INVESTIGATION ON MECHANICAL & THERMAL BEHAVIOR OF HEMPCRETE

FINAL YEAR PROJECT UG-2012

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This is to certify that the Final Year Project Titled

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DEDICATED TO OUR PARENTS

& TEACHERS

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ABSTRACT

This was an industrial based project, with main focus on the sustainability development and construction of energy efficient buildings. Inspiration of choosing this project was our seniors, and civil engineering graduates of NUST Institute of Civil Engineering (NICE) from batck-2011 who worked on the same material and presented their research in competition, organized on national level by UNIDO and won a notable position of being in top twenty projects. Research's main objective was to investigate the mechanical and thermal properties of Hempcrete, and developing a mix design with best possible results. Hempcrete is a low-density, energy and cost efficient concrete with a substantial porous structure resulting in interesting properties related to thermal conductivity and hygrothermal behavior. It has low carbon footprints and contains a renewable bio-based material that can sequester CO_2 during its cultivation and keep the environment healthy by not contributing to the global warming. Compressive Strength, Thermal conductivity, Density test results were taken as the performance indicators for all the mixes. Based on these, some deficiencies were recognized to improve the mix design. First mix "Control Mix Design" was developed by keeping 50% water, 18.6% hemp and 31.4% binder content with lime and cement to be 70% and 30% of binder content respectively. Results of specimen for the control mix were quite up to expectations. Density, Thermal Conductivity and Compressive Strength was found out to be 34.72 lb/ft^3, 0.0773 W/m.K and 432 psi respectively. All other mixes were formed by varying the percentages of hempcrete contents in Control Mix Design. Problem in some of the mix designs was due excessive amount of lime and cement which increased the density of specimen affecting their thermal insulation results comparative to Control Mix Design. Density is directly related to the thermal performance of hempcrete. Denser specimen showed larger values of thermal conduction, affecting thermal insulation property. A lot more work need to be done in addressing the challenges like climate change and sustainability development by making "Hempcrete" subject of main focus. And future research should focus on establishing methods for formulating consistent specimens and also formulation of specific building element 'systems' that would assist in developing design and performance standards. The current research represents a first step towards the development of hempcrete in Pakistan.

Contents

List of Tables 9

List of Figures 10

Chapter 1 11

INTRODUCTION 11

1.1 Introduction 11

1.2 Study background 13

1.3 Problem Statement 13

1.4 Objectives 14

1.5 Scope of study 14

1.6 Significance of study 15

Chapter 2 16

LITERATURE REVIEW 16

2.1 General 16

2.2 Hempcrete 16

2.2.1 Introduction 16

2.2.2 History of Hempcrete 17

2.2.3 Nature of Hemp 18

2.2.4 Hemp shiv for Building 18

2.2.5 Vapor permeability and Hygroscopicity 19

2.2.6 Insulation 20

2.2.7 Thermal Mass 20

2.2.8 Cast-in-situ Hempcrete 21

2.3 Lime 23

2.3.1 Physical Forms of Lime 23

2.3.2 Lime Classification 24

Chapter 3 25

MATERIALS AND METHODOLOGY 25

3.1 Introduction 25

3.2 Materials: 25

3.3 Mixture Proportions 26

3.4 Sieving 29

3.5 Preparation of Specimens 29

3.5.2 Curing 29

3.6 Test on Fresh Hempcrete 30

3.7 Test on Hardened Hempcrete 30

Chapter 4 33

RESULTS AND DISCUSSIONS 33

4.1 Introduction 33

4.2 Fresh Properties of Hempcrete 34

4.2.1 Workability 34

4.3 Physical Properties of Hempcrete 34

4.3.1 Density 34

4.4 Thermal Properties of Hempcrete 36

4.4.1 Thermal Conductivity Test 36

4.5 Mechanical Properties of hempcrete 42

4.5.1 Compressive Strength 42

Chapter 5 45

CONCLUSIONS AND RECOMMENDATIONS 45

References 46

List of Tables

Table 1: Advantages and Disadvantages of Lime.. 23

Table 2: Mix design with reapect to %age.. 27

Table 3: Mix design with reapect to weight.. 28

Table 4: Average densities of hempcrete specimens for each mix design 35

Table 5: Thermal Conductivities of various known insulators... 38

Table 6: Thermal Conductivity results for proposed mix designs.. 42

Table 7: Compressive Strength results for proposed mix designs.. 43

List of Figures

Figure 1: Hemp Plant 17

Figure 2: Hemp Hurds 18

Figure 3: A building with high Thermal mass, day time and night time temperature variation (Alex Sparrow, “The Hempcrete Book”, 2014).. 21

Figure 4: Application of Hempcrete 22

Figure 5: Hemp Hurds 26

Figure 6: Collection of Hemp 26

Figure 7: Average densities of hempcrete specimens for each mix design 33

Figure 8: Density results for proposed mix designs comparative to concrete 35

Figure 9: Heat flow results for proposed mix designs comparative to concrete........................... 36

Figure 10: Hempcrete sample under applied stress 44

Figure 11: Fractured hempcrete specimen on subjection to compressive stress 44

Chapter 1

INTRODUCTION

This chapter focuses on introduction about Hempcrete and background study on this material, scope, significant and objectives of the research.

1.1 Introduction

Concrete is the most common used material in the construction industry. The mix of the normal concrete is cement, fine aggregate, coarse aggregate and water. The rapid development of composite structure nowadays requires a better quality material. Concrete is the most economical material used but because of its high density, so the dead load of the building also increases. In result reducing the dead load of building would leave us with so much advantages and lead us towards efficient construction.

Concrete is the conventional and one of the most durable building material for most civil engineering works in the world. It provides outstanding fire resistance. Structure made of concrete have a long service life. Reinforced concrete and precast concrete are mostly used types of concrete functional extensions in modern days.

The construction industry consumes natural resources than any other industry. With increasing public needs and demands of sustainable development and environmental conservation, no other industry is called on as much as the country’s construction and building industry to involve their practices to satisfy the needs of our current generation. For example, concrete accounts for the most important building and billions of tons are produced annually worldwide, and without which the nation’s infrastructure is unimaginable. Considerable progress and breakthroughs have been achieved recently in concrete technology, which has largely gone ignored by the majority of public.

One way to make concrete lighter is introduction of lightweight concrete in the construction industry. Lightweight concrete has been used recently because of its performance capability to reduce the dead load and earthquake forces. Density of lightweight concrete is about 80% of that of normal concrete and ranges from 1440 to 1840 kg/m^3 (90-115 lb/ft^3). Whereas the values for normal concrete ranges from 2240 to 2400 kg/m^3 (140-150 lb/ft^3). Even more light material was introduced many years ago and recently is in its development stage, known as “Hempcrete”.

Hempcrete is a mixture of hemp hurds and lime (possibly including natural hydraulic lime, sand, pozzolanz or cement) used as a material for construction and insulation. The typical compressive strength is around 150 psi, and maximum strength we can achieve, considering the economic purpose of hempcrete is 350-400 psi, and density is about 15% of the concrete. Hempcrete is a material that uses part of a hemp plant as bio-aggregate. Hemp grows faster than trees, has similar composition as timber and hempcrete made using hemp and lime as a binder has in fact a negative rather than positive carbon footprint, i.e. it removes CO^2 from the atmosphere as opposed to releasing carbon pollutants during its lifetime.

Hempcrete, from view point of some researchers is called Lime-Hemp, or in reverse: hemp-lime, Concrete/Composite (LHC), it’s a light composite building material with building lime as binding agents and hemp as a renewable raw material from agriculture. Contemporary LHC only uses the woody core part of the hemp, the shive/hurd. “Hemp-lime is a sustainable lowcarbon composite building material that combines renewably sourced hemp shiv (a co-product of hemp fibre crop production) with formulated lime-based binders” (Hirst et al., 2012). Lime hemp is a bio-composite material formed by the mixture of the woody core of the hemp plant, also known as hurd, and a lime based binder with the addition of water. Hemp acts as the lightweight filler, or aggregate, and lime is the binder and preservative. When setting, the composite forms a rigid lightweight material with excellent insulation and durability characteristics (HLCPA cited in Ronchetti 2007).

Development of hempcrete is a major breakthrough in a sector of sustainable development and it’s a very compatible material in fighting all those challenges associated to climate change like global warming the most significant of all. Commercialization of hempcrete surely would reduce the production of cement the production and formation of which involves exothermic reactions at major scale contributing towards global warming. Whereas lime boils at far lower temperature than cement and above all it’s a natural material with good hygrothermal properties beneficent to the health of habitants living in environment.

1.2 Study background

Claims of an archeological evidence of using hemp and lime in construction of a bridge from the Merovingian period (500–751 A.D.) in the south of France have been found, but these have not been verified (Allin 2012). Tan (2013) suggests that dating back 300 years ago, hemp buildings were used in Japan, predominantly for residential homes. The more recent history of using hempcrete is associated with France. This technique was first developed by an expert in repairing historical buildings, Charles Rasetti, in 1986 in restoration of buildings made of oak frame infilled with lime, straw and rubble typically for the Champagne region in France. Rasetti found that hempcrete 13 achieved much better results than cement, as the use of cement to repair these buildings resulted in moisture build up and further deterioration of the infill (Allin 2012).

Since then, hundreds of projects utilizing hemp and lime have been undertaken in not only restoration of existing buildings but also in the construction of new buildings. France remains the center of hempcrete construction and research, although, the construction and research projects in other countries most notably United Kingdom, Ireland, Netherlands, Switzerland, Italy, Canada, New Zealand, US and Singapore have also been undertaken. The use of hempcrete as a building material is gaining momentum around the world and the International Hemp Building Association was established in 2009 to develop, promote and support the production and use of all hemp based construction materials and their by-products in a sustainable and bioregional manner for the benefit of the ecology and communities of all regions of the world.

1.3 Problem Statement

Environmental challenges regarding climate changes mainly global warming are one of the major problems that need to be addressed. We have come a long way in developing this world through infrastructure consuming today's resources and leaving less for our generations to come in future. Ecosystem gets unbalanced if such issues will not be taken care off. One of the solution proposed to this problem by us is the construction of non-load bearing members using hempcrete. Number of countries are commercializing this material which has proved to be beneficent according to sustainability, environment and economy.

Let's talk about the development of hempcrete in Pakistan. It's in the very initial phase of development. Commercialization of hempcrete in Pakistan is another challenge. Solution to this problem is that we need to do the organized farming of hemp which is recently growing wildly at random places naturally. And advanced technology is also required for the fast and efficient cultivation of hempcrete. While working on this project, all work regarding cutting of hemp from the field, separating green part from the stem, and then fibers from the stem was done manually and it was very time consuming. All this because of the unavailability of hemp decorticator an advanced technology being utilized in the foreign countries to save a lot of time and give more efficient and better end product. Hemp decorticator is a machine which runs on hemp field and do all the operations like discussed above in one go.

1.4 Objectives

The objectives of this research are listed as following:

- To study the properties of hempcrete.
- To explore the physical and mechanical properties of hempcrete.
- To examine the thermal behavior of hempcrete and find the best optimum mixture proportions for the purpose of saving energy and development in sustainability.

1.5 Scope of study

The study is focused on the use of hemp in lime-cement (hydraulic lime and Ordinary Portland Cement OPC) paste to form the best mix for hempcrete to determine its workability, density, compressive strength and thermal properties. This research does not include the cost analysis of hempcrete in comparison to other construction materials like brick masonry used for partitioning purpose but doesn't intend to ignore the basic knowledge on the economic aspect, rather it is believed that technical issues, as explained in problem statement. The scope of the study can be achieved by carrying the research according to the standards of the methods and materials.

1.6 Significance of study

The main scope of this research is to assist in the sector of sustainability development by making the best mix for hempcrete and giving awareness to the importance of its commercialization, ultimately saving our economy as well as environment. Hempcrete holds many advantages over traditional concrete like low bulk density which helps in reducing the cost in term of low reinforcement required in structural members of building, better heat preservation and heat insulation property which makes energy efficient and green building material and low pollution for environment etc.

Large increasing gwoth in the population of the world requires a large establishment of the settlement. Thus new techniques should be designed to construct green buildings. Beside significant number of the settlement security of those buildings against a natural disaster is the durability of the construction and also the thermal conductivity. Hempcrete is a very versatile material for construction, which offers a wide range of technical, economic and environment-enhancing advantages and is sure to become a dominant material for the construction in the new millennium.

Chapter 2

LITERATURE REVIEW

2.1 General

Sustainability is fast becoming a significant concern for the construction. Companies have to comply with more complex green building standards, improve their environment health and safety records, and manage issues of waste disposal.

(Lippiatt 1999) Buildings account for thirty-eight percent of the CO_2 emissions in North America (according to U.S green building council).

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2.2 Hempcrete

'Hempcrete' is the popular term for a hemp–lime composite building material. It is created by wet mixing the chopped woody stem of the hemp plant (hemp shiv) with a lime-based binder to create a material that can be cast into moulds. This forms a non-load-bearing, sustainable, 'breathable'(vapor permeable) and insulating material that can be used to form walls, floor slabs, ceilings and roof insulation, in both new build and restoration projects

2.2.1 Introduction

Hemp is a rapidly growing, annually renewable plant Hemp is a multipurpose plant that has been domesticated for bast fibre in the stem, a multi-purpose fixed oil in the seeds, and an intoxicating resin secreted by epidermal glands.

Hemp can be harvested after about 4 months. So theoretically grown twice or three times a year. With an average yield of 10-12 tones/ha. Hemp is relatively easy to grow with low demand on inputs (pesticides, Herbicides, fertilizers). Modern applications of hempcrete includes insulation, paper, cloth, biofuel, cosmetics, food, bioremediation of contaminated soils, and bio-composite materials.

Figure 1: Hemp Plant

2.2.2 History of Hempcrete

Hempcrete was developed in France in the mid-1980s, when people were experimenting to find an appropriate replacement for deteriorated wattle and daub in medieval timber-frame buildings. A replacement was sought that would not only preserve the vapor-permeable nature of a building's fabric, thereby keeping it in good health, but also provide insulation.

He studied the mechanical and thermal properties of hemp mortars and wools using experimental and theoretical approaches(Arnaud et al 2000). Compressive strength tests were carried on hempcrete cylinders of various formulations of hemp mortar and age. It was found that compressive resistance increases with increase in binder percentage and age of the sample. A theoretical model was proposed which predicted the conductivity of bulk hemp or hemp mortar as a function of density and formulations of mortar and it was found to be in good agreement with lab results. It indicated that the conductivity of hempcrete increases with increase of density and binder content of hempcrete. Thus there is a trade-off between the insulation capability and structural strength. These must be balanced so that hempcrete can be used as a suitable building material.

Busbridge (2009) suggests that hemp is a suitable building material due to its low thermal conductivity (λ = 0.047 to 0.058W/m2K) and cellular structure and composition being very similar to some hardwoods being mainly composed of cellulose (50%), lignin (28%) and hemicellulose (20%).

(Bruijin et al. 2009) found out using a hemp material that includes both shive and fibers does not appear to create a mechanically stronger hempcrete compared to only using shive. Compressive strength values in combination with the low Young's modulus of the hempcrete mixtures tested indicate that the material in its present form cannot be used as a load bearing material. More rigidity and higher compressive strength are needed. However, it can be used in combination with other structural material to form load bearing structures.

2.2.3 Nature of Hemp

(Alex Sparrow,"The Hempcrete Book", 2014)It was discovered that the stem of the hemp plant, highly durable and comprised of strong cellulose (capable of going from wet to dry and vice versa almost indefinitely without degrading), was the ideal aggregate to add to lime mortars to achieve this effect. Thanks to the cell structure of the hemp stalk and the matrix structure created by the individual pieces of hemp inside the wall, together with the properties of the lime binder itself, a hempcrete wall has a good ability to absorb and release moisture. Also, since a great deal of air is trapped inside a hempcrete wall(both within the hemp itself and within the matrix of the hemp shiv in the cast material), it is a surprisingly good insulating material, and the density which the lime binder adds gives the finished material a good amount of thermal mass. Almost as soon as this technique was developed for the repair of historic buildings, people started experimenting with its use in sustainable new build and found that it was equally suitable for this application

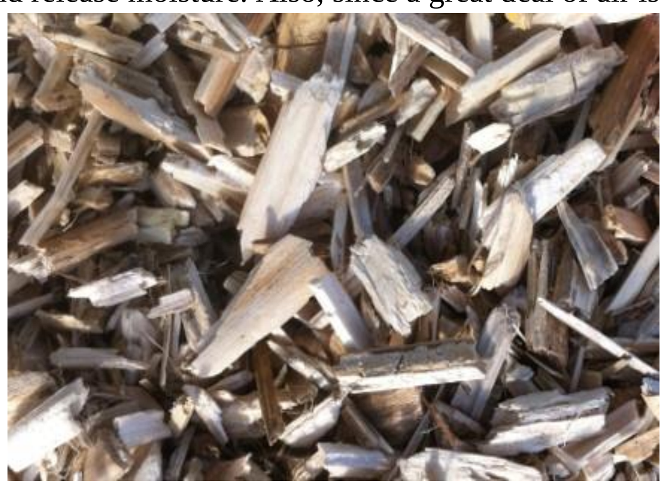

Figure 2: Hemp Hurds

2.2.4 Hemp shiv for Building

The processing of hemp shiv for use as a building aggregate (once all the leaves, seeds and bast fibers have been removed) involves breaking it up into small pieces and removing any remaining fiber and dust. Hemp shiv for building should be as dry and clean as possible, with a minimum of fines (small pieces of bast fiber) and dust present. The length of the pieces should be between about 10mm and 25mm, but this is not absolutely critical: successful walls have been made with shiv that contains shorter pieces. but it is generally acknowledged that pieces of this length produce a good matrix structure within the wall, which is beneficial for its thermal performance (a material's 'success' in conserving heat and power in a building) and vapor permeability (the degree to which a material allows water vapor through it). Walls are also regularly built with hemp shiv that contains a certain amount of fines, although the proportion must be low, otherwise the fines can soak up too much water and potentially affect the setting of the binder. The absence of dust from the shiv is far more important, since excessive dust can have an even more significant impact on the structural integrity of the wall. This is because the dust soaks up a very high proportion of the water added at the mixing stage, causing the binder to fail. The only way to avoid this is to compensate by adding a lot more water, but this will significantly extend the drying time of the hempcrete. The presence of excessive amounts of dust in hemp shiv for building is to be avoided at all costs. Hemp should be stored dry. The shiv should go in the mixer as dry as possible, to avoid excess water entering the mix, but if some areas of a bale do get wet it will not affect the quality of the finished hempcrete. However, if the shiv has been subject to prolonged exposure to moisture and starts to show signs of rotting (the color changing to black), all black areas should be scraped out and removed from the bale before adding it to the mix. There is no need for any treatment of hemp shiv with fire retardants or preservatives as long as it is being used with a lime-based binder for hempcrete. Once cast as hempcrete, the lime in the binder acts to effectively inhibit insect attack and protect from dampness and fire.

2.2.5 Vapor permeability and Hygroscopicity

Hemp shiv is a naturally vapor-permeable material, meaning that it allows water vapor to travel through it, it has a microscopic structure of tiny capillaries created by the cell walls, orientated in the direction of the plant's stem. This capillary structure accounts for the hemp shiv's hygroscopic behavior its ability to attract and hold moisture from the surrounding atmosphere, releasing it again in response to changes in the humidity of the environment. (Rhydwen, , 2011)

These properties of the hempcrete vary according to the type of lime used and in what quantity: binders rich in calcium lime allow a greater degree of vapor permeability and hygroscopicity, while those containing a higher proportion of Portland cement allow less.

The ability of the hemp shiv to allow water vapor to condense on the interior surface of its pores when environmental humidity is high, and to reverse this process when the air dries out, inhibits the formation of condensation on the surface of the walls. This is beneficial for the indoor air quality, and also has implications for the thermal performance of hempcrete

2.2.6 Insulation

Hempcrete is a medium-density material compared with other building materials and, in contrast to other walling materials (e.g. stone, brick or concrete), it is relatively lightweight, as it contains a lot of air. In the finished hempcrete wall, air is trapped not only in the microscopic pore structure of the hemp shiv but also in the air channels and pockets formed by the interlocking particles of hemp shiv in the cast material.

(Alex Sparrow,"The Hempcrete Book", 2014)Because of this trapped air, a hempcrete wall provides a much better level of insulation than other general walling materials, although compared with specific insulation products However, because hempcrete is much cheaper than processed insulation materials, and because it is of medium density, it can be (and usually is) used to create the whole thickness of a monolithic wall, with only thin render and plaster finishes or cladding on the exterior and interior surfaces. This means that the thickness of the cast hempcrete insulation is commonly between 300mm and 400mm – the whole thickness of the wall – which is enough material to provide a very high standard of insulation. Typical U-values achieved for such a wall are 0.2-0.15W/m^{2}K

2.2.7 Thermal Mass

The 'thermal mass' of a building describes its ability to absorb heat from the nearby air and release it again slowly when the air cools down, thereby 'flattening out' temperature fluctuations in the surroundings. The high thermal mass of an old building's thick walls allowed the heat produced by the fire burning during the day to be slowly absorbed by the walling materials and just as slowly released again during the night, when the fire was banked down. In the summer, the walls had the opposite effect, absorbing and holding the heat from the sun during the day and releasing it at night

Hempcrete combines the naturally insulating hemp, a cellulose material, with a lime-based binder, which gives a moderate density to the cast material as it sets hard. For this reason, hempcrete is unique among natural sustainable materials in offering a substantial degree of insulation combined with a good amount of thermal mass.

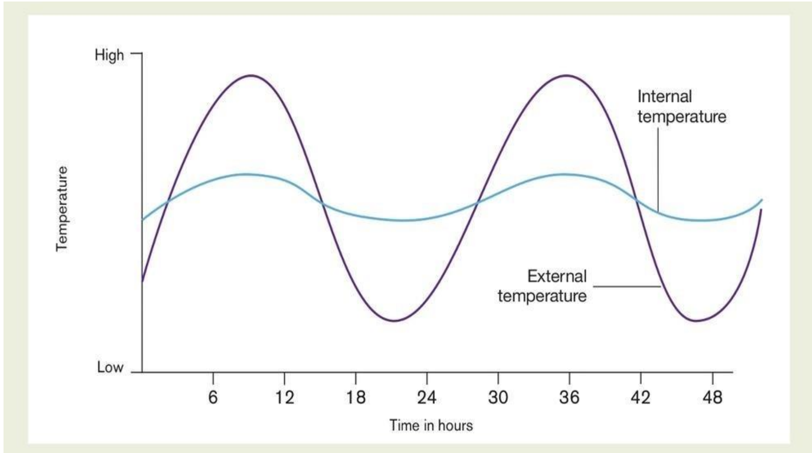

Figure 3: A building with high Thermal mass, day time and night time temperature variation (Alex Sparrow, "The Hempcrete Book", 2014)

This aspect of its thermal performance, combined with its good insulation value, makes hempcrete very efficient at regulating and maintaining internal temperatures. The building's heating and/or cooling system therefore uses less fuel than it would in an environment in which heat is lost quickly and the indoor air frequently has to be brought back up to a comfortable temperature from a low starting point.

2.2.8 Cast-in-situ Hempcrete

Cast-in-situ hempcrete refers to mixing hempcrete on-site and casting it into moulds constructed from shuttering, or formwork, to form the walls, floor or roof in the exact position that they will remain within a building. The shuttering may be temporary or permanent. Because hempcrete is a non-load-bearing material, it is always cast around a structural frame, which provides the main load-bearing element of the building. This is usually, but not always, built of timber. This applies whether it is being used in a new build or a restoration context. In new builds the usual method is to construct a simple studwork frame from softwood, and bury this with in the center of the hempcrete wall, but alterations can be made to the frame to accommodate different design details, both of the wall itself and of internal and external finishes. Mixing the hemp shiv and binder together with water can be done with a variety of types of mechanical mixer, depending on the quantity needed, the speed at which it is required, the method of application and access to the site. The freshly mixed hempcrete is either placed), or sprayed into the void created by the shuttering. It is left for a short time to take an initial set (i.e. set hard enough to bear its own weight), after which the shuttering, if it is temporary, is removed and the hempcrete is allowed to dry out gradually over the next few weeks, until it is dry enough for finishes to be applied.

Hand Placing

The hand-placing of cast-in-situ hempcrete refers to the use of manual labor to place the hempcrete into the void created by the shuttering, as well as to ferry it from the mixer to the place where it is needed. The placing process needs to be carried out carefully to ensure both the quality and certain desirable characteristics of the finished material. The manual transport of the hempcrete is done using large tubs or buckets, since it is a relatively lightweight material. The hempcrete is cast in shuttering, usually temporary, around the structural frame, which is usually placed centrally within the wall. Hand-placing is the ‘standard ’method of building with hempcrete, although, since it is quite a labor-intensive process, mechanical delivery systems have been developed. These are particularly suitable for very largescale commercial applications.

Figure 4: Application of Hempcrete

2.3 Lime

Lime is a general term that includes various forms of lime which include hydrated lime, quick lime and hydraulic lime. It may be high-calcium, magnesium or dolomite. In recent times cement has replaced use of lime to a great extent. Though cement is a remarkable material of construction yet lime has some advantageous properties like good workability, plasticity, less shrinkage on drying, durability and above all is cheap.

Ronchetti (2007) summarized the advantages and disadvantages of using lime as shown in Figure

Table 1: Table 1: Advantages and Disadvantages of Lime

Advantages	Disadvantages
Breathability Due to high porosity and high permeability of lime, this assists the drying out of buildings and the avoidance of condensation problems, which greatly contributes to the comfort of people using the buildings.	Lack of strength
Autogenous healing Rather than forming large cracks like concrete due to expansion and contraction of the building, small cracks are more likely to form and can undergo self-healing aided by water penetrating these cracks and bringing the free lime to the surface.	Setting times
Low thermal conductivity Contributes to the feeling of comfort.	
Workability Helps to achieve good joints and bonding with other materials.	
Durability Examples are the Great Wall of China, the Pantheon in Rome and the little remaining plaster on the top of the Egyptian pyramids.	

2.3.1 Physical Forms of Lime

Lime is available in two physical forms

Quick Lime:

Lime for building is produced from calcium carbonate ($CaCO_3$), found naturally in quarried limestone, chalk, coral rocks or shell. The raw materials are burnt in a kiln, causing a chemical change to occur: carbon dioxide (CO_2) is given off, leaving behind calcium oxide (CaO) a substance known as ‘quicklime’. Quicklime is a highly reactive material that produces a large amount of heat when mixed with water. It needs storing and handling very carefully, as it can easily cause serious injury during handling and can start fires if it gets damp during storage

Hydrated Lime

When quicklime is mixed with water, in a process known as ‘slaking’, calcium hydroxide ($Ca(OH)_2$) is produced. This is called ‘hydrated lime’. This lime, when applied to a building in the form of mortar or plaster, will harden slowly by ‘carbonation’ – reacting with carbon dioxide from the air.

2.3.2 Lime Classification

Lime is usually divided into three classes according to chemical composition. In many books only two have been mentioned i.e. fat lime and hydraulic lime ignoring lean lime

Fat Lime

It is obtained by calcination of nearly pure limestone, chalk or seashells. Addition of water to quick lime produces heat and increase volume two to three times. It is slow setting, takes long to harden and contain less than 5% impurities like silica and alumina. It is also termed as rich, pure or high calcium lime.

Lean Lime

It contains more than 5% of clayey impurities because of which it takes longer to slake than the fat lime. It sets and hardens slowly. It is used both for plaster and mortar.

Hydraulic Lime

It is obtained by calcination of limestone possessing appreciable quantity of silica ad alumina in the form of clay. On calcination carbon dioxide escapes leaving behind quicklime which reacts with silica and alumina forming silicates and aluminates of lime. On addition of water to finally ground lime, chemical action starts among constituents resulting in setting and hardening. It possesses less tendency to shrink.

Chapter 3

MATERIALS AND METHODOLOGY

3.1 Introduction

This chapter explains the materials used in hempcrete, the mixing proportions which we adopted, preparation of samples and the test method employed to study the mechanical and Thermal properties of it. Detail description of the experimental setup developed, and the testing method are provided.

3.2 Materials:

This section gives an outline about the various materials used in the experimental investigation. The materials are kept constant throughout the experiment as to nullify the influence of change in materials on the physical, mechanical and thermal properties of hempcrete.

3.2.1 Cement

'Bestway' Ordinary Portland Cement (OPC), grade 43, type I manufactured in Pakistan, confronting to ASTM standard C150-04, having average particle size 15.41µm, was used.

3.2.2 Water

Normal tap water of the laboratory was used. Source was kept same throughout the project to ensure consistency in results

3.2.3 Lime

Hydraulic lime was used in our experiments which is also called slaked lime. Crushed limestone was bought from a local shop in G-11 markaz, Islamabad. It was collected in bags and brought to our laboratory where water was sprinkled on it to make it in powder form. It has faster initial strength and higher compressive strength

3.2.4 Hemp

The hemp used in these experiments were acquired from different parts of Islamabad (NUST & I-13 sector Islamabad). The hemp plant was harvested, bailed and stored. The bales were processed in Hatar Industry which is near Haripur. Which reduces the hemp hurds sizes ranges up to 30 mm to 40 mm. Then it was grinded in grindstone to reduce the size of hemp hurds and to separate the fibers from the shives, which ranges between 5 mm to 15 mm in size.

Figure 5: Hemp Hurds

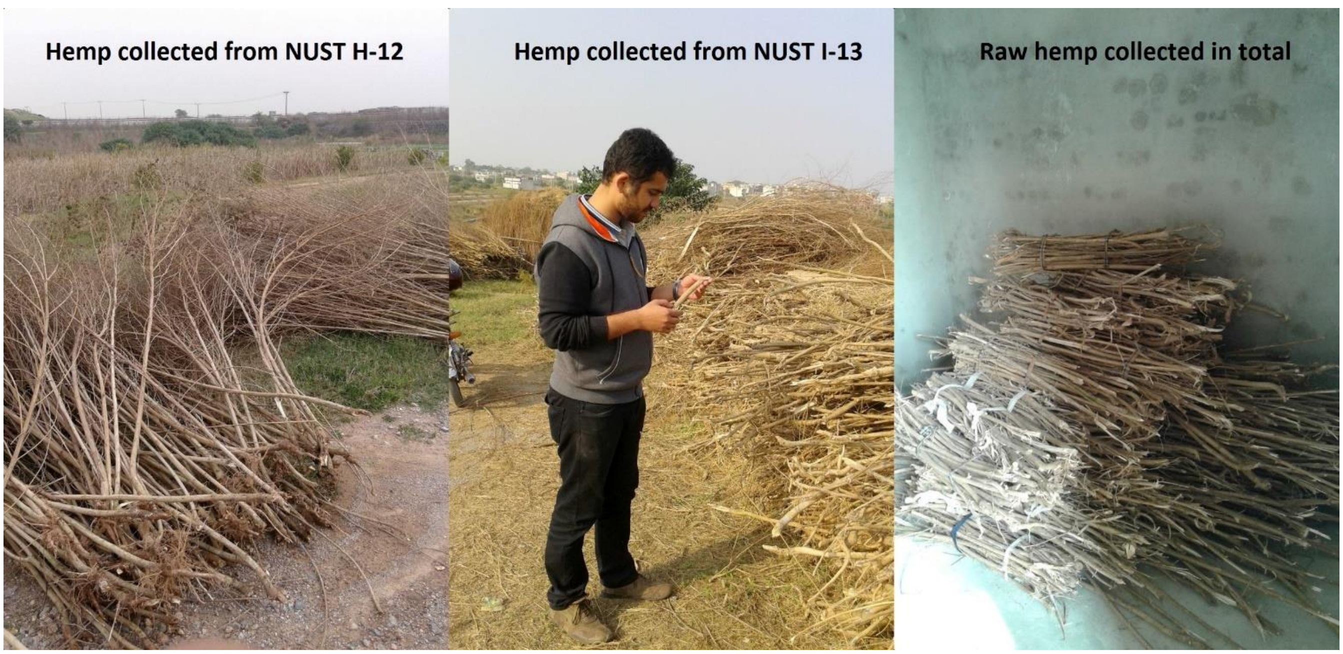

Figure 6: Collection of Hemp

3.3 Mixture Proportions

First mix design (water=50%, hemp=18.6%, binder=13.4%, lime=70% of binder and cement=30% of binder) was developed on the basis of research studies over literature. First mix design was made the benchmark for developing further mix designs for hempcrete. (Alex sparrow, "The Hempcrete Book", 2014)

Table 2: Mix design with respect to %age

Mix design	Date	Water %age	Hemp %age	Binder %age	Cement %age	Lime %age
1	11/3/2016	50	18.60	31.40	30	70
2	14/3/2016	50	18.60	31.40	40	60
3	15/3/2016	50	20.00	30.00	30	70
4	16/3/1016	50	20.00	30.00	40	60
5	17/3/2016	47	18.60	34.40	30	70
6	18/3/2016	47	18.60	34.40	40	60
7	21/3/2016	47	20.00	33.00	30	70
8	22/3/2016	47	20.00	33.00	40	60
9	23/3/2016	50	17.00	33.00	30	70
10	24/3106	50	17.00	33.00	40	60
11	25/3/2016	50	15.00	35.00	30	70
12	28/3/2016	50	15.00	35.00	40	60
13	29/3/2016	47	18.00	35.00	30	70
14	30/3/2016	47	18.00	35.00	40	60

Difference in every two consecutive mix designs was due to varied percentages of lime and cement in binder, everything else was kept same. i.e,

1. Sample 1 (water=50%, hemp=18.6%, binder=13.4%, lime=70% of binder, cement=30% of binder)
2. Sample 2 (water=50%, hemp=18.6%, binder=13.4%, lime=60% of binder, cement=40% of binder)
3. For sample 3, water percentage was kept same at first and hemp percentage was varied due to which binder percentage was changed.
4. For sample 4, only lime and cement percentages in binder were changed to 60% and 40% from 70% and 30% respectively as explained in point 3.

5. Main change in sample 5, 6, 7 and 8 was percentage of water, which was changed from 50% to 47%. And sequence of varied hemp percentages across sample 5, 6, 7 and 8 were same as that of in sample 1, 2, 3 and 4. So, 3% decrement from water caused 3% increment in binder. Mix designs for sample 6 and 8 were developed from mix of sample 5 and 7 just by varying lime cement percentages as explained in point 3.
6. For sample 9, 10, 11 and 12, water percentage was kept same as in sample 1, 2, 3 and 4.
7. Sample 9 and 10 share the same percentages except lime cement ratios. Similar is the case for sample 11 and 12.
8. Sample 13 was developed from sample 5 by changing hemp percentage from 18.6% to 18% due to which binder was increased from 34.4% to 35%. And mix for sample 14 was formed from that of sample 13 by varying lime cement percentages in binder.

Hemp percentages were changed which contributed to change the binder percentages which is shown in table

Table 3: Mix design with respect to weight

Mix Design	Date	Water (Kg)	Hemp (Kg)	Binder (Kg)	Cement (Kg)	Lime (Kg)
1	11/3/2016	4.50	1.67	2.79	0.84	1.953
2	14/3/2016	4.50	1.67	2.79	1.12	1.674
3	15/3/2016	4.50	1.80	2.18	0.65	1.528
4	16/3/1016	4.50	1.80	2.18	0.87	1.308
5	17/3/2016	4.42	1.67	3.05	0.92	2.135
6	18/3/2016	4.42	1.67	3.05	1.22	1.830
7	21/3/2016	4.42	1.80	2.40	0.72	1.679
8	22/3/2016	4.42	1.80	2.40	0.96	1.439
9	23/3/2016	4.50	1.53	2.40	0.72	1.679
10	24/3106	4.50	1.53	2.40	0.96	1.439
11	25/3/2016	4.50	1.35	2.54	0.76	1.780
12	28/3/2016	4.50	15.00	2.54	1.02	1.526
13	29/3/2016	4.42	18.00	2.54	0.76	1.780
14	30/3/2016	4.42	18.00	2.54	1.02	1.526

3.4 Sieving

Unlike coarse aggregate in concrete sieve analysis on hemp is almost impossible as the particle has not enough weight to perform sieving on it and also the fibers make it more difficult to separate them. And it is obvious that the chopped hemp would contain particles of all sized so we will assume mean size and well gradation.

We got different sizes by processing it through different machines. The bales were processed in Hatar Industry which is near Haripur. Which reduces the hemp hurds sizes ranges up to 30 mm to 40 mm. Then it was grinded in grindstone to reduce the size of hemp hurds and to separate the fibers from the shives, which ranges between 5 mm to 10 mm in size

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3.5 Preparation of Specimens

3.5.1 Batching, mixing and casting

We followed standard procedure for mixing the ingredients by hand mixing process. First we mixed up water and lime to get a uniform past and then added cement to it. After that we started adding hemp shives slowly and gradually to ensure uniform mix design. The mixing process is carried out from 5 to 10 minutes, after which a gray colored mixture is obtained, confirms uniform and good mixing.

After that we started adding the mix into a mold of 6x6x6 in-cube in three layers, each layer tamped 25 to 30 time with a tamping rod. After getting a sample with finished surface, the sample is then placed under environmental condition that trigger the process of carbonation it takes about 24 hours for initial set of the sample.

3.5.2 Curing

After one day we removed the sample from the mold, the sample is still not much hardened as it takes years to complete carbonation process so proper care had to be taken in order to avoid any effect to external texture of the sample, samples were cured for 29 days at room temperature.

3.6 Test on Fresh Hempcrete

3.6.1 Workability Test

Workability refers to the ease of handling a hempcrete mixture .Slump test was conducted to evaluate the workability of the hempcrete. Slump test was conducted on samples as per ATM C-143, Slump cone and base plate were wetted and placed on a level surface. Hempcrete was added in the cone in three steps. Slump reading was noted subsequently with the help of a ruler.

3.7 Test on Hardened Hempcrete

3.7.1 Density

The density of a material is the measure of its unit weight. Density is the mass of the object divide by its volume. After curing the hempcrete sample, the weight of the hempcrete sample was measured with the help of weight balance and the volume of the sample was known to us. As it was cube of 6x6x6 inch size, so the volume of the cube was 3.53961 x 10^3 m^3.

3.7.2 Compressive Strength

Hempcrete has low compressive strength which does not make it suitable for direct load bearing structural material. Compressive test was carried out on Universal Testing Machine. For each test specimen, cube specimens were cured 28 days prior to testing. Samples were stored in cool and dry place and were mounted on UTM. The loading rate was kept 0.2MPa/s. Compressive strength was recorded on cracking.

3.7.3 Thermal Conductivity Test

First we found out thermal diffusivity of concrete by CRD –C-36-73 method. Then by using formula we have found out the thermal conductivity of concrete. Thermal diffusivity apparatus was available at Lahore WAPDA town phase 2 in CMTL (Central Material Testing Lab).

Scope

this method of test determines the Thermal diffusivity of concrete. Thermal diffusivity of concrete equals to Thermal Conductivity divided by the Heat capacity per unit volume.

Apparatus

This apparatus consists of four parts:

1. A heating bath in which concrete samples can be raised to a uniform high temperature (212F or 100^0C)
2. A diffusion Camber in which cold water is present.
3. Temperature Recording Instruments consisting of iron constantan thermocouples, Type K potentiometer, ice bath, standard cell, galvanometer, switch and storage battery.
4. Time for recording time.

Procedure

1. Preparation of Specimen:

   The test specimens were in cube shapes. A thermocouple placed at the center of the specimen. It should be axially drilled hole 3/8 in. (9.5 mm) in diameter which has been subsequently grouted. Molded specimens had been moist-cured for 28 days prior to testing.
2. Heating:

   Each specimen was being heated to the same temperature by continuous immersion in boiling water until the temperature of the center is 212 F (100 C). The specimen was then transferred to a bath of running cold water, and suspended in the bath so that the entire surface of the specimen is in contact with the water. The temperature of the cold water was then determined by means of another thermocouples.
3. Cooling:

   The cooling history of the specimen was obtained from readings of the temperature of the interior of the specimen at 5-min intervals from the time when the temperature difference between the center and the water is 120 F (67 C) until the temperature difference between the center and water is 8 F (4 C). The data was then recorded.

Calculation

Formula to find thermal conductivity and thermal diffusivity for 1 sample is shown. The temperature difference in degrees F was plotted against the time in minutes on a semi logarithmic scale. The best possible straight line was drawn through the points so obtained. The time elapsed between the temperature difference of 80 F (44 C) and 20 F (11 C) was read from the graph, and this value inserted in equation below, from which the thermal diffusivity was calculated.

As

$$\alpha = M / (t_1 - t_2) \quad \text{Eq. (3.1)}$$

Where,

α= Thermal Diffusivity

M = Factor depending upon the size and shape of specimen

$(t_1 - t_2)$ = Elapsed time between temperature differences 80 F (44 C) and 20 F (11 C), minutes

Also,

$$\alpha = K / (\rho \times C) \quad \text{Eq. (3.2)}$$

So,

$$K = \alpha \times \rho \times C \quad \text{Eq. (3.3)}$$

Where,

K= Thermal conductivity

ρ = Density

C = Specific heat capacity

Chapter 4

RESULTS AND DISCUSSIONS

This chapter focuses on the experimental results and general discussion about the reason behind these results and followed trend.

4.1 Introduction

Since it has already been discussed that hempcrete's major role includes providing thermal insulation, so main concern of this project has also been oriented towards the testing involving thermal investigation of hempcrete over different mix designs. Mechanical property is the secondary parameter to be worked upon as hempcrete is a very low density concrete (around 15% of normal concrete) and its merely impossible to achieve more than 450psi compressive strength without using any pozzolanic materials, addition of which can further reduce the thermal properties of hempcrete. So main tests performed over different mix design were thermal conductivity test and compression test to investigate thermal and mechanical behavior of hempcrete respectively.

Hempcrete is a mixture of hemp hurds and lime (possibly including natural hydraulic lime, sand, cement) used as a material for construction and insulation. So other factors affecting the mix design are properties of hemp plants and purity of lime. So the composition of hemp components, used are shown below in a chart as,

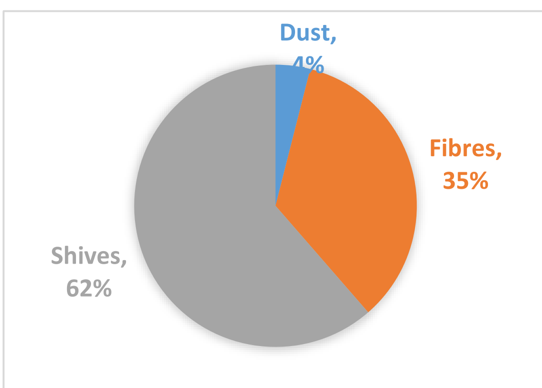

Figure 7: Average densities of hempcrete specimens for each mix design

4.2 Fresh Properties of Hempcrete

4.2.1 Workability

Workability is one of the most important factor in the application of concrete which was significantly reduced due to the presence of lime and hemp as they both are porous material with ability to absorb the moisture content. Slump test was applied to measure the slump and it was almost equal to zero.

4.3 Physical Properties of Hempcrete

4.3.1 Density

Three 6 cubic inch samples were casted and each sample weighed around 2.31 kg (5.1 lb) on average. So average density calculated was around 650.83 kg/m^3 (40.63 lb/ft^3) which in case of ordinary concrete is 2400 kg/m^3 (150 lb/ft^3).

Hempcrete is very low density and light weight concrete. It's a non-load bearing member of building and such members demand to be light. As their purpose is partitioning only, so hempcrete would not only make the building energy efficient but also cost efficient.

Hempcrete itself is a cheaper material than brick masonry (most commonly used material for partitioning now-a-days), and it would also reduce the weight on beams and ultimately on columns, hence reducing the amount of reinforcement required in the design of frame structure. So, low density is very beneficent in reducing the cost of building as well. Results for the density and variation among densities in case of each mix has shown in table and graph respectively.

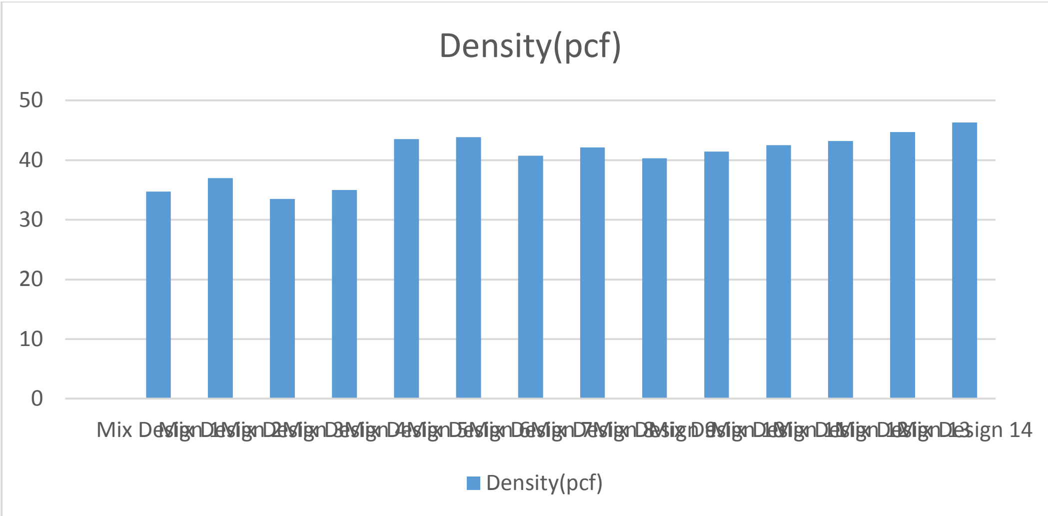

Figure 8: Density results for proposed mix designs comparative to concrete

Table 4: Average densities of hempcrete specimens for each mix design

Mix Design	**Weight (lbs)**	**Density (lb/ft^3)**
1	4.34	34.72
2	4.63	36.96
3	4.18	33.5
4	4.38	35
5	5.44	43.52
6	5.48	43.84
7	5.1	40.72
8	5.26	42.1
9	5.05	40.32
10	5.18	41.44
11	5.31	42.48
12	5.4	43.2
13	5.59	44.72
14	5.79	46.32

4.4 Thermal Properties of Hempcrete

4.4.1 Thermal Conductivity Test

Purpose of construction through hempcrete is to make structures cost efficient and mainly energy efficient. From research point of view, this is the most important test to study the flow of heat across the sample. The very low apparent density of the hemp hurds refers to lime and hempcrete lightness and low thermal conductivity. The high open porosity results in low dry thermal conductivity ranging normally between 0.06W/mK and 0.12W/mK depending on the mix design formulation which was verified from results as well. Smaller the value of thermal conductivity is, more perfect thermal insulator the sample would be. Concrete's normal thermal conductivity value is around 0.8W/mK to 1.28W/mK. So by comparing the results for thermal conductivity value to the results of thermal conductivity for hempcrete, it is very much clear that how far better insulator hempcrete is as compared to that of normal concrete. Results of thermal conductivity tests are discussed below for proposed mix designs. And graph shows the variation of thermal conductivity values for different mix designs and comparison to ordinary concrete's k-value. All values are expressed with a margin of ±5% of calculated values, because the trend was followed in such a way that the values for three different specimen for one mix design were deviating ±5% from the average value.

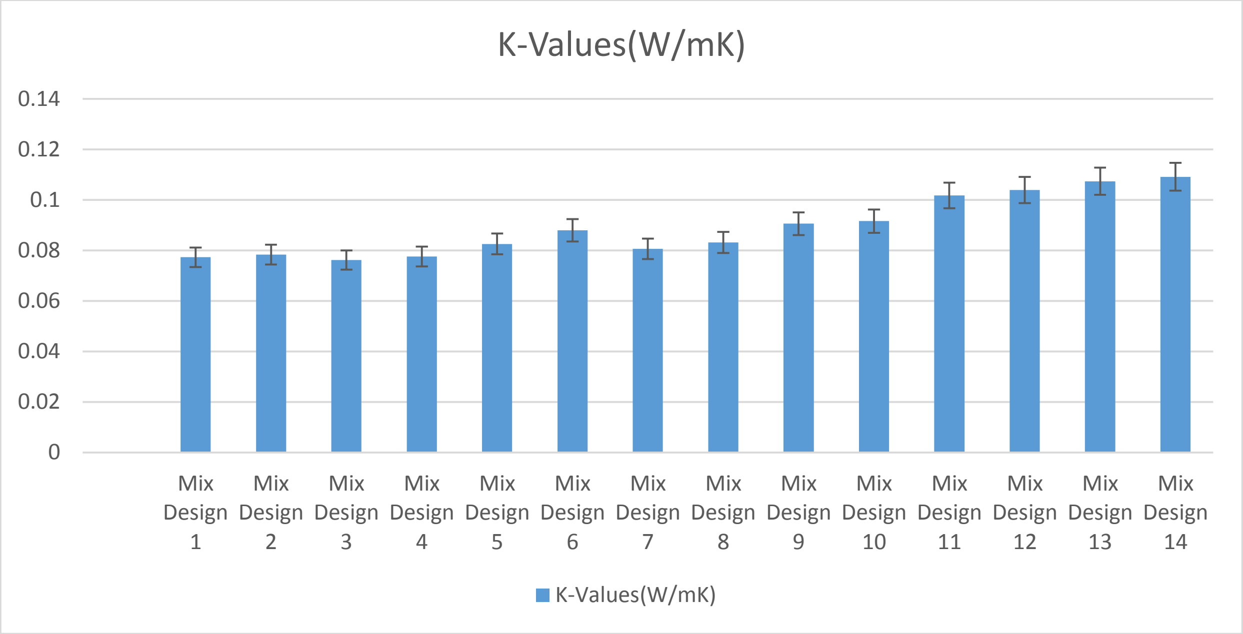

Figure 9: Heat flow results for proposed mix designs comparative to concrete

Mix Design 1

Water=50%, Hemp=18.6%, Binder=31.4%, Lime=70% of binder and Cement=30% of Binder

Thermal conductivity(k)= 0.0773W/mK

Thermal conductivity results for the first mix design are very much promising when you compare these to the values of other notable thermal insulators. Material with this thermal conductivity value can provide insulation up to 5^0C, means 5^0C temperature difference can be maintained between internal and external atmosphere. This mix design was developed by the personal understanding after doing research over different books and journals written over hempcrete. 0.0773W/mK thermal conductivity means hempcrete would allow 0.0773 watt of energy to be conducted through unit area(m^2) with temperature difference of 1 kelvin on the opposite sides. Insulation is mainly due to usage of hemp and lime and their breathable property due to pores and vacant spaces present in between hemp hurds in hempcrete. In coming samples, hemp percentage, lime percentage and further lime-cement percentages in binder.

Agnita Mukhergee states in her book “STRUCTURAL BENEFITS OF HEMPCRETE INFILL IN TIMBER STUD WALLS” about the results of experimentation results that, thermal conductivities of hempcrete of densities 548 kg/m^3 and 245 kg/m3 are 0.114W/mK and 0.071W/mK, respectively. The thermal conductivity of aerated concrete 500kg/m3 is 0.12W/mK while the thermal conductivity of fiber board insulation is 0.048W/mK. Since densities of hempcrete samples calculated were around 650.83 kg/m^3 (40.63 lb/ft^3), so result in case of mix design 1 shows that even more less value of thermal conductivity has been achieved as compared to the research work of Agnita Mukhergee which would result in even more good insulation.

Results for thermal conductivity observed in case of mix design 1 can also be compared to other known insulators as listed below in a table;

Table 5: Thermal Conductivities of various known insulators

Material	Thermal Conductivity (W/mK)
Air	0.025
Water	0.6
Concrete	0.8 - 1.28
Sand(dry)	0.35
Sand(saturated)	2.7
Glass	0.93
Mineral insulation materials	0.04
Plastic insulation materials	0.03

Hempcrete's thermal conductivity for mix design 1 is very much comparable to that of other insulators like plastic and glass etc. But hempcrete has advantage of this thing over others that it is environment friendly and would be very cheap once it gets commercialized. It would be major breakthrough in construction of green buildings and sustainable development of construction material with such efficient performance of low heat conduction.

Mix Design 2

Water=50%, Hemp=18.6%, Binder=31.4%, Lime=60% of binder and Cement=40% of Binder

Thermal conductivity(k)= 0.0784W/mK

Very minor changes were made in mix design 1 for the formulation of mix design 2. Cement was increased to 40% from 30% in binder, and thermal behavior was studied again. K-value found out to be 0.0784W/mK which is very minutely greater than the previous result in case of mix design 1 or almost equal. Increasing cement makes samples of hempcrete denser, hence reducing aeration inside sample to control the temperature and ultimately lowering down the thermal insulation.

Mix Design 3

Water=50%, Hemp=20%, Binder=30%, Lime=70% of binder and Cement=30% of Binder

<u>**Thermal conductivity(k)= 0.0762W/mK**</u>

If this k-value is compared to that of in case of mix design 1, it would be observed that value is a little less which means improved thermal conductivity in this case. Same general logic that, more the binder is, denser would be sample, and hence bad thermal properties comparatively. In sample for mix design 1, 31.4% binder was used and in this case 30%. So decreased percentage of binder has increased hemp percentage (as water is kept constant equals to 50%), and both factors have collectively improved thermal property in case of mix design 3. Let see the effect of changing lime cement percentage in binder of mix design 3 over thermal conductivity.

Mix Design 4

Water=50%, Hemp=20%, Binder=30%, Lime=60% of binder and Cement=40% of Binder

<u>**Thermal conductivity(k)= 0.0776W/mK**</u>

Comparing results with previous mix design's k-value, thermal conductivity has shown significant change. It has changed from 0.0762W/mK to 0.0776W/mK, means decrement in the thermal performance. Reason behind in increased k-value is the increased amount of cement in binder composition to 10%.

Mix Design 5

Water=47%, Hemp=18.6%, Binder=34.4%, Lime=70% of binder and Cement=30% of Binder

<u>**Thermal conductivity(k)= 0.0826W/mK**</u>

K-value has even further increased because of increased binder percentage and decreased water content, resulting in denser sample formation and hence lowering down the thermal properties with more heat conduction. These results can directly be related to that of mix design one, because only difference in these two mixes are that of water content which has been demoted to 47% from 50% keeping the hemp percentage same due to which binder content was raised to 34.4% from 31.4%.

Mix Design 6

Water=47%, Hemp=18.6%, Binder=34.4%, Lime=60% of binder and Cement=40% of Binder

<u>**Thermal conductivity(k)= 0.088W/mK**</u>

Varying lime cement percentages only differentiate mix design 6 from 5. Increased cement content has increased thermal conductivity value from 0.0826W/mK to 0.088W/mK.

Mix Design 7

Water=47%, Hemp=20%, Binder=33%, Lime=70% of binder and Cement=30% of Binder

<u>**Thermal conductivity(k)= 0.0806W/mK**</u>

These results when compared with mix design 5, it is observed that thermal property is a little improved one in this case. This is because binder in mix design 6 is 34.4% and in this case is 33%. Mix design 7 is also comparable to mix design 3 because it was developed by changing water percentage in mix 3 from 50% to 47% while keeping hemp in same percentage equals to 20%. So according to logic, mix design 3 must show better thermal behavior than mix 7 because of lower binder percentage and results also support this thing.

Mix Design 8

Water=47%, Hemp=20%, Binder=33%, Lime=60% of binder and Cement=40% of Binder

<u>**Thermal conductivity(k)= 0.0832W/mK**</u>

Increased percentage of cement in binder by 10% has increased the thermal conductivity of hempcrete from 0.0806W/mK to 0.0832W/mK.

Mix Design 9

Water=50%, Hemp=17%, Binder=33%, Lime=70% of binder and Cement=30% of Binder

<u>**Thermal conductivity(k)= 0.0906W/mK**</u>

Mix design 9 was basically developed from mix 1 by changing hemp percentage by keeping water content constant due to which binder percentage was changed. Hemp percentage has been lowered down while binder has increased. This variation has caused a significant change in the value of thermal conductivity, changing from 0.0773W/mK to 0.0906W/mK.

Mix Design 10

Water=50%, Hemp=17%, Binder=33%, Lime=60% of binder and Cement=40% of Binder

<u>Thermal conductivity(k)= 0.0916W/mK</u>

Results for mix design 10 are directly comparable to that of mix 9. Because lime cement content is the only different thing in these mix. Increased value of thermal conductivity in this case is because of increased cement content.

Mix Design 11

Water=50%, Hemp=15%, Binder=35%, Lime=70% of binder and Cement=30% of Binder

<u>Thermal conductivity(k)= 0.1018W/mK</u>

Thermal performance is going to be even more insufficient because hemp has gone to 15% and binder to 35%. In mix design 9, hemp is 17% and binder is 33% and calculated thermal conductivity is 0.0906W/mK, while in this case it has increased to 0.1018W/mK because of increased density of sample due to greater amount of binder and smaller amount of hemp.

Mix Design 12

Water=50%, Hemp=15%, Binder=35%, Lime=60% of binder and Cement=40% of Binder

<u>Thermal conductivity(k)= 0.104W/mK</u>

Increased cement content has further increased the density of sample for this mix and hence increasing the k-value from 0.1018W/mK to 0.104W/mK, when compared to previous mix design.

Mix Design 13

Water=47%, Hemp=18%, Binder=35%, Lime=70% of binder and Cement=30% of Binder

<u>Thermal conductivity(k)= 0.1074W/mK</u>

Results in case of this mix design can be compared to that of mix design 5 in which hemp is 18.6% while in this case it has been lowered to 18%, hence increasing binder to 35%. This variation is the reason that thermal conductivity has increased from 0.0826W/mK to 0.1074W/mK.

Mix Design 14

Water=47%, Hemp=18%, Binder=35%, Lime=60% of binder and Cement=40% of Binder

<u>Thermal conductivity(k)= 0.1092W/mK</u>

Comparing to the results of mix 13, increased k-value is due to the increased density of hempcrete sample, as cement content in this mix design is 40% of binder while in previous case it 30% of binder.

Table 6: Thermal Conductivity results for proposed mix designs

	Mix Design	K-value (W/mK)		Mix Design	K-value (W/mK)
Lime=70% of binder Cement=30% of binder	1	0.0773	Lime=60% of binder Cement=40% of binder	2	0.0784
	3	0.0762		4	0.0776
	5	0.0826		6	0.088
	7	0.0806		8	0.0832
	9	0.0906		10	0.0916
	11	0.1018		12	0.104
	13	0.1074		14	0.1092

4.5 Mechanical Properties of hempcrete

4.5.1 Compressive Strength

The flexibility and porosity of the hemp shiv however contributes interesting and useful qualities in terms of elasticity. But, these properties mean that hempcrete is not suitable in load-bearing applications. Maximum compressive strength can’t be achieved more than around 450psi approximately without using any chemical or mineral additives like pozzolans. But if pozzolans are added to achieve more strength then primary purpose of hempcrete can’t be achieved because addition of pozzolans fill up the cavities in hempcrete and hence reducing thermal performance and vapor permeability. So addition of pozzolans in this project has been avoided to keep the main focus on thermal insulation behavior of this bio concrete.

The combination of the flexible hemp shiv particles with the rigid setting binder forms a material which, in comparison to other building materials, also shows a high deformability under applied stress, a lack of fracturing and the ability to sustain significant changes in shape without fracturing, even after the full mechanical strength of the binder has been attained. These properties, with a little improved mechanical strength that hempcrete brings to a frame, have clear possibilities to be used for seismic design, which aims to produce safe buildings in earthquake-prone areas, structures that are capable of withstanding the shock of earth tremors without collapsing.

Table 7: Compressive Strength results for proposed mix designs

	Mix Design	**Compressive strength (psi)**		**Mix Design**	**Compressive strength (psi)**
Lime=70% of binder Cement=30% of binder	1	432	**Lime=60% of binder Cement=40% of binder**	2	439
	3	429		4	436
	5	457		6	461
	7	444		8	449
	9	441		10	446
	11	452		12	456
	13	468		14	480

Since we have already discussed the details of every mix design in every aspect regarding percentages of different content, water, hemp, binder and further lime-cement percentages as well in binder. We also have discussed about detailed inter comparison of all the mix designs.

Now we know that every two consecutive mix designs are directly comparable because only difference in both is due to that of greater amount of cement by 10% than the previous one. So, second one must show greater mechanical strength than its previous one because of greater cement content. From table, this trend can directly be observed being followed.

Figure 10: Hempcrete sample under applied stress

As it has been discussed earlier that hempcrete instead of being bearing very small compressive strength is very suitable for earthquake-prone areas due its flexible nature which prevents it from cracking even after applied compression force. This thing can be observed in a picture shown below in which hempcrete sample shows deformed shape without any cracks development.

Figure 11: Fractured hempcrete specimen on subjection to compressive stress

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

Hempcrete is a multi-purpose building material with superior insulation properties and positive carbon footprint that reduces energy costs for heating and cooling of buildings and maintains a healthy environment within buildings. Hempcrete has capability to be used as an alternative sustainable product in building construction for commercial buildings in Pakistan in response to the varying weather conditions that can change significantly throughout the year. Tests were performed to investigate the mechanical and thermal behavior of hempcrete samples for each mix and it was concluded that both properties were directly proportional to the density. Increasing density on one side if improves strength, on the other side it affects thermal insulation property as well. Density of hempcrete specimen is directly related to hemp proportion, size of hemp hurds, lime-pozzolanz or lime-cement ratios.

Owing to the growing population and environmental challenges, it is demanded that construction should be economic and buildings should be energy efficient. Hempcrete being the lighter and energy efficient construction material is highly recommended to be used by construction industry. For this purpose, it needs to be commercialized by arranging awareness seminars and conferences on national level with the participation of government officials who can perform this task in a quick better way if guided properly about its worth.

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