1.15	5.0%
10.59	1.06	5.5%
9.82	0.98	6.0%
8.98	0.90	6.5%
8.24	0.82	7.0%
7.67	0.77	7.5%
7.07	0.71	8.0%
6.52	0.65	8.5%
6.02	0.60	9.0%
5.58	0.56	9.5%
5.23	0.52	10.0%

Average Density	1088	[kg/m^3]
Average Max. Force	17.31	[kN]
Average Max. Strength	1.73	[N/mm^2]

Tested on Wed, 2nd Feb.		**Sand 3:1:3**
Displacement Rate:	**3 mm/min**	

Cube Number	**28**	**29**	**30**
Density [kg/m^3]	**1196.4**	**1190.5**	**1200**

Cube	**A**	**B**	**C**
Displacement [mm]	**Force [kN]**	**Force [kN]**	**Force [kN]**
0	0	0	0
0.5	1.90	5.00	5.50
1.0	4.03	10.75	12.27
1.5	6.13	12.06	13.57
2.0	7.88	12.12	13.90
2.5	9.46	11.59	13.59
3.0	10.51	10.71	13.04
3.5	11.30	9.75	12.34
4.0	11.81	8.72	11.35
4.5	12.11	7.85	10.34
5.0	12.26	7.11	9.16
5.5	12.20	6.54	8.16
6.0	12.06	6.01	7.07
6.5	12.00	5.44	6.16
7.0	11.83	4.77	5.31
7.5	11.63	4.28	4.67
8.0	11.27	3.85	3.92
8.5	10.95	3.54	3.36
9.0	10.56	3.20	2.93
9.5	10.07	2.89	2.52
10.0	9.48	2.68	2.19

Average Force [kN]	**Stress**	**Strain (%)**
0	0	0.0%
3.50	0.35	0.5%
7.67	0.77	1.0%
8.54	0.85	1.5%
8.67	0.87	2.0%
8.39	0.84	2.5%
7.92	0.79	3.0%
7.36	0.74	3.5%
6.69	0.67	4.0%
6.06	0.61	4.5%
5.42	0.54	5.0%
4.90	0.49	5.5%
4.36	0.44	6.0%
3.87	0.39	6.5%
3.36	0.34	7.0%
2.98	0.30	7.5%
2.59	0.26	8.0%
2.30	0.23	8.5%
2.04	0.20	9.0%
1.80	0.18	9.5%
1.62	0.16	10.0%

Average Density	1196	[kg/m^3]
Average Max. Force	12.76	[kN]
Average Max. Strength	1.28	[N/mm^2]

Tested on Wed, 2nd Feb.		Sand 3:1:4
Displacement Rate:	3 mm/min	

Cube Number	40	41	42
Density [kg/m^3]	1203.6	1187.6	1180.8

Cube	A	B	C
Displacement [mm]	Force [kN]	Force [kN]	Force [kN]
0	0	0	0
0.5	1.16	3.02	5.08
1.0	2.58	5.56	5.95
1.5	3.90	6.36	6.14
2.0	4.91	6.34	6.07
2.5	5.40	6.09	5.85
3.0	6.02	5.63	5.54
3.5	6.40	4.98	5.13
4.0	6.62	4.33	4.54
4.5	6.71	3.59	4.02
5.0	6.90	3.00	3.38
5.5	6.97	2.55	2.80
6.0	6.94	2.22	2.28
6.5	6.90	1.95	1.86
7.0	6.73	1.75	1.55
7.5	6.52	1.53	1.30
8.0	6.15	1.33	1.16
8.5	5.83	1.15	1.01
9.0	5.61	0.93	0.92
9.5	5.32	0.84	0.85
10.0	4.99	0.77	0.56

Average Force [kN]	Stress	Strain (%)
0	0	0.0%
2.70	0.27	0.5%
3.84	0.38	1.0%
4.17	0.42	1.5%
4.14	0.41	2.0%
3.98	0.40	2.5%
3.72	0.37	3.0%
3.37	0.34	3.5%
2.95	0.30	4.0%
2.54	0.25	4.5%
2.13	0.21	5.0%
1.78	0.18	5.5%
1.50	0.15	6.0%
1.27	0.13	6.5%
1.10	0.11	7.0%
0.94	0.09	7.5%
0.83	0.08	8.0%
0.72	0.07	8.5%
0.62	0.06	9.0%
0.56	0.06	9.5%
0.44	0.04	10.0%

Average Density	1191	[kg/m^3]
Average Max. Force	6.49	[kN]
Average Max. Strength	0.65	[N/mm^2]

5 References

Byrne, M. E. (2001). *A Guide to the use of Lime in Historic Buildings*. Edward M. Byrne, Tullow, Co. Carlow.

British Standards (2004). BS ISO 844:2004 for Rigid Cellular Plastics; BS 8110 for Structural Use of Concrete

Building Research Establishment. (2002). *Report on the Construction of the Hemp Houses at Haverhill, Suffolk*. BRE Report No. 209-717.

Burguenoa R., Quagliataa M. J., & Mohantyb A.K., (2004). “Load-bearing natural fiber composite cellular beams and panels” *Composites: Applied Science and Manufacturing*.

Chudley, R. & Greeno, R. (2004). *Building Construction Handbook*. Butterworth-Heinemann, Oxford.

Cowper, A. D. (1998). *Lime and Lime Mortars*. Donhead Publishing Ltd., Shaftesbury.

Crowley, J.G. (2001). *The Performance of* Cannabis Sativa *(Hemp) as a Fibre Source for Medium Density Fibreboard (MDF)*. Teagasc, Ireland.

Duggal, S. K. (1998). *Building Materials*. A. A. Balkeman, Rotterdam.

Elizabeth, L. Adams, C. (2000). *Alternative Construction: Contemporary Natural Building Methods*. John Wiley & Sons, America.

Encyclopaedia Britannica (1987). 15th Ed., University of Chicago, USA.

Nova-Institut. (2003). “Materials for the future” Cologne, Germany.

Halliday, D., Resnick, R. & Walker, J. (2001). *Fundamentals of Physics*. Wiley, New York.

Herrmann A. S., Nickel J. & Riedel U. (1998). “Construction materials based upon biologically renewable resources-from components to finished parts.” *Polymer Degradation and Stability*, Vol. 59, Issues 1-3.

Hill, N., Holmes, S. & Mather, D. (1992). *Lime and Other Alternative Cements*. Intermediate Technology Publications Ltd., London.

Holmes, S. & Wingate, M. (2002). *Building With Lime A Practical Introduction*. 2nd Ed., ITDG Publishing, London.

Isochanvre Technical Document (2004). Périer, F. “*Hemp: A valuable resource*.” Ralph Carpenter.

Kennedy, J. Smith, M.G.& Wanek, C. (2002). *The Art of Natural Building*. New Society Publishers, Canada.

Keohane, F. (2001). *Period Houses A Conservation Guidance Manual*. Dublin Civic Trust, Dublin.

Lindsay, A. M. (1998). *An investigation into the historic use of lime in some buildings in Ireland*. University College Dublin, Dublin.

Lloyd, S. Muller, H.W. & Martin, R. (1972). *Mesopotamia, Egypt, Crete, Greece*. London.

McCay, A. (1985). *Vitruvius: Architect and Engineer*. Bristol Classical Press, Britain.

Morgan C. & Scott C. (2002). “Light Earth.” *Building for a future*, Volume 12, No. 3.

Moropoulou A., Bakolas A. & Anagnostopoulou S. (2005). “Composite materials in ancient structures” *Cement & Concrete Composites*, Vol: 27.

Murdock, L.J., Brook K.M. & Dewar, J.D. (1991). *Concrete materials and practice*. 6th Ed., Edward Arnold, London.

Neville, A. M. (1995). *Properties of concrete*. 5th Ed., Longman, Harlow.

Pasley, C. W. (1997). *Observations on Limes*. Donhead Publishing Ltd., Shaftesbury.

Pavía, S. & Bolton, J. (2000). *Stone, Brick & Mortar: Historical Use, Decay and Conservation of Building Materials in Ireland*. Wordwell Ltd., Co. Wicklow.

Pultron (2004). *Composite Materials*. http://www.pultron.com [accessed 15 November 2004]

Quinnlite Technical Document http://www.quinn-group.com [accessed 20 January 2005]

Ranalli, P. (1999). *Advances in Hemp Research*. The Haworth Press, New York.

Roaf, S. (2001). *Ecohouse – A Design Guide*. Architectural Press, Oxford.

Roulac, J.W. (1997). *Hemp Horizons*. Real Goods Solar Living, America.

Rowell, R.M., Young, R.A & Rowell, J.K. (1997). *Paper and Composites from Agro-Based Resources*. CRC Press, America.

Smith, M.G. (2000). *The Cobber's Companion*. America.

Vicat, L. J. (1997). *Mortars and Cements*. Donhead Publishing Ltd., Shaftesbury.

Vitruvius (1914). *The Ten Books on Architecture*. Morgan, M. H., Constable and Company Ltd., London.

Wambua, P., Ivens J. & Verpoest I. (2003). "Natural fibres: can they replace glass in fibre reinforced plastics?" *Composites Science and Technology*, Vol. 63, Issue 9.

Wingate, M. (1987). *An Introduction to building limes*. Society for the Protection of Ancient Buildings, London.