The Pennsylvania State University

The Graduate School

STUDY OF EFFECTIVE EXPERIMENTAL APPROACHES TO IMPROVE HEMPCRETE'S COMPRESSIVE STRENGTH

A Thesis in

Architectural Engineering

By

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Submitted in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science

August 2024

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Abstract

This research explores the enhancement of hempcrete's compressive strength to establish it as a viable, sustainable alternative to traditional concrete in the construction industry. Hempcrete, a composite material made from hemp hurds, water, and lime-based binders, offers a promising solution to reduce the environmental impact of construction activities. However, its low compressive strength compared to conventional concrete hinders its widespread application in load-bearing structures.

The primary objective of this study was to investigate various strategies to improve the compressive strength of hempcrete, including the use of alternative binders like magnesium oxide (MgO), the incorporation of additives such as metakaolin, fly ash, and nanosilica, and the optimization of mixture proportions. The research also examined the impact of sand as a fine aggregate on the mechanical properties of hempcrete.

The experimental program involved preparation and testing of three distinct mixture designs, each comprising different combinations of binders, hemp hurds, water, and additives. Mixture Design 1 focused on hydrated lime as the primary binder, while Mixture Design 2 explored the use of MgO. Mixture Design 3 built upon the findings of the first two designs, incorporating sand as an additional component to enhance compressive strength.

Hempcrete specimens were prepared in 2x2 inch cubes, following a standardized mixing, molding, and curing process. The specimens were cured for 7 days under controlled conditions of 100% relative humidity and 23°C temperature. Compressive strength tests were conducted using an MTS testing apparatus, adhering to ASTM C-109 guidelines.

The results demonstrated a significant improvement in the compressive strength of hempcrete, with values ranging from 58 psi to 655 psi, depending on the mixture design. The use of MgO as a binder, coupled with the incorporation of additives and sand, led to the most substantial enhancements in compressive strength. Notably, specimen 2LS60 from Mixture Design 3, containing 45% MgO, 5% hemp, 60% sand, and 4% nanosilica, achieved the highest compressive strength of 655 psi, representing a 2,126% increase compared to the original hempcrete specimen without additives or sand (29 psi).

The analysis of the results revealed that increasing the binder content, particularly MgO, and reducing the hemp hurd content contributed to improved compressive strength. The synergistic effects of pozzolanic additives, such as metakaolin and fly ash, and the inclusion of sand as a fine aggregate further enhanced the mechanical properties of hempcrete.

In conclusion, this study successfully demonstrated the potential for significantly enhancing the compressive strength of hempcrete through the optimization of mixture proportions, the use of alternative binders, and the incorporation of additives and sand. The findings pave the way for the development of high-performance hempcrete mixtures suitable for load-bearing applications in the construction industry. By achieving compressive strength values comparable to conventional concrete, this research contributes to the growing body of knowledge on sustainable construction materials and supports the adoption of hempcrete as an eco-friendly alternative to traditional concrete.

Keywords: hempcrete, sustainable material, magnesium oxide, fly ash, metakaolin, nano-silica, compaction, mechanical properties.

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Acknowledgements

I would like to express my deepest gratitude to my esteemed advisor, Professor Ali M. Memari, for his unwavering support, guidance, and mentorship throughout this research journey. His profound knowledge, invaluable insights, and constant encouragement have been the driving force behind the success of this study. I am truly privileged to have had the opportunity to work under his supervision and learn from his expertise.

I extend my sincere appreciation to my respected thesis committee members, Professor Hojae Yi, Professor Eshther Obonyo and Professor Corey Gracie-Griffin, for their willingness to serve on my committee and provide their valuable input. Their constructive feedback, thought-provoking questions, and expert guidance have greatly contributed to the refinement and enhancement of this work.

Words cannot adequately express my profound gratitude to my beloved Mother, Father, and my Brother, for their unconditional love, unwavering support, and endless encouragement. Their belief in me has been the cornerstone of my achievements, and I am forever indebted to them for their sacrifices and the values they have instilled in me.

Finally, I would like to express my deepest appreciation and love to my wife, Leila, for being my rock throughout this journey. Your patience, understanding, and unwavering support have been my source of strength and motivation. I am truly blessed to have you by my side, and I dedicate this thesis to you.

Chapter 1

Introduction

1.1 Background Information

Climate change refers to the long-term alterations in temperature and weather patterns, which can be caused by natural factors such as variations in the solar cycle. However, since the 1800s, human activities have become the primary driver of climate change, largely due to the burning of fossil fuels like coal, oil, and gas. The combustion of these fuels releases greenhouse gas emissions, which act as a blanket around the Earth, trapping the sun's heat and increasing temperatures. Examples of greenhouse gas emissions that contribute to climate change include carbon dioxide and methane, which are produced by activities such as driving a car using gasoline or heating a building with coal. Carbon dioxide is also released when land and forests are cleared, while landfills are a significant source of methane emissions.

As the global population and standard of living continue to rise, there has been a corresponding increase in worldwide energy consumption, carbon emissions, and waste generation. The construction industry is a major contributor to these indicators in developed countries, accounting for approximately 40% of total energy use and CO2 emissions [1-3]. When Embodied Carbon (EC) and Embodied Energy (EE) are taken into account, these percentages increase to around 50% [4, 5]. Consequently, it is crucial to identify methods to reduce the building sector's high energy and carbon demands in order to improve sustainability and minimize environmental impact.

Concrete, the most widely used material in the construction industry, with an annual production of 10 billion tons, is often considered non-sustainable due to the high EE of cement, which is produced in a kiln at 1450 ◦C. Additionally, cement has a high EC, as each ton of cement produced releases approximately one ton of CO2 into the atmosphere [1, 6]. Moreover, achieving low Operational Carbon (OC) and Operational Energy (OE) levels in buildings requires the use of insulating materials, which typically have high levels of EC and EE that are not offset by the OC and OE reductions achieved over the building's life cycle [1, 7].

To address these challenges, sustainable construction materials must be developed to reduce the environmental impact of the building sector. One innovative concept gaining attention is hempcrete, also known as Lime-Hemp Concrete (LHC). Hempcrete is a sustainable construction material composed of hemp shives as bio-aggregates and lime as a binder [8]. Hemp shives, a by-product of the hemp fiber industry, account for 65–70 percent of the hemp plant's total output by mass. They are lightweight and have a low thermal conductivity, indicating good thermal insulation properties due to their high porosity [1].

Compressive strength, one of the most important properties of construction materials, refers to a material's ability to withstand compressive loads without changing its shape or failing. While hempcrete's performance may vary slightly due to its natural composition, commercial hemp lime wall systems typically achieve a compressive strength of 0.1 to 0.2 MPa [9], which is approximately 1/20 that of concrete blocks. The addition of cement to hempcrete has been found to improve its strength. As a low-density material resistant to cracks under movement, hempcrete is highly suitable for use in earthquake-prone areas.

Several factors can influence the compressive strength of hempcrete, including the type of binder, the Hemp/binder ratio (S/B), the water/binder ratio (W/B), curing and molding conditions, compactness, and the use of nanoparticles in the mixture. Studies have examined how different curing conditions (30%, 75%, and 90%), binder content, and particle size affect the setting, hardening, and critical mechanical properties of the material, such as compressive strength and modulus of elasticity [10]. These studies indicate that the young modulus of hempcrete with intermediate performances (compressive strength between 0.19 MPa and 1.18 MPa) can range from 7-160 MPa [11]. Despite variations in hempcrete mixture compositions, the compressive strength measured in different studies remained below 1 MPa for both molded and sprayed mixtures. Due to carbonization, the compressive strength of hempcrete increases over time. It has been reported [12] that under outdoor conditions, the compressive strength of hempcrete reached 0.43 MPa and 1.01 MPa after one and ten months of curing, respectively. In contrast, samples with the same properties only reached a compressive strength of 0.73 MPa after a 10-month indoor curing period [12].

In summary, the construction industry's significant contribution to energy consumption, carbon emissions, and waste generation necessitates the development of sustainable construction materials like hempcrete. By utilizing hemp shives and lime as primary components, hempcrete offers a low-density, thermally insulating, and crack-resistant alternative to traditional concrete.

While its compressive strength is lower than that of concrete, various factors such as binder type, mixture ratios, curing conditions, and the use of additives can influence and improve its mechanical properties. As research continues to explore the potential of hempcrete, this innovative material holds promise for reducing the environmental impact of the building sector and promoting sustainable construction practices.

1.2 Objective

This research endeavors to transform hempcrete from an auxiliary insulation material into a robust load-bearing composite, suitable for the construction of structures like single-story homes. This shift towards using hempcrete as a primary building material is pivotal for promoting sustainable construction practices that maintain structural integrity while advocating for environmental stewardship. Through a series of methodical experimental approaches, this study will concentrate on enhancing binder formulations, fine-tuning the proportion of hemp to binder, applying innovative compaction methods, and integrating additives and nanoparticles into the hempcrete composition.

This study is structured around several key objectives designed to enhance the utility of hempcrete in the construction sector:

1. Undertake an exhaustive review of existing literature and historical studies to build a comprehensive understanding of the subject. This foundational knowledge will facilitate a systematic exploration and classification of various binders, including traditional natural hydraulic limes, pozzolanic substances, and modern alternatives like magnesium oxide-cement, along with innovative additives such as class F fly ash, metakaolin, GGBS, and nano-silica. The efficacy and compatibility of these materials in bolstering hempcrete's compressive strength will be critically analyzed.
2. Experiment with diverse hemp-to-binder ratios, aiming to find an optimal mix that strikes a perfect balance between strength and environmental sustainability, thereby minimizing the ecological impact of the final product.
3. Delve into the compaction process of hempcrete mixtures to understand the relationship between density and mechanical strength. The goal is to identify and apply compaction

techniques that improve the compressive strength of hempcrete, making these methods adaptable for large-scale use.

4. Investigate the use of nanotechnology and a variety of additives to fortify hempcrete's mechanical properties. The study will examine how nanoparticles affect the composite's microstructure and overall performance, with a focus on enhancing durability and strength.
5. Perform detailed testing on different hempcrete mix designs to evaluate their workability and compressive strength, following established standards such as ASTM-C109 to ensure the validity and reproducibility of the results.
6. Execute pilot tests to gauge the practical application of the improved hempcrete mixtures in real-world scenarios, measuring their compressive strength against conventional building materials.

By meeting these objectives, the study aims to contribute valuable insights towards making hempcrete a practical and sustainable alternative to traditional construction materials. Achieving an equilibrium between environmental sustainability and structural efficiency, this research endeavors to advance the adoption of hempcrete in structural applications, heralding a new era in eco-conscious building practices.

1.3 Thesis Outline

This thesis is organized into five chapters, systematically presenting the research undertaken and its findings. Chapter 2 lays the groundwork with a thorough literature review, summarizing the current state of knowledge and previous research pertinent to hempcrete and its applications. In Chapter 3, the research methodology is outlined, detailing the selection of materials, preparation methods for hempcrete mixtures, and the experimental framework designed for this study. The focus of Chapter 4 is on the empirical investigation, where various hempcrete specimens are subjected to compressive strength testing. This chapter also delves into the exploration of different binders, the incorporation of additives, and the utilization of nanoparticles, presenting a detailed analysis of their impact on the hempcrete's performance. The findings from these experiments, including discussions on their implications, are comprehensively presented and scrutinized. Chapter 5, the concluding chapter, synthesizes the key insights derived from the research, offering conclusions drawn from the experimental results. It also outlines recommendations for future research, aiming to contribute to the advancement of hempcrete as a sustainable construction material.

Chapter 2

Literature Review

2.1 Introduction

The construction sector is a significant energy consumer, accounting for nearly 40% of total energy consumption, with 60% of this energy being used for indoor heating and cooling in developed countries [13]. It is responsible for approximately 32% of global energy demand and contributes to 30% of energy-related CO2 emissions [14]. In Europe, the building sector is responsible for nearly one-third of greenhouse gas emissions [15], while the construction material sector accounts for 10% of global CO2 emissions [16]. To address this issue, researchers are seeking eco-friendly, sustainable, and carbon-negative materials that can partially or fully replace carbon-positive materials in the construction and building industry. Natural resources such as plant or animal fibers and straw have been used as building materials since ancient times, with hemp being utilized as early as the 6th century AD [17].

Hempcrete is regarded as a carbon-negative composite material due to its ability to sequester CO2 during the growth of hemp and the manufacturing and installation processes, which is crucial for mitigating the impacts of climate change (see Figure 2-1) [18]. Carbon sequestration refers to the capacity of certain materials to absorb and store atmospheric carbon dioxide in a stable form. This property is particularly important in the context of hempcrete because of the unique characteristics of the hemp plant. Hemp actively participates in the carbon cycle, a natural process essential for maintaining ecological balance. During photosynthesis, hemp efficiently absorbs CO2 from the atmosphere and converts it into biomass, storing a significant portion in its roots, stems, and leaves [19]. When hemp is used to create hempcrete, a mixture of hemp shiv (the woody core of the hemp stalk), lime binder, and water, it brings along a material that has sequestered carbon during its growth. The lime binder in hempcrete further enhances carbon sequestration through carbonation, a process in which lime absorbs CO2 from the atmosphere as it sets and hardens over time. This dual action of hemp and lime binder makes hempcrete an effective carbon store, locking away CO2 for the lifetime of the building [20].

The carbon sequestration mechanism of hempcrete consists of two components: biogenic and non-biogenic. The biogenic component, hemp shives, contains 45% carbon [21], which is a direct result of the atmospheric CO2 absorbed by the plant through photosynthesis during its growth. The non-biogenic component, the lime binder, surrounds the hemp shives in a hardened matrix and also consumes CO2 through carbonation [22].

By using hempcrete in construction, we can reduce the overall carbon footprint of buildings, which is a significant step towards sustainable construction practices, considering the building industry's major contribution to global greenhouse gas emissions. The carbon sequestration capabilities of hempcrete, contributed by both the hemp plant and the lime binder, make it a highly beneficial material in the effort to combat climate change, highlighting its potential as a key player in sustainable and environmentally responsible construction practices.

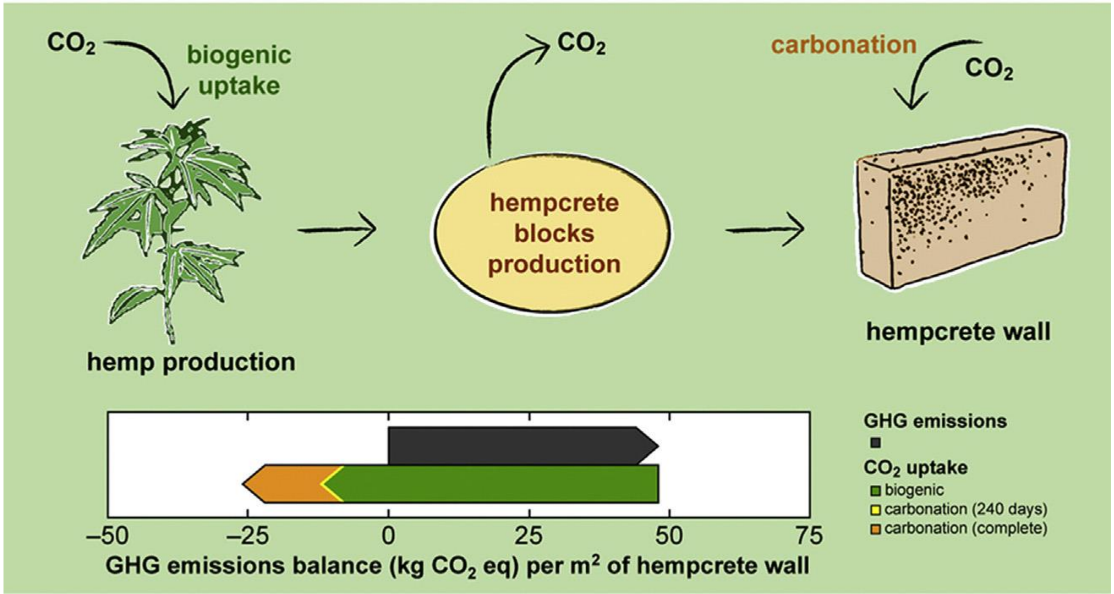


Figure 2-1. Illustration of carbon emission and sequestration of hempcrete with a net emissions balance demonstrating carbon negativity. Adapted from [23].

Recently, hempcrete, also known as hemp-lime composite, has garnered significant attention as a natural resource for building materials. This composite consists of a mineral binder and plant-based aggregates derived from the woody core or shiv of the hemp plant, which are ground to a length of 5–40 mm [24]. The properties of hempcrete are influenced by several factors, including the type of binder used, the ratio of aggregate to binder, the size and porosity of the aggregates, and the level of compaction applied during the manufacturing process [25]. The use of hempcrete in construction began in the early 1980s [26], and as illustrated in Figure 2-2, it has proven to be a suitable material for various applications such as walls, floors, and roof insulation

[18]. This versatility can be attributed to hempcrete's desirable characteristics, including its lightweight nature, excellent moisture buffering capabilities, effective thermal insulation, and impressive acoustic properties [25, 27]. These features make hempcrete an attractive choice for builders and architects seeking sustainable and environmentally friendly building solutions.

Figure 2-2. Different forms of Hempcrete. Adapted from [28].

Hempcrete, a versatile and sustainable building material, finds application in various parts of a structure, including floors, roofs, and walls. When used in flooring, hempcrete provides insulation and vapor permeability, but it often requires considerable thickness to achieve optimal efficiency. To enhance thermal mass and minimize thermal bridges, hempcrete is frequently combined with other similar materials in floor construction. Compared to its use in walls, hempcrete for flooring necessitates a higher proportion of binder, which can compromise its insulative properties. Typically, hempcrete floors are installed over a water-resistant and insulating sublayer, eliminating the need for plastic damp-proof membranes. Sustainable sub-base materials, such as coated expanded clay or recycled glass foam aggregate, are preferred choices. The overall thickness of hempcrete floors is generally less than that of conventional concrete floors, with the hempcrete layer being relatively thin (80-150 mm) to ensure structural stability, while the sub-base thickness compensates for thermal resistance (120-180 mm) [28].

Due to cost considerations, the use of hempcrete in internal floors is limited, except in cases where superior acoustic and thermal properties are required between building levels. In such instances, timber battens are employed to provide structural support in hempcrete ceilings. When it comes to roofing applications, hempcrete is cast between rafters, utilizing a very low-density mix to achieve better insulation. Alternatively, if a hempcrete ceiling is not desired, insulation can be cast onto permanent shuttering made from breathable carrier boards, such as wood wool boards.

Cast-in-situ hempcrete is formed on-site using either temporary or permanent shuttering. This process involves creating a simple softwood studwork for structural support and casting hempcrete between the studs. The breathability of hempcrete allows for the use of untreated timber in this method. Hempcrete can be placed either manually or using mechanized spray, with the latter employing finer hemp shives. Although cast-in-situ hempcrete offers higher insulative performance compared to prefabricated hempcrete blocks, it has lower mechanical strength, and its final performance is less predictable due to variable production and drying conditions on site [29].

On the other hand, prefabricated hempcrete blocks are advantageous for large-scale projects. Produced in controlled environments, these blocks exhibit more predictable properties and their off-site drying reduces on-site construction time. The blocks are connected using a thin mortar of hydraulic lime and sand, either between the blocks or around a timber frame. To ensure sufficient structural integrity during manufacture, storage, or transport, denser hempcrete mixtures with higher binder content are used, which can potentially reduce insulation performance and sustainability. Despite attempts to create structural hempcrete blocks, the necessary increase in binder leads to decreased insulation, making them less suitable for exterior walls [30, 31].

When constructing walls with hempcrete blocks, a thin mortar layer of hydraulic lime and sand is used. This mortar must strike a balance between minimizing thermal bridging and maintaining wall integrity. While hempcrete blocks typically meet modern standards, additional insulation methods can be employed when necessary. Combining hempcrete blocks with in-situ hempcrete can be an effective and sustainable approach.

One notable advantage of hempcrete blocks over in-situ hempcrete is the quicker construction process. Cast-in-situ hempcrete requires weeks of drying and is influenced by climate, whereas plastering and rendering of hempcrete block walls can commence immediately after construction. Hempcrete blocks are less sensitive to temperature, exposure, humidity, and drying conditions, which streamlines the building process [32].

Maintaining the breathability of hempcrete is essential, necessitating the use of vapor-permeable renderings. Options include breathable plasters and finishes or external cladding with vented air gaps. The permeability of the plasters should match or exceed that of hempcrete, with two-coat lime finishing plasters often chosen for cost efficiency. Clay plasters, offering aesthetic appeal and moisture regulation, are another option for internal use. Both clay and lime plasters can be reinforced with hemp shiv, fines, chopped straw, or commercial meshes. Compared to lime plasters, clay plasters provide superior moisture buffering, higher thermal mass, and lower carbon footprints, aiding in the regulation of moisture in hempcrete walls. Lime plasters, more suitable for external applications, are durable and can self-repair small cracks, especially air-limes and feebly hydraulic limes. Plastering with lime is best carried out at temperatures between 8°C and 22°C [33].

In certain situations, particularly on facades with limited sunlight where moisture may accumulate, plastering may not be ideal. In such cases, cladding with a vented gap is preferable, accompanied by measures to prevent moisture ingress and ensure wall airtightness. During construction, it is crucial to protect hempcrete walls from rainwater.

Due to hempcrete's non-loadbearing nature, a structural frame is necessary for windows, doors, and cupboards. Window frameworks typically involve a box form of timber elements with a lintel to transfer loads. Airtightness and watertightness are achieved using sealing beads made from materials such as stainless steel, PVC, glass-fiber, or hardwood, with hardwood beads sealed post-rendering using burnt sand mastic [28, 31].

In high-moisture areas like kitchens and bathrooms, hempcrete's moisture-regulating properties are advantageous. Non-porous materials, such as tiles and waterproof paints, should be limited to areas prone to water accumulation. Hempcrete is unsuitable for shower walls due to the potential for degradation from stagnant water. Using moisture-regulating renderings, such as clay plasters, enhances wall breathability in these rooms.

When working with hempcrete, it is crucial to take into account the material's high alkalinity and its potential impact on other materials, particularly metals. Hempcrete's alkaline nature can cause corrosion in metals like steel if they are not adequately protected. To prevent this issue, any structural fixings that come in direct contact with hempcrete should be made from materials other than ungalvanized steel. Instead, these fixings should be properly galvanized to withstand the alkaline environment. Furthermore, secondary materials, such as screws and joist hangers, should be chosen with care. Stainless steel, galvanized, or coated options are recommended to ensure their durability and resistance to corrosion when used in conjunction with hempcrete [31]. By selecting compatible materials and taking the necessary precautions, builders can ensure the longevity and structural integrity of hempcrete constructions.

2.2 Definition and Properties of Hempcrete in Greater Detail

Hempcrete is understood to be a bio-aggregate-based material that is formed by wet-mixing the chopped woody core of the hemp plant with a lime binder, as shown in Figure 2-3. The incorporation of hemp in construction is a long-established practice. Evidence of hemp shives in the construction of a French bridge dating back to the 6th century AD has been uncovered by archaeologists [34]. In its contemporary form, hempcrete first emerged in France during the 1980s as builders sought effective alternatives to repair degraded wattle and daub sections in medieval timber frames. It was discovered that the application of ordinary Portland cement mortars to these sections caused moisture retention, leading to further deterioration of the timber structures [30, 31].

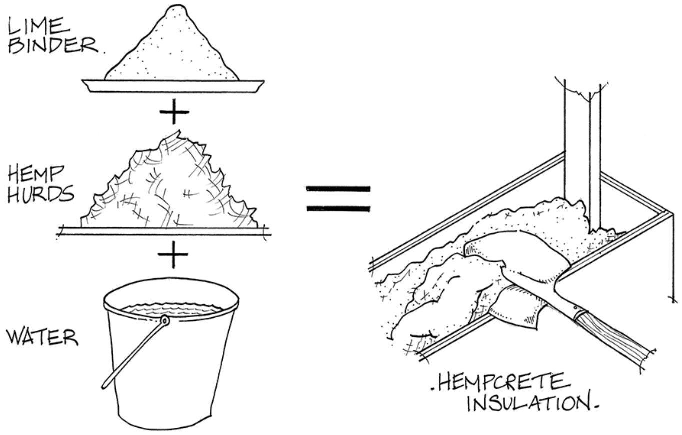


Figure 2-3. Common ingredients used for hempcrete material mixture.

Hemp is commonly referred to as the varieties of the Cannabis sativa plant, a once overlooked crop now experiencing rising popularity among professionals and entrepreneurs. Historically cultivated by humans since around 8000 BCE [35] for non-recreational purposes, hemp offers a significant dry matter yield of 7-34 metric tons per hectare annually [36]. Its cultivation is not only easy but also provides a high operating margin, yielding substantial economic benefits for farmers and ensuring a consistent, sustainable source of raw materials for various industries, including construction.

The botanical designation for hemp is Cannabis sativa L., which is divided into three subspecies: Cannabis sativa (used industrially and as the source of technical fibers), Cannabis ruderalis (wild hemp), and Cannabis indica L. (characterized by high levels of tetrahydrocannabinol (THC), the primary psychoactive compound) [37].

The structure of the hemp stem is composed of two distinct cellular zones: the inner woody core or pith and the outer bark or epidermis [37, 38]. Each of these zones includes several layers, as depicted in Figure 2-4 and described in the accompanying text.

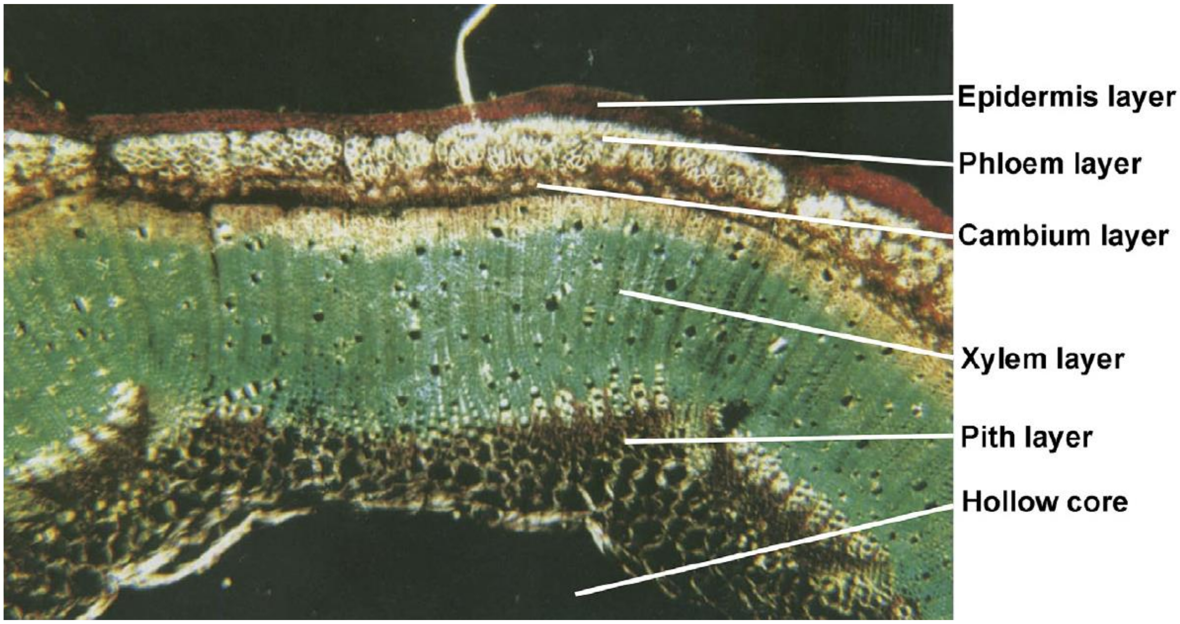


Figure 2-4. An optical micrograph of a hemp stem. Adapted from [39].

The epidermis and phloem layers are the parts of the hemp stalk most frequently utilized. It is in the phloem layer where the vital task of transporting organic nutrients from the sites of photosynthesis to other plant parts is carried out. Originating from this layer, the primary fibers of the plant are notably long. Adjacent to the cambium layer, secondary fibers are found. Once harvested and combined, these primary and secondary fibers are known as technical fibers. Below the cambium, layers predominantly consist of dead cells arranged to facilitate the transport of water and soluble minerals. The Xylem layer is made up of vessels and fibers [21, 23, 37].

Typically, the cambium layer and layers beneath it yield the hemp shives/hurds utilized in producing hempcrete. These shives lack the epidermal and phloem layers, which are removed for use in textile manufacturing and other fibrous products such as insulation. As illustrated in Figure

2-4, hemp shives are characterized by their porosity and the presence of interconnected voids capable of absorbing significant amounts of water [21, 23, 37]. The hemp hurds/shives are cut into lengths ranging from approximately 5–25 mm, commonly processed with a decorticator; as depicted in Figure 2-5.

Figure 2-5. Hemp shives with different sizes. Adapted from [40].

The composition of hemp hurds (Table 2-1) varies depending on the growing environment and available nutrients. The structure of the hemp plant at the cellular level is similar to timbers such as birch (lat. betula) or willow (lat. salix) [41, 42].

Table 2-1. Composition of Hemp hurds

Study	Cellulose	Hemicellulose	Lignin	Pectin	Wax	Protein	Ashes
Vignon et al. [39]	44%	18%	28%	4%	1%	3%	-
Thomsen et al. [43]	34-44%	31-37%	19-28%	4%	1%	-	1-2%
Evrard [41]	50-60%	15-20%	20-30%	-	-	-	4-5%

The composition of hempcrete, particularly the cellulose, hemicellulose, lignin, pectin, and ash content found in hemp shiv, the woody core of the hemp plant, significantly influences its distinctive properties. Cellulose, a strong and durable fiber, imparts tensile strength to hempcrete. Its highly porous structure contributes to hempcrete's excellent thermal insulation, moisture regulation, and sound absorption properties. Hemicellulose, which binds cellulose fibers together, enhances moisture regulation due to its hygroscopic nature, allowing hempcrete to absorb and release moisture, thus regulating indoor humidity.

Lignin provides compressive strength and stiffness to hempcrete, and its complex aromatic structure protects it from decay, rot, and makes it more fire-resistant. Pectin, found in the middle lamella between plant cells, acts as an adhesive, binding the lime and hemp shiv together in hempcrete. Interestingly, removing pectin can improve hempcrete strength. Lastly, ash, a source of silica, can react with lime to form calcium silicate hydrates, improving hempcrete's strength. However, a high ash content might reduce strength if it negatively impacts the hemp-lime bonding.

Lime is derived from calcium carbonate (CaCO3), which can be found in quarried limestones, coral rocks, chalk, or shells. To produce lime, limestone is heated in a pre-heater with a counter-current combustion process, where flue gases flowing in the opposite direction dry and heat the limestone [44]. The preheated material is then introduced into a rotary kiln, where its temperature is homogenized. The kiln's rotation and inclination force the material towards the outlet, where a gas burner is situated. The limestone absorbs the generated heat through convection and radiation, and when it reaches the calcination temperature, the material starts to decompose. During calcination, carbon dioxide (CO2) is released, and quicklime (CaO) is collected [31, 45]. The residual CO2 content depends on the customer application but usually ranges between 0.1-0.2 mass percent. According to the mass balance, at full calcination, 44% of the feed is released as CO2. Lime production is characterized by two types of emissions: combustion emissions associated with carbon-based fuel combustion and process emissions associated with the amount of CO2 emitted by the raw material during production. The latter account for 60-75% of the total CO2 emissions [44].

For building applications, quicklime is mixed with water (slaking), producing calcium hydroxide (Ca(OH)2). The material reacts with carbon dioxide in the air and hardens through carbonation, converting back to calcium carbonate (CaCO3). This entire process of limestone treatment is known as the lime cycle [31, 44]. Studies suggest that a 1m3 hempcrete box consisting of hemp shives and 90% hydrated lime has a carbon sequestration potential of 470 kg of CO2, while reaching 307 kg of CO2 sequestration in a 28-day growth period [21, 22].

Hempcrete's setting occurs in two phases. During the initial setting phase, hempcrete needs formwork support until its strength is sufficient to carry its self-weight. The second setting phase begins when the formwork is removed and lasts for weeks. During this phase, excess water dries out, and hempcrete continues to harden until reaching its final strength. The binder's nature and characteristics significantly influence the setting process and the end product's properties. Depending on the application, the desired properties of the end results may differ. Choosing the appropriate binder and ingredient proportions is essential to achieve the desired properties. However, in general, all hempcrete binders should allow hempcrete to reach sufficient strength levels to carry its self-weight after the initial set, retain enough permeability to let excess water drain, and achieve sufficient long-term structural strength [30, 31].

2.3 Binder Characteristics of Hempcrete

The binder is the most crucial component of any concrete, and hempcrete is made with a lime-based binder due to its abundant supply and low production emissions. Lime is also considered superior to cement for use with hemp shiv [46]. Lime's ability to absorb large amounts of water and obstruct hydraulic movement can prevent the interior parts of the concrete from setting properly. The binder used and its dosage significantly influence the mechanical, thermal, hygrothermal, and acoustic properties of hempcrete [47-51]. Hydrated lime (Ca(OH)2) is the most commonly used binding agent in hempcrete.

The hydraulicity of lime is a crucial characteristic, and researchers have employed pozzolanic elements such as fly ash, GGBS, and silica fume to enhance the strength and setting qualities of hydrated lime [42, 51]. The combination of lime and pozzolana is not a new concept, as ancient structures that have remained structurally sound demonstrate the potential of lime to build strength over time. Walker [42, 51] discovered that hydrated lime performed better than fly ash when combined with GGBS and metakaolin. Activators like sodium sulphate and calcium chloride can be used to overcome the limited reactivity of lime and fly ash, promoting the formation of C-S-H, ettringite, and mono-sulphoaluminate, which contribute to early and 28-day strength improvement.

Magnesium-based binders can also be used as a replacement for lime to increase the strength of hempcrete. These binders have a significantly higher compatibility with organic fillers compared to calcium binders [52]. During the mixing process, calcium binders create an alkaline environment that allows lignin and other organic components to be released from bio-based products, slowing the setting of lime [53]. There are two types of magnesium-based binders: magnesium oxychloride cement and magnesium phosphate cement, which differ in the amount of chemicals added to the mixture, the required hardening conditions, and the final properties of the material. Despite receiving less attention than lime, both magnesium binders are viable alternatives due to their high strength, fire resistance, and compatibility with organic aggregates [54-56].

Studies have been conducted on the use of lime mixed with various materials such as pulverized fuel ash, ground granulated blast furnace slag (GGBS), metakaolin, silica fumes, pumicite, and clays in hempcrete. Walker [42, 57] found that adding approximately 25% of hydraulic and pozzolanic material improves performance. In their hempcrete investigation, Walker [42, 57] tested nine different pozzolans readily available in and near Ireland for their reactivity with hydrated lime. Their research indicated that calcium silica hydrates are the compounds responsible for the strength of lime-pozzolana concrete. However, hydrated lime exhibited better reactivity with GGBS and metakaolin compared to other products like pulverized fuel ash.

Tronet et al. [24] used the same commercial binder (Tradical® PF 70 by Lhoist Group) as Walker [42] in their study and disclosed the binder's composition as 75% hydrated lime Ca(OH)2, 15% hydraulic lime, and 10% pozzolana (undisclosed) [24].

Sassoni et al. [58] revealed exceptional mechanical performance values for their hemp composites made using a patented binder manufactured from three components: magnesium oxide, magnesium sulfate or magnesium chloride solution, and a reactive vegetable protein in a flour-like form [58, 59]. Although Sassoni et al. [58] did not disclose the curing characteristics, such as setting time and type of curing, they briefly explained the manufacturing method, showing that the mixed hempcrete was subjected to a thermo-mechanical pre-treatment. It is worth noting that the binder is suitable for producing both hempcrete and hemp composites for replacing formaldehyde-bonded wood boards.

2.4 Density

Hemp shives have a lower density compared to conventional concrete aggregates, resulting in hempcrete having a significantly lower density than regular concrete. Ordinary Portland cement (OPC) concrete typically has a density of 2400 kg/m3, regardless of its grade, while hempcrete exhibits a wide range of densities due to variations in the mass composition of the composites. Ohmura et al. [60] suggest that the density of a product is determined by its spatial orientation within the volume. In the case of hempcrete, both the material composition and the manufacturing process influence the density. Additionally, compaction plays a role in density, with higher density hempcrete exhibiting higher strength. The amount of humidity trapped in the walls also has a minor effect on density. Sinka et al. [61] highlight that density fluctuations heavily impact the thermal performance of hempcrete, with thermal conductivity increasing by 0.005 W/m.K for every 50 kg/m3 increase in density.

Ohmura et al. [60] demonstrate that the nature of spatial orientation within the product's volume affects its density. As the composition of the material and the manufacturing process change, so does the density of hempcrete. Consequently, hemp composites with higher strength have a higher density due to the degree of compaction [62]. The amount of humidity trapped in the walls has been shown to have a negligible effect on density. However, variations in density can significantly impact thermal performance, making it an important variable. This postulation is supported by the studies conducted by Sinka et al. [61], which found that the thermal conductivity of lightweight hemp concrete (LHC) increases by 0.005 W/m.K for every 50 kg/m3 increase in density.

A commercial hempcrete organization produces a product with a density of 275 kg/m3 [23, 63], while Sutton et al. [9] report that the density of hempcrete varies between 270 and 330 kg/m3. Sassoni et al. [58] manufactured hemp concrete using a patented binder, achieving densities ranging from 300 kg/m3 to 1300 kg/m3. The binder to shiv ratio by mass is denoted as B/S, while the water to binder ratio by mass (W/B) is equal to 0.55 for all LHC mixtures. This value aligns with the findings of Nguyen et al. [64, 65]. Currently, conventional lime concretes or mortars also use similar W/B ratios: 0.5 for high-density lime (NHL5), 0.55 for medium-density lime (NHL2), and 0.6 for limes with a bulk density lower than 600 kg/m3. Lanos et al. [66] determined that the ideal W/B ratio for hempcrete is 0.56 for natural hydraulic lime (NHL) to optimize lime porosity and restrict water suction by shiv into the fresh mixtures.

2.5 Compressive Strength

The ability of a material to resist compressive loads without failing or deforming is a measure of its compressive strength. As hempcrete is derived from hemp, a natural product, its compressive performance may exhibit slight variations. Compared to concrete, hempcrete's compressive strength is significantly lower, making it unsuitable for use as a standalone load-bearing material. Several factors contribute to hempcrete's limited compressive strength, including the arrangement of the shives, the high flexibility of the aggregate, the nature of the binder, and the end product's high porosity.

The majority of studies consistently report hempcrete samples with compressive strengths below 1 MPa. However, there are notable exceptions, such as the research conducted by Tronet et al. [24], where the use of commercial pre-formulated lime-based binders resulted in compressive strengths reaching 4.74 MPa. Similarly, Sassoni et al. [58] achieved a maximum compressive strength of 3.04 MPa using a patented MgO-based binder with water-soluble vegetable protein [58]. Kioy's studies also indicated hempcretes with increased densities and higher compressive performances reaching 1.98 MPa, although the mixture composition was not specified [22, 23].

Murphy et al. [67] examined the mechanical properties of hempcrete made with commercial binders and hydrated calcitic lime. The results showed that composites prepared with commercial hydraulic binders exhibited higher final compressive strengths compared to those made with calcitic lime. Murphy et al. [67] also found that increasing the binder concentration in hempcrete leads to improved compressive strength. They used the following notations: CL90H10 for 10% hemp, CL90H50 for 50% hemp, and CL90H75 for 75% hemp with 90% calcitic lime binder; TH10 for 10% hemp, TH50 for 50% hemp, and TH75 for 75% hemp with Tradical® binder.

O'Dowd and Quinn [68] created hemp-lime composites with compressive strengths ranging from 0.65 to 1.9 MPa. They observed that increasing the hemp content beyond a 3:1 volumetric ratio had a minimal impact on further reducing the composites' compressive strength.

Tronet et al. [16, 24] investigated the compressive behavior of hempcrete and discovered that limiting the binder proportions enhances the mechanical properties of hempcrete blocks. Jami et al. [21] stated that the strength of hardened hempcrete is determined by the characteristics and mix proportion of the binder used in the formulation.

Several researchers have reported that compaction significantly improves the compressive strength of hempcrete [67]. This technique not only enhances the material's mechanical strength by reducing the amount of binder required but also increases its ability to resist deformation before failure. Elfordy et al. [69] confirmed this finding and highlighted the relationship between density, compressive strength, and compaction. They observed that mixes with higher densities exhibited higher compressive strengths, indicating a correlation between density and compaction.

Walker et al. [57] studied the effect of binder type on the mechanical strength of hempcrete. They found that increasing binder hydraulicity promotes early strength development; however, all concretes achieved similar compressive strengths after one year, regardless of binder type. Cigasova et al. [70, 71] reported that hempcrete with an MgO-based binder had a compressive strength of approximately 2 MPa. Evrard [72] developed hempcrete mixtures with compressive strengths ranging from 0.2 to 0.5 MPa, while Arnaud et al. [73] found values ranging from 0.4 MPa to 1.2 MPa. According to Walker [42], the compressive strength of hempcrete can be 0.2 MPa after 28 days and 0.4 MPa after a year.

Haik et al. [74] studied hemp-lime mixtures in a 1:2 hemp-lime ratio, with two samples generated by replacing 50% and 90% of the lime with Israeli clay. The compressive strengths of mixtures with 90% clay, 50% clay, and 0% clay were 0.07 MPa, 0.09 MPa, and 0.04 MPa, respectively, as shown in Figure 2-6. The findings suggest that substituting 50% of the lime with clay led to the formation of hydraulic compounds, resulting in a marginal improvement in strength.

Ngo et al. [75] conducted research on designing soil concrete using hemp, investigating the influence of clay and hemp amounts on soil concrete. Figure 2-7 illustrates the effects of clayey soil and hemp fibers on compressive strength after 7, 28, and 180 days of curing at 20 ◦C and 90–100% relative humidity. The data shows a standard deviation of less than 0.025 MPa after 7 days, which is approximately 4%. This variation is influenced by the differences in sandy and clayey soil, as well as the porous multi-scale structure [76, 77].

The compressive strength decreases slightly with the addition of clayey soil after 7 days, ranging between 0.6 and 1.2 MPa. After 28 days, the compressive strength varies between 1 and 2.4 MPa, and after 180 days, it ranges from 2.5 to 5 MPa, as shown in Figure 2-7. However, the influence of clay percentage on compressive strength is minimal when the volume fraction of clayey soil is increased from 20% to 40% (less than 0.3 MPa). Once the compressive strength has stabilized at 180 days, the effect is negligible.

The compressive strength of soil concrete with 0% clayey soil decreases when fibers are added after 7, 28, and 180 days. The effect is more pronounced at 28 and 180 days (about 0.8 MPa of variation). However, when clayey soil is added, the influence of fibers is only slightly different. Only 1.2% of the fiber has any effect at 28 and 180 days, when the compressive strength drops by approximately 0.5 MPa. The detrimental impact of fibers on compressive strength may be attributed to reduced density, changes in soil concrete structure, intergranular void and pore dispersion, all of which create voids and discontinuities [78].

Fibers used as reinforcement in soil concrete specimens have been shown to reduce lateral strain during compressive loading [79], which could account for the ductility observed in soil concrete with fiber stress-strain curves. The increased friction angle at the shear cracking surface could be due to the presence of fibers [80].

It is crucial to note that hempcrete behaves linearly and elastically under compression until it reaches 10% strain. Consequently, when investigating the behavior of hempcrete under compressive pressure, several researchers terminate studies at 10% strain [46, 81]. While hempcrete's low strength prevents it from fully supporting roof loads, it does play a limited structural role in construction when formed over standard timber wall framing or double-stud framing.

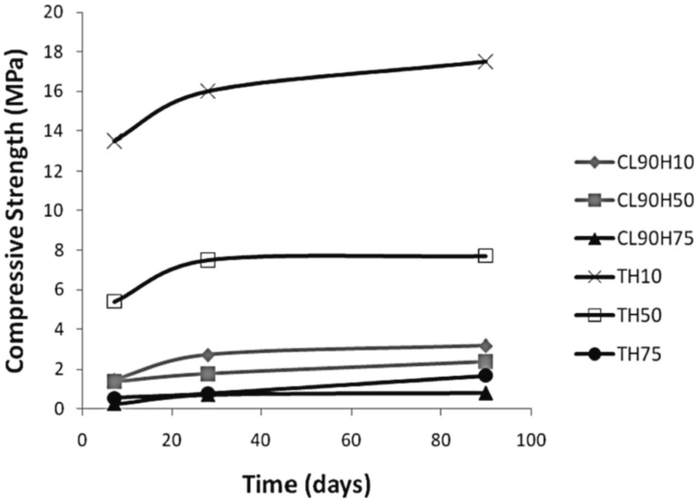


Figure 2-6. Compressive strength development of hempcrete. Adapted from [67]

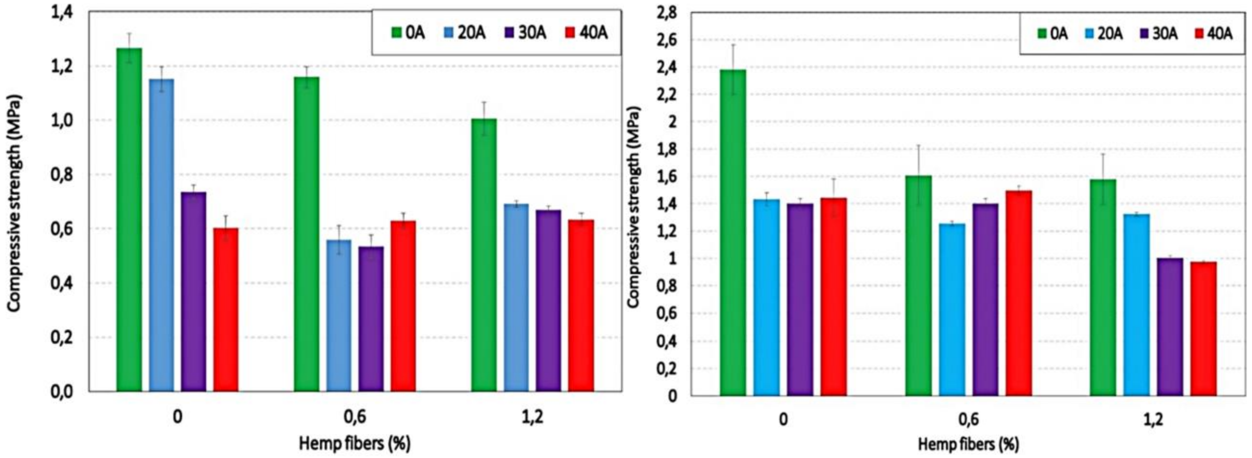


Figure 2-7. Effect of clayey soil and fibres on the compressive strength at 7 and 28 days. Adapted from [75]

The performance of hempcrete under compression can be enhanced by adjusting the binder proportions and increasing the mixture's density through compaction. Moreover, research [74, 82] has demonstrated that substituting a portion of lime with clay leads to the formation of hydraulic compounds, which can positively impact the compressive strength. As reported by Murphy et al., samples with a lower hemp content exhibit higher compressive strengths but are more prone to brittle failures [67]. The influence of time and hemp proportions in hempcrete prepared with commercial binders (TH) and hydrated calcic lime binders (CL90) has been investigated. Incorporating cement into the mixture has been shown to result in increased levels of compressive strength [23, 67, 83].

The ongoing discourse surrounding the compressive strength of hempcrete, as explored in contemporary studies and literature, reveals a multifaceted understanding of its capabilities and potential improvements. Hempcrete, primarily composed of the hemp plant's woody core, lime binder, and water, has attracted attention in sustainable construction due to its environmental advantages, such as carbon sequestration and excellent thermal properties. However, its relatively low compressive strength compared to conventional construction materials like concrete has been a central focus for researchers aiming to expand its application in the building industry.

Recent progress in the field has demonstrated that several key factors can influence the compressive strength of hempcrete. The type of binder employed, such as hydraulic lime, natural hydraulic lime (NHL), or magnesium oxide (MgO), plays a crucial role. Research suggests that formulations with hydraulic binders tend to achieve higher early strength, which converges to a similar value across different binder types over time. For example, hempcrete with MgO-based binders has exhibited compressive strengths of approximately 2 MPa, representing a significant improvement over traditional lime-based mixtures.

The ratio of hemp shives to the binder is another essential factor. Studies have indicated that increasing the binder content can improve the compressive strength of hempcrete. This is likely due to the binder providing more cohesion within the mix, resulting in a denser and stronger material. Furthermore, the water-to-binder ratio and curing conditions, including the environment and duration, significantly impact the final compressive strength. Hempcrete typically gains strength over time, with outdoor-cured samples demonstrating greater strength development compared to indoor-cured ones.

Compaction has also emerged as a crucial method for enhancing hempcrete's strength. Compacting the mixture leads to increased density, which positively correlates with higher compressive strengths. This relationship between density and compaction has been consistently observed across various studies.

Moreover, the incorporation of additives and novel materials into hempcrete mixtures is a growing area of research. For instance, the use of nanoparticles and pozzolanic materials like fly ash or silica fume has shown promise in improving the mechanical properties of hempcrete. These additives can interact with the lime binder to form stronger bonds, thereby contributing to higher compressive strengths.

However, it is crucial to recognize that while increasing hempcrete's compressive strength is desirable for expanding its structural applications, this should not compromise its inherent advantages, such as its thermal insulation properties and environmental benefits. The challenge lies in achieving a balance between enhancing mechanical strength and retaining the ecological and health benefits that make hempcrete a unique and valuable material in sustainable construction.

2.5 Flexural Strength

The flexural strength of a building material is another crucial mechanical property, as it determines its capacity to withstand bending stresses. According to The Limecrete Company Ltd [63], their commercial hempcrete product exhibits a flexural strength ranging from 0.30 to 0.40

MPa. Sassoni et al. [58] reported flexural strength values for hempcrete produced using a patented binder [59]. It is important to note that the hemp composites labeled HD1-HD3 were created as a substitute for formaldehyde-bonded wood boards. As a result, these composites may not be directly comparable to regular hempcrete. However, the mixtures denoted by LD and MD are intended for walling units similar to hempcrete, with the key difference being the use of MgO instead of lime.

Murphy et al. [67] investigated the mechanical behavior and flexural strength development of various hemp composites over a 90-day period. The composites were prepared with hydrated lime and a commercial binder containing hydraulic and pozzolanic additions in different volumetric lime-hemp ratios (1:9, 1:1, and 3:1). The researchers observed that increasing the binder content from 25% to 50% led to an increase in flexural strength. However, a further increase in binder content to 90% had little to no impact on the flexural strength, suggesting a possible contribution of lime-hemp bonds to the mix's flexural strength. The commercial composites demonstrated significantly higher flexural strength compared to those made with CL90s. The flexural strength of composites consisting of 75% hemp and Tradical® binder, which were equivalent in composition and density to the hempcrete blocks studied by Elfordy et al. [69], exhibited a comparable 28-day flexural strength of 1.20 MPa and 1.19 MPa, respectively [67].

With the exception of the TH50 specimen, all samples attained over 90% of their total 90-day flexural strength within 28 days. The commercial samples achieved their early flexural strength slightly faster than the CL90s samples, which could be attributed to the early formation of hydraulic products. All the high hemp content samples gained their flexural strength significantly slower than the low hemp specimens. A slight decrease in flexural strength was recorded for TH75 and CL90H50 between 28 and 90 days. In the case of hydraulic binder mixes, the decrease in flexural strength after 28 days was attributed to the formation of hydration products [67].

The composites with 50% and 75% hemp content exhibit a lower load-carrying capacity, and progressive failure occurs in a ductile manner. The type of binder has the greatest influence on stiffness, with the commercial samples having a greater Young's modulus at higher binder contents. Interestingly, the Young's modulus of the commercial composites did not increase with time. The TH10 and TH50 samples decreased by 11% and 22%, respectively, between day 7 and day 90. In contrast, the CL90s hemp composites increased in stiffness over time, owing to carbonation [23, 67].

2.6 Shear Strength

The particle size distribution of hemp shives plays a crucial role in the shear strength of hempcrete, as it can facilitate better compaction. The variation in the shapes, rigidity, and surface characteristics of the shives contribute to an increased friction angle. Moreover, hempcrete exhibits remarkable ductility. Experiments conducted by [12, 80] revealed that hempcrete samples subjected to triaxial compression tests for shear strength evaluation did not reach the critical state within the strain limits due to their high ductility. It was observed that ductility increased with higher confining pressure, and the samples demonstrated a significant evolution towards deviatoric behavior. The strain capacity at failure ranged from 6% under unconfined compression conditions to 19% under confined compression conditions. Most of the samples exhibited localized bulging and crushing at their lower parts, which was attributed to non-uniform pore distribution, high compressibility of the hemp shives, and densification occurring at the lower portions of the specimens. This resulted in a large strain capacity accompanied by localized lateral expansion. A small number of samples displayed a more brittle failure mode characterized by localized shear banding. Different Young's modulus values were observed for the various failure modes, with higher modulus values associated with shear banding failures and significantly lower values for bulging failures. Specimens exhibiting a combination of banding and bulging failures, which constituted the majority, were characterized by intermediate Young's modulus values. The maximum friction angle of the hemp shiv mixtures was found to be 46 degrees. For design purposes, the authors recommended using a cohesion strength of 0.36 MPa to ensure a conservative shear strength value.

2.7 Dynamic Resistance

The unique combination of flexible hemp shives and the rigidity provided by the binder gives rise to a material that can withstand significant deformations under stress without fracturing or failing, even when the binder's full mechanical strength is exceeded. The lack of a brittle phase in the shear response allows for energy dissipation through deformation during lateral loading, such as earthquakes [84]. This resistance to cracking under deformation, coupled with the additional racking strength that reinforces the load-bearing timber frame, renders hempcrete constructions remarkably resilient to lateral and seismic loading [28]. By leveraging these advantageous properties, hempcrete has the potential to enhance the structural integrity and safety of buildings in seismically active regions, offering a sustainable and effective solution for mitigating the impact of earthquakes and other lateral forces.

2.8 Performance against Moisture

Building materials have the ability to exchange moisture with their surroundings, and a material's capacity to absorb, release, and store moisture is characterized by its vapor sorption isotherm. This capability is crucial for maintaining human comfort within living spaces [27]. Hemp shiv, being highly porous and hydrophilic, can absorb up to 270% of its weight in water within a few minutes [16] and up to 400% of its weight after a 48-hour immersion [65]. Hempcrete exhibits significantly higher permeability compared to other construction materials and can function as a moisture buffering material [25, 29, 85] due to its rapid moisture transport and retention ability, as well as its high permeability [86]. This buffering characteristic provides better control over extreme humidity, reduces vapor condensation, restricts the growth of microorganisms, and ultimately ensures indoor comfort [18, 85]. Lower density hempcrete, with its higher porosity, offers a larger surface area and absorbs and stores more moisture compared to higher density materials [27]. The type of binder used can influence capillary action within the material, and increasing the hydraulicity of the binder or using a water retainer can reduce capillary absorption [13, 57, 87]. However, hempcrete is not immune to degradation when exposed to prolonged periods of rain or extreme humidity [85], and noticeable deformation may occur when the moisture content exceeds 60% [24]. Nevertheless, during short-term exposure, moisture may not penetrate deeply into the hempcrete [88]. Under normal conditions, the shiv undergoes slow mineralization under the action of lime, rendering the composite inert and reducing the risk of rot and mold growth [18]. To prevent the absorption of rain and excessive humidification within the wall, some researchers have recommended the use of coatings or breathable finishes [82] to mitigate the potential issue of mold growth over an extended period [88].

2.9 Performance in Thermal Insulation

Thermal conductivity, a material property that describes the ability to transfer heat under a temperature gradient, is influenced by the material's characteristics, the path length of heat flow, and the temperature difference between the two ends. In the context of building materials, this phenomenon plays a crucial role, as the energy efficiency of a building is significantly impacted by the hygrothermal behavior of its constituent materials [48]. Air, known for its low thermal conductivity, contributes to the lightweight and thermally insulative properties of bio-based materials like hempcrete, which possess a highly porous structure, ultimately enhancing thermal comfort within the building [85, 87, 88]. The heat transmission of hempcrete spans from 0.06 to 0.19 W.1/m.1/K, corresponding to dry densities ranging between 200 and 840 kg/m3 [24]. Owing to its low thermal conductivity, hempcrete is well-suited for use in building envelopes [89], where it can effectively regulate heat waves during summer and minimize heat loss in winter [90] without necessitating additional insulation in masonry works [16]. As previously mentioned, hempcrete exhibits high moisture permeability and can absorb substantial amounts of moisture. This characteristic enables it to delay fire spread by facilitating the phase change of capillary water and the transformation of hydraulic lime to limestone, which entangles charred hemp in a brittle configuration [25], resulting in a fire separation medium that can last up to 2 hours [29]. Hempcrete outperforms hollow concrete blocks in terms of thermal performance and provides superior summer performance compared to Autoclaved Aerated Concrete [82]. The thermal conductivity of hempcrete is influenced by factors such as formulation, density, water content [13, 87, 91], mold growth, and aging [29, 89]. Lower density corresponds to lower thermal conductivity and improved insulation. In fact, the impact of hempcrete's density on thermal performance surpasses that of moisture [48]. Consequently, higher compaction aimed at achieving a denser and stronger composite leads to reduced insulation efficiency [26, 29, 69]. Moisture content exerts a notable influence on thermal performance, with values ranging from 0.11 W m_1.K_1 for dry samples to 0.32 W m_1.K_1 for samples at 100% relative humidity [25]. Altering the binder type does not substantially affect thermal conductivity and specific heat capacity [82, 87], although some researchers have observed that increasing binder hydraulicity or employing water retainers can elevate conductivity [13]. With aging, it has been noted that moisture storage and water vapor permeability decrease, resulting in an increase in the thermal conductivity of the composite [29, 89].

2.10 Acoustic Performance

The acoustic property of a material determines how it reacts to sound waves within a frequency range spanning from 16 to 16,000 Hz. To achieve acoustic comfort by minimizing unwanted noise, it is crucial for building materials and the overall building design to exhibit excellent sound insulation characteristics [29]. Hempcrete's inherent high porosity contributes to a higher sound absorption coefficient, which directly influences the reverberation time within a room, causing sound waves to dissipate rapidly [25]. The acoustic performance of this composite is influenced by several factors, including the properties of the aggregate, the type and content of the binder, and the density of the material. Retted hemp has been found to outperform unretted hemp in terms of acoustic performance, while hydraulic lime binders demonstrate superior sound absorption capabilities compared to cement binders [25]. Smaller particle sizes tend to perform better acoustically, whereas higher binder content or increased material density significantly reduces the sound absorption capacity of hempcrete [49]. By carefully considering these factors and optimizing the composition of hempcrete, it is possible to create building materials that effectively dampen noise and promote a more acoustically comfortable environment.

2.11 Sustainability

Sustainable materials play a crucial role in creating energy-efficient constructions that prioritize environmental, social, and user well-being. These materials offer eco-friendly solutions that foster high levels of indoor comfort while minimizing energy consumption and environmental or social implications. In today's world, a material's sustainability is determined by various parameters, such as the emissions generated throughout its lifetime, embodied energy, impact on nature and landscape, circularity, reusability, and recyclability potential, durability, resource type and use, and efficiency in reducing energy consumption and creating comfortable indoor environments.

Hempcrete stands out as a bio-based, carbon-negative material (-0.15 kg CO2/kg) [92]. The production of the binder contributes to the highest environmental impact, while hemp, the primary material, absorbs significant amounts of CO2 during cultivation. Studies have shown that hemp sequesters 1.84 kg of CO2 per kg of dry hemp through photosynthesis during its growth. Moreover, hempcrete continues to absorb CO2 from the atmosphere through carbonization after manufacturing. The total amount of sequestered CO2 is estimated to offset the production of lime, potentially resulting in negative levels of embodied carbon.

Hempcrete is a durable and long-lasting material, with carbonization occurring during its operational phase, leading to increased mechanical strength over time. This durability minimizes the need for material substitution. While hempcrete can be recycled by crushing and reusing it in new mixtures or as insulation fillers, this process is preferably avoided as it results in down-cycling [18]. On the other hand, cast hempcrete blocks can be reused without any additional processing or treatment. Furthermore, hempcrete's favorable hygrothermal properties contribute to high levels of energy efficiency and indoor comfort.

Hemp is a fast-growing annual plant that can reach heights of 4m and thrive in various temperatures and neutral to alkaline soils ($pH \geq 6.5$). Its local cultivation helps avoid transportation-related costs and CO2 emissions [28, 31]. Cultivating hemp requires no pesticides, fungicides, or significant nutrients, ensuring that the soil remains free from toxic and quality-degrading substances [31]. The deep roots of hemp break the soil and contribute to its health, making it suitable for rotational cultivation [28]. Hemp's rapid growth and exceptional CO2 sequestration capabilities make it more efficient in absorbing CO2 than agro-forestry [28][40], [41].

In summary, sustainable materials like hempcrete offer environmentally friendly solutions that prioritize energy efficiency and indoor comfort while minimizing negative environmental and social impacts. Hempcrete's carbon-negative nature, durability, recyclability, and favorable hygrothermal properties make it a promising choice for sustainable construction. The cultivation of hemp, its primary material, not only sequesters significant amounts of CO2 but also contributes to soil health and avoids the use of harmful chemicals. These factors, along with hemp's fast growth and superior CO2 absorption compared to agro-forestry, highlight the potential of hempcrete as a sustainable building material for a greener future.

2.12 Carbon Sequestering

Climate change has emerged as one of the most significant threats to life on Earth, prompting various initiatives to mitigate its effects. The European Union has set an ambitious target of reducing greenhouse gas emissions by 40% by 2030 [29, 88][195]. The construction industry, which includes the building of structures and roads, consumes nearly half of the world's raw materials and energy [13, 29][169]. Furthermore, indoor utility services such as lighting, heating, and air conditioning are responsible for approximately 47% of CO2 emissions in the UK [29, 93][199]. Given these statistics, it is evident that the construction sector is a major contributor to global climate change. As a result, there is an urgent need to review material design, sourcing, and building design practices to promote green building and reduce greenhouse gas emissions.

Hempcrete has emerged as a promising alternative to conventional filling materials due to its numerous advantages. These include its lighter weight, superior hygrothermal and acoustic performance, carbon negativity, and ability to act as a natural sink for CO2 [13, 29][169]. Studies have shown that a 260 mm thick, 1 m2 hemp-lime wall requires up to 394 MJ of energy and can sequester up to 35 kg of CO2 over a 100-year lifespan. In contrast, an equivalent Portland cement-based concrete wall requires 560 MJ of energy and releases an additional 52.3 kg of CO2 [29, 49][189].

One of the most significant advantages of using hempcrete in terms of CO2 sequestration is its short regrowth cycle. Hemp can be harvested and regrown within a single year, which is significantly shorter than the time required for forest regrowth. This rapid regrowth allows hempcrete to store carbon throughout the lifetime of the composite, effectively delaying the emission of greenhouse gases [29, 94][15]. By incorporating hempcrete into construction projects, the industry can take a significant step towards reducing its carbon footprint and combating climate change.

In conclusion, the construction sector plays a crucial role in addressing the global climate crisis. By adopting sustainable materials like hempcrete, which offer superior performance, carbon negativity, and CO2 sequestration capabilities, the industry can make a significant contribution to reducing greenhouse gas emissions. The shorter regrowth cycle of hemp compared to traditional forest regrowth further enhances the potential of hempcrete as a green building material. As the world continues to grapple with the challenges posed by climate change, the widespread adoption of hempcrete and other sustainable construction practices will be essential in creating a more sustainable and resilient built environment.

2.13 Durability

The durability and cost-effectiveness of structures are heavily influenced by the longevity of the materials used. Extensive research has been conducted on the durability of hempcrete, examining a broad spectrum of factors. In their studies, the mechanical properties and durability of hemp-lime concretes were explored by Walker et al. [23, 57], where various binder mixtures were utilized, including commercial binders, GGBS, and lime. The following parameters of durability were investigated:

1. Resistance to freeze-thaw,
2. Resistance to salt exposure, and
3. Resistance to biological deterioration.

Hempcrete exhibited poor freeze-thaw resistance due to mass washout during the freeze and thaw cycle, resulting in decreased compressive strength. However, it demonstrated good resistance to sodium chloride salt exposure, as the large pores were unsuitable for crystallization. Despite repeated heavy microbial inoculations, biological deterioration was non-existent in hempcrete due to the lack of nutrients to support microorganism growth. To enhance the strength and durability of lime-pozzolan binder based hempcretes, Walker et al. [23, 57] recommended the use of additives. Interestingly, Piot et al. [23, 88] observed mold growth beneath a hand-mixed exterior coating on their hempcrete walls during a year-long outdoor exposure study. In contrast, Walker et al. [23, 57] attributed hempcrete's resistance to microbial attack to the alkalinity of lime, insufficient nutrition for microbial growth, and/or unsuitable environmental conditions in their seven-month study using a similar binder composition and mix design. The natural decomposition of vegetal materials raises concerns, but hemp shives do not completely decompose within the composite due to mineralization caused by calcium carbonate precipitation on individual elementary fibers following an alkaline degradation mechanism. These mineralized hemp particles become inert, brittle, less porous, and weak in tension [23, 95]. In wetting and drying cycles and full immersion and drying cycles, particularly with calcic lime binders, the binder leaches out, reducing mass and compressive strength. However, in cases of hydraulic binders, cyclic wetting and drying has been found to improve the composite's compressive strength [23, 95].

2.14 Fire Safety

Reaction to fire is a crucial factor to consider when assessing building safety, as it affects building permissions and insurance. Although not extensively studied, the limited research available consistently suggests that hempcrete exhibits favorable fire resistance properties [67]. Fernea et al. [96] investigated hempcrete's reaction to fire and found that the material met the necessary fire test requirements. The studied samples were designed as an acoustic absorption material, with a composition consisting of white cement, lime, and water. Three samples were tested, each with a different hemp-cement ratio (1:1, 2:1, and 3:1), while the volume of cement remained constant. The 2:1 ratio sample served as the control/reference. The water-cement ratio was maintained at 1:2 for all samples. However, no information regarding the curing period was provided. The samples underwent a reaction to fire test in accordance with Standard SR EN520/A1:2010 [23, 96].

In a multi-criteria study conducted by Sassoni et al. [58], the fire resistance of hemp composites was also examined. The samples were categorized based on their densities: low density (LD; 330 kg/m3) and medium density (MD; 640 kg/m3). The fire resistance test was performed according to EN 13823, with the LD samples achieving class 'C' fire resistance and the MD samples achieving class 'B' fire resistance [23].

Furthermore, according to Hemp-TODAY® (2020) [83, 97], "hempcrete scored a perfect '0' under ASTM fire testing in the USA," which is the highest possible rating on a scale of 0 to 450. To assess hempcrete's resistance to fire, a propane gas-powered blow torch was directed against a well-set and dried wall. Photographs were taken at one-minute intervals throughout the 8-minute test duration to observe the progression of the burnt area's size [83, 98]. Even after 10 minutes, the darker areas remained hot. Upon further examination of the burnt area, it was discovered that the flame only managed to penetrate half an inch from the surface. This demonstrates the strong fire-resisting properties of hempcrete, making it a suitable candidate for building construction [83].

These studies highlight the promising fire resistance characteristics of hempcrete, despite the limited research available. The favorable results obtained from various testing methods, such as the reaction to fire test according to Standard SR EN520/A1:2010, EN 13823, and ASTM fire testing in the USA, provide evidence of hempcrete's potential as a fire-resistant building material. However, further research is needed to fully understand and quantify the fire resistance properties of hempcrete under different compositions, densities, and testing conditions.

Summary and Conclusion

The construction sector is a predominant energy consumer and a significant contributor to global CO2 emissions, with the majority of energy usage allocated to heating and cooling spaces in developed countries. In the pursuit of sustainable and eco-friendly alternatives, the industry has turned its focus to carbon-negative materials like hempcrete, which can potentially replace carbon-positive materials in construction. Hempcrete's ability to sequester CO2 during both the growth of the hemp and the curing process of the lime binder positions it as a vital material for climate change mitigation efforts.

Hempcrete offers a twofold carbon sequestration mechanism: the biogenic absorption by hemp shives and the non-biogenic capture by the lime binder. Hemp shives, comprising 45% carbon, embody carbon dioxide from the atmosphere during the plant's growth phase, while the lime binder absorbs CO2 during the carbonation process, further solidifying hempcrete's status as a carbon store.

Historically, hemp has been used in construction, with its contemporary form gaining traction in France during the 1980s for restoring medieval buildings. Hempcrete's viability is underscored by its favorable attributes such as lightness, thermal insulation, moisture regulation, and acoustic properties.

Hempcrete's structural applications vary from floors to roofs, providing excellent insulation. However, its efficacy is contingent upon thickness and density. Prefabrication of hempcrete blocks streamlines construction by mitigating on-site curing and drying challenges, although this can sometimes impact the material's insulation performance and sustainability.

Hempcrete's mechanical characteristics, such as compressive and flexural strength, are affected by binder choice, hemp to binder ratio, and compaction level. While the compressive strength of hempcrete is lower than that of concrete, its flexibility and ductility under shear stress are significant. Durability studies reveal that hempcrete resists biological deterioration effectively and displays robustness against freeze-thaw cycles and salt exposure, highlighting its potential for long-term structural integrity.

Acoustically, hempcrete's high porosity confers sound absorption, an asset for noise reduction in living spaces. Sustainability-wise, hempcrete is carbon negative and exhibits impressive energy efficiency and indoor comfort, thanks to its hygrothermal properties. Its low-density allows for excellent thermal insulation, making it an ideal material for building envelopes that moderate heat waves and reduce heat loss.

In terms of safety, hempcrete demonstrates strong fire resistance, capable of acting as an effective barrier against the spread of fire. This resistance is attributed to the material's composition, which includes a blend of lime, water, and hemp—a plant with inherent fire-retardant properties.

Hempcrete stands out in the construction industry as a sustainable, carbon-negative material with commendable mechanical and thermal properties. Its versatility, coupled with its positive environmental impact, offers a desirable approach to building practices that align with contemporary needs for sustainable development. The application of hempcrete in modern construction not only reduces the carbon footprint of buildings but also presents a recyclable, durable material that enhances indoor air quality and comfort. Its potential to rejuvenate and revitalize conventional construction methodologies, while upholding eco-friendly principles, is evident and promising.

Despite the ecological advantages of hempcrete, there remains a notable gap in enhancing its structural attributes without sacrificing its environmental benefits. Past investigations into various binders and additives often involved complex or unsustainable practices that could undermine the inherent carbon-negative qualities of hempcrete, such as the use of Portland cement or water-soluble proteins. This thesis addresses these challenges by adopting innovative strategies aimed at bolstering hempcrete's compressive strength while preserving its ecological integrity. The research explores the efficacy of potent pozzolanic additives such as metakaolin, Class F fly ash, and nano-silica to substantially improve mechanical strength. It also evaluates the substitution of magnesium oxide for traditional lime binders, which could potentially enhance compressive strength and expedite setting times. Additionally, the study incorporates compaction methods to increase the density and strength of hempcrete, targeting an unprecedented compressive strength of at least 300 psi—far exceeding the achievements of conventional formulations without the complexities previously encountered in other research, such as pre-soaking hemp shives or using complex, environmentally unfriendly additives. Furthermore, the research aims to simplify the curing process, making it feasible across various environmental conditions without the need for specialized controls. This comprehensive approach seeks not only to close the existing knowledge gap but also to establish a viable, load-bearing version of hempcrete that aligns with modern construction standards and significantly advances sustainable building practices.

Chapter 3

Research Plan

3.1 Introduction

This research focuses on enhancing the properties of hempcrete, particularly aiming to boost its compressive strength to position it as an effective and environmentally friendly building material. Considering the substantial impact of the construction industry on global carbon emissions, hempcrete presents a viable sustainable alternative. However, its practical application is currently limited due to its relatively low compressive strength compared to traditional concrete.

The primary objective of this study is to explore and test various methods and strategies to increase the compressive strength of hempcrete, thus reinforcing its role as a robust and eco-friendly option for construction. The research will investigate multiple approaches, including:

1. **Advanced Material Enhancement**: Examining the integration of specific additives, such as lime-pozzolana blends and mechanical treatments of hemp fibers, to enhance the structural integrity and mechanical strength of hempcrete.
2. **Optimization of Mix Proportions**: Adjusting the mix ratios to optimize the amounts of hemp, binders, and supplementary materials in order to significantly boost compressive strength.
3. **Exploration of Compaction Methods**: Assessing the effects of innovative compaction and pre-compression techniques on hempcrete’s mechanical properties, with a focus on improving its density and strength.
4. **Innovative Use of Additives for Improvement**: Researching the inclusion of various additives and treatments like sand, Class F Fly Ash, Metakaolin, NanoSilica, and MgO as alternatives to traditional lime, aiming to enhance the compressive strength properties of hempcrete.

This extensive approach will include thorough testing to assess the modified hempcrete's compressive strength, workability, and durability, while also evaluating the environmental and sustainability benefits of these improvements.

The goal is to achieve a breakthrough in increasing hempcrete’s compressive strength through these advanced methods, thereby paving the way for its broader application in the construction industry. The successful implementation of this research could position enhanced hempcrete as a fundamental element in various construction projects, contributing to a significant reduction in the environmental impact of the building sector. This study aims to unlock hempcrete’s potential as a transformative and eco-efficient material, heralding a new era in sustainable building practices.

3.2 Experimental Program

3.2.1 Materials and Methods

Research of efficient binders is vital to the development of hempcrete as an eco-friendly construction material. Magnesium oxide cement (MgO), a novel alternative to the conventional hydrated lime, and the experimental program that tested them are detailed in this chapter of the thesis. In order to improve hempcrete's qualities, especially its compressive strength, two binders were chosen: one from Premier Magnesia's Magox XL brand and the other from Sarl Lisbonis Chaux Grasses (LCG).

3.3 Binder Characteristics

3.3.1 Hydrated Lime

Because of its compatibility with hemp and its simplicity of mixing, hydrated lime is a traditional binder for hempcrete. It helps the carbonation process along, which increases the material's strength as time goes on. Because of its inferior starting strength and slower healing rate in comparison to MgO, however, other options are being considered. Figure 3-1 shows the Lisbonis Chaux Grasses (LCG) product that was employed in the study, which is one of the hempcrete combinations researched. The other ingredients were sand and pre-formulated hydrated lime.

Figure 3-1. Formulated Hydrated Lime and Sand used in Hempcrete Mixture

3.3.2 Magnesium Oxide Cement (MgO)

Magnesium oxide cement, obtained through the calcination of magnesium hydroxide at temperatures ranging from 600°C to 1000°C, emerges as a compelling alternative. This process yields a highly reactive and porous MgO powder, known for its rapid curing and environmentally friendly attributes. As illustrated in Figure 3-2, Premier Magnesia's Magox XL, a magnesium oxide (MgO) cement, was employed as a key binder in the hempcrete mixtures investigated in this study.

Figure 3-2. Premier Magnesia MgO-Cement; Magox XL used in Hempcrete Mixture

3.3.2.1 Advantages of MgO in Hempcrete

The introduction of magnesium oxide (MgO) into hempcrete presents numerous benefits critical to the construction industry's transition to sustainability:

- **Strength and Durability**: MgO markedly improves the compressive strength of hempcrete, providing a strong fill that rivals traditional concrete while still maintaining environmental advantages.
- **Rapid Curing**: MgO cures quickly, which is especially beneficial in moist climates as it helps prevent the growth of mold.
- **Resistance to Mold, Pests, and Fire**: Hempcrete enhanced with MgO naturally resists mold, pests, and fire, extending its use across diverse environmental conditions.
- **Eco-Friendliness and Non-Toxicity**: MgO is an environmentally friendly and non-toxic material, reducing the carbon footprint and making it an ideal choice for green building projects.
- **Vapor Permeability**: MgO maintains the breathability of hempcrete, essential for regulating indoor air quality and humidity.

This research evaluates the effectiveness of MgO as a binder in hempcrete through controlled experimental studies. By contrasting MgO's performance with that of traditional hydrated lime, the research seeks to thoroughly understand its benefits, uses, and optimal combinations for hempcrete construction. The experimental procedures include:

- **Hempcrete Mixture Preparation**: Crafting hempcrete samples with both types of binders to assess uniformity and reproducibility.
- **Mechanical Testing**: Performing tests to measure the compressive strength enhancements provided by MgO.

This investigative work positions MgO as a viable substitute for traditional lime in hempcrete construction, highlighting its superior strength, curing speed, and environmental benefits. The goal is to confirm MgO's effectiveness and promote its wider acceptance in the construction sector, contributing significantly to sustainable building practices.

3.3.3 Hemp Hurd

For the core component of the hempcrete, industrial hemp hurd was procured from La Chanvriere de l'Aube, branded as KANABAT. This product is distinguished by the "GRANULAT CHANVRE BÂTIMENT" label, assuring adherence to the specifications required for building with hempcrete as per the Professional Rules, Figure 3-3. The selection of KANABAT was predicated on its validated performance with lime-based binders, crucial for achieving the desired properties in hempcrete.

The intrinsic characteristics of hemp, including composition and density, play a significant role in defining the mechanical properties and usability of hempcrete. The composition of hemp shiv, primarily consisting of 55% cellulose, 16% hemi-cellulose, 18% pectin, and 4% lignin, along with 7% of waxes, fats, ash, and proteins, significantly impacts the material's strength, thermal insulation, and moisture regulation properties.

Figure 3-3. Hemp Hurd obtained from; La Chanvriere de l'Aube, branded as KANABAT.

Evrard [41] categorizes hemp bulk density into three distinct types based on the compaction method: loose density, vibrated density, and layered density, Table 3-1. These density measures are critical for understanding how hempcrete will perform in various applications, including walls, slabs, roofs, and renders. The variation in density affects not only the structural integrity but also the thermal and acoustic insulation properties of hempcrete.

Table 3-1. Density of Hemp Hurds

Loose Density	Vibrated Density	Layered Density
112.4 ± 2.2 kg/m3	170.5 ± 2 kg/m3	165.8 ± 4.5 kg/m3

3.3.4 Additives

3.3.4.1 Pozzolanic Materials and Nano-Particles

To enhance the properties of hempcrete, three pozzolanic materials were incorporated into this research: Fly Ash Class F, and Metakaolin. The selection of these additives was based on their potential to improve the compressive strength, durability, and environmental performance of hempcrete.

In the pursuit of enhancing hempcrete's mechanical properties and sustainability, this research integrates two pivotal pozzolanic materials: Metakaolin, and Fly Ash. Each of these additives plays a significant role in improving hempcrete's compressive strength, durability, and overall performance, supported by extensive studies that illuminate their beneficial effects.

The compressive strength of hempcrete is greatly improved by the addition of metakaolin, which is made by calcining kaolin clay. The development of more calcium silicate hydrate (CSH) and calcium alumino-silicates is the outcome of the pozzolanic interaction between metakaolin and lime, which is responsible for this outstanding improvement. Because of these reactions, hempcrete is not only stronger right once, but it also becomes more durable over time, making it more resistant to changes in humidity. While the addition of metakaolin greatly increases the mixture's potency, getting the most out of it requires precise calibration and balancing with the other ingredients. So, finding the right ratio of metakaolin is essential.

Figure 3-4. Highly Reactive Metakaolin Pozzilanic material obtained from two different supplier; BURGESS OPTIPOZZ & R-E-D Industrial Products.

As depicted in Figure 3-4, metakaolin samples obtained from two distinct suppliers, BURGESS OPTIPOZZ and R-E-D Industrial Products, are recognized for their highly reactive pozzolanic properties, though they differ in color.

Fly ash, a by-product of coal combustion, is renowned for its pozzolanic qualities that enhance the strength and durability of hempcrete. The reaction between fly ash and lime facilitates the production of additional calcium silicate hydrate (CSH), which is crucial for improving compressive strength. Moreover, the integration of fly ash into hempcrete mixes has proven to benefit significantly from accelerated carbonation, boosting the pozzolanic reaction and thus the strength of the material. Like metakaolin, the proportion of fly ash in the mixture must be finely tuned to maximize its advantages while maintaining the insulative and environmental benefits of hempcrete, as illustrated in Figure 3-5.

The strength enhancements provided by these materials are primarily due to their pozzolanic reactions with lime, which promote the formation of more CSH and enhance the microstructure of hempcrete. This process of densification reduces voids and compacts the material, directly leading to increased compressive strength and durability.

Figure 3-5. Fly Ash (Class F) Additive obtained from two different supplier; Diversified Minerals Inc. & R-E-D Industrial Products

Furthermore, the integration of metakaolin and fly ash into hempcrete formulations is demonstrated as a comprehensive strategy to not only enhance the material's compressive strength and durability but also foster more sustainable construction techniques. By carefully examining optimal mix ratios and discerning the distinctive contributions of each pozzolan, this study contributes significantly to advancing hempcrete as a robust, eco-friendly construction material. These improvements solidify hempcrete's credibility as a viable building material and reinforce its role in advancing sustainable building practices.

Nano silica's role in the science of modern construction materials is notably significant, particularly in enhancing the properties of both traditional and innovative material matrices. Highlighted in Figure 3-6, this portion of the thesis explores the potential of nano silica (nSiO2) in boosting the mechanical strength, durability, and other essential properties of cementitious materials like hempcrete. The focus on nano silica aims to delve into its impact on enhancing the performance and application spectrum of such materials, potentially transforming them into more effective solutions for modern construction challenges.

Figure 3-6. Ultrapure 99% Silicon Dioxide Nanoparticles 20nm obtained from R-E-D Industrial Products

Characterized by its ultra-fine particles, nanosilica is utilized to augment flexural, compressive, and tensile strengths across a variety of matrices, including cement, lime, biomass, biopolymers, and polymer nanocomposites. Its effectiveness is attributed to its capacity to act as a nano-filler, filling microscopic gaps within the Calcium-Silicate-Hydrate (C-S-H) gel particles in cement. This process not only minimizes porosity at the nanoscale but also enhances the interfacial transition zone between cement and aggregates, leading to enhancements in the overall strength, durability, shrinkage control, and bonding with steel reinforcements.

It has been reported that with the inclusion of 1 wt.% of nanosilica in cement, compressive strength increased by 37% compared to the control sample of pure cement [99]. In further studies, varying concentrations of nanosilica (1, 3, 5, 7, and 10%) were added to a cement-to-sand ratio of 1:2.75 with a water-to-cement ratio of 0.485; after 28 days, the highest recorded compressive and flexural strengths were 36.8 MPa and 5.7 MPa, respectively, an increase from 23.6 MPa and 3.6 MPa in pure cement [100]. Moreover, the use of nanosilica in ultra-lightweight cement composites (ULCC) has been shown to enhance their microstructures, mechanical properties, and durability performances. Improvements were noted in compressive strength, as well as resistance to water and chloride ion penetration, with 1 and 2% additions of nanosilica [101, 102].

3.4 Mixture Design and Testing Configuration for Hempcrete

3.4.1 Mixture Matrix

This chapter outlines the methodical development of hempcrete samples within a laboratory setting, focusing on enhancing their mechanical properties, particularly compressive strength. It details a testing matrix and mixture design incorporating a variety of binders and additives, each carefully prepared and compacted to determine their impact on the structural integrity and environmental sustainability of the final product.

The foundation of this experimental approach is the creation of ten distinct batches. Each batch consists of three replicate samples, forming a robust dataset for the compressive strength test conducted on 50 mm cubes after a seven-day curing period.

The formulation of mixture ratios was derived from an in-depth analysis of existing research, aiming to achieve a balanced blend that optimizes both mechanical strength and workability. The chosen ratios were based on a thorough review of previous experiments to maintain consistency with established benchmarks.

Initially, the mixture design incorporated a binder content of 35% by total weight, with 25% hemp hurds and the remaining 40% water. This configuration was influenced by median lime content observed in prior studies, specifically Paper A [83] (39.1%) and Paper C [62] (33.4%), which indicated similar hemp content but significant variations in water ratios, as depicted in Table 3-2. The selected water content is intended to ensure adequate hydration for activating the binder while preserving the structural integrity required for durable hempcrete.

The subsequent series adjusted the binder content to 40% and reduced the hemp proportion to 15%, with the water content increased to 45% of the total weight. This adjustment addresses the structural needs for a higher concentration of binder, as indicated in Paper A, while aligning the water amount with the requirements for effective curing and compaction noted in various studies.

Table 3-2. Different Hemp Mixtures ingredients according to previous studies

Material	Study A [83] (% by weight)	Study B [103] (% by weight)	Study C [62] (% by weight)
Hemp	15.6	53.6	15.6
Lime	39.1	21.4	33.4
Water	45.3	25	51

Finally, our third series escalates the binder to 45%, reduces the hemp content to 5%, and increases the water to 55% by total weight. This approach is an innovative venture to explore the outcomes of a higher binder dominance over the hemp content, in contrast to the higher hemp concentration of 53.6% noted in Paper B [103], coupled with an elevated water ratio similar to Paper C's 51%. This adjustment is postulated to investigate the effects of a binder-enriched mixture, hypothesizing a potential increment in compressive strength and durability, which could be critical for specific structural elements like load-bearing walls.

Batch 1: This batch focuses on traditional hempcrete formulations using lime as the primary binder. Three distinct ratios of lime, hemp shives, and water are tested to evaluate their impact on the material's strength and sustainability.

Batch 2: Here, the emphasis shifts to magnesium oxide as an alternative binder. Its potential for improving compressive strength is assessed through three different mixture designs, each varying in their ratios of MgO, hemp, and water.

Batch 3: This batch investigates the effect of incorporating metakaolin with lime as a binder. The three mixture designs in this batch aim to understand how this additive influences the mechanical properties of hempcrete.

Batch 4: This batch explores the incorporation of fly ash with lime binder. The varying proportions of fly ash in the mixtures are designed to examine its role in enhancing the strength and durability of hempcrete.

Batch 5: Combining both metakaolin and fly ash with lime binder, this batch explores the synergistic effects of these additives in hempcrete mixtures.

Batch 6: Focusing on the combination of magnesium oxide and metakaolin, this batch seeks to understand how these components interact to improve the compressive strength of hempcrete.

Batch 7: Similar to Batch 6, but replacing metakaolin with fly ash, this batch assesses the impact of this specific additive when combined with magnesium oxide as the binder.

Batch 8: Exploring a more complex mixture, this batch combines both metakaolin and fly ash with magnesium oxide binder, examining their collective influence on the hempcrete's properties.

Batch 9: Introducing nano silica to the lime binder mix, this batch aims to determine the effects of nanotechnology on the performance of hempcrete.

Batch 10: Finally, this batch tests the combination of magnesium oxide binder and nano silica additive, exploring innovative ways to enhance the mechanical strength of hempcrete.

Each of these batches is prepared with the option of compaction, allowing for a comprehensive analysis of how compaction influences the density, strength, and overall performance of the hempcrete samples. The outcomes from these experiments will provide valuable insights into optimizing hempcrete mixtures for enhanced mechanical properties and sustainability in construction applications.

Mixture Design 1 (MD1); Table 3-3 encompasses a range of specimens, each formulated with hydrated lime as the binder and differing in their incorporation of additional substances to enhance the material's properties. The specimen names within MD1 are as follows:

- **1A**: This specimen includes a blend of 35% hydrated lime, complemented by 25% hemp shives and 40% water, integrated with 6% metakaolin based on the binder's weight.
- **1B**: In this mix, the lime content is increased to 40%, with hemp shives at 15% and water at 45%, also with 6% metakaolin.
- **1C**: With the highest lime content at 45%, this specimen reduces hemp shives to 5% and raises water to 50%, maintaining the 6% metakaolin additive.
- **1D, 1E, 1F**: These specimens mirror the lime, shives, and water ratios of 1A, 1B, and 1C, respectively, but instead of metakaolin, they each contain 6% Class F fly ash as the additive.
- **1G, 1H, 1K**: These specimens are distinctive as they include both 6% metakaolin and 6% Class F fly ash, along with the respective lime, shives, and water proportions found in 1A, 1B, and 1C.
- **1M, 1N, 1L**: The final set within MD1 replaces the fly ash with 4% nano silica, following the same pattern of lime, hemp shives, and water contents as the first three specimens.

As seen in Figure 3-7, the pre-compression form of hempcrete specimens 1A, 1E, 1H, and 1L from Mixture Design 1 are ready for testing, providing insight into the varying effects of binders and additives on compressive strength.

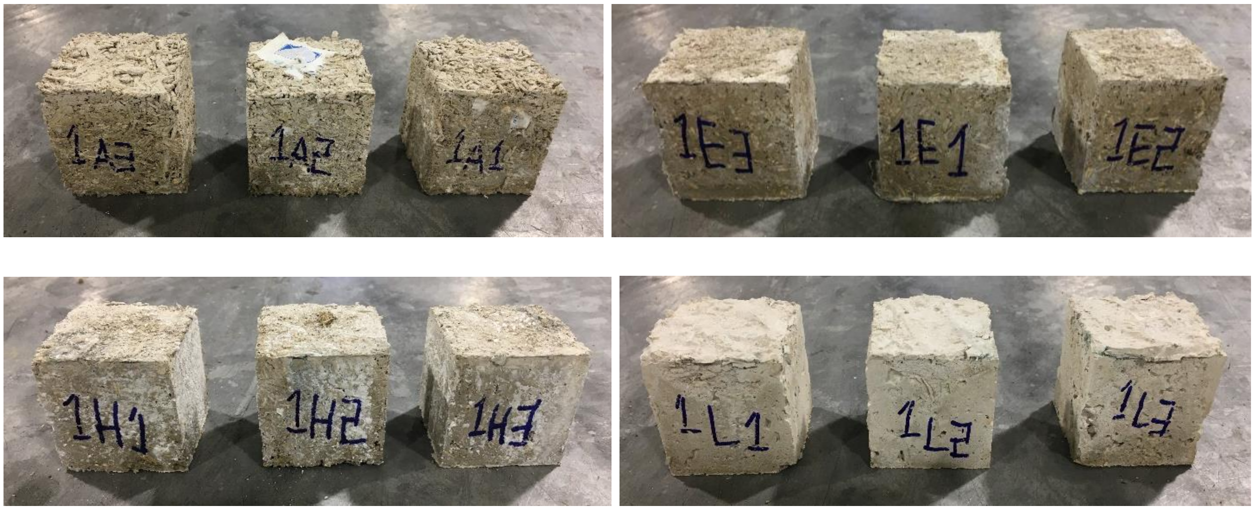


Figure 3-7. Pre-Compression Test Form of 1A, 1E, 1H and 1L Hempcrete Specimens

Transitioning to Mixture Design 2 (MD2); Table 3-3, the use of magnesium oxide (MgO) as an alternative binder marks the primary distinction from MD1. The specimens included in MD2 are:

- **2A, 2B, 2C**: These specimens correspond to the first set in MD1, with the same proportions of hemp shives and water but with MgO as the binder. Metakaolin remains the additive at 6%.
- **2D, 2E, 2F**: Parallel to the second set in MD1, these mixes contain MgO as the binder and Class F fly ash at 6%, following the established pattern for lime, hemp shives, and water contents in MD1.
- **2G, 2H, 2K**: These specimens also mimic their MD1 counterparts, employing both 6% metakaolin and 6% Class F fly ash, alongside the MgO binder in place of hydrated lime.
- **2M, 2N, 2L**: Reflecting the final trio in MD1, these specimens are notable for their inclusion of 4% nano silica with MgO as the binder, following the structure established in the preceding sets.

As illustrated in Figure 3-8, the hempcrete specimens 2B, 2F, 2G, and 2M are prepared and set before undergoing compressive strength tests to evaluate the influence of varying binder types and additive contents from Mixture Design 2.

Figure 3-8. Pre-Compression Test Form of 2B, 2F, 2G and 2M Hempcrete Specimens

Each specimen within both mixture designs serves a distinct purpose, acting as a variable in the research to assess and compare the influence of binders and additives on the compressive strength performance of hempcrete.

Table 3-3. Mixture Matrix 1 and 2

Mixture Design	Binder Types		Hemp (% by total Weight)	Additives			Compaction
	Lime (%total Weight)	MgO (%total Weight)		Metakaolin (%binder Weight)	Fly Ash (%binder Weight)	NanoSilica (%binder Weight)	
1A	35	-	25	6	-	-	Yes
1B	40	-	15	6	-	-	Yes
1C	45	-	5	6	-	-	Yes
1D	35	-	25	-	6	-	Yes
1E	40	-	15	-	6	-	Yes
1F	45	-	5	-	6	-	Yes
1G	35	-	25	6	6	-	Yes

1H	40	-	15	6	6	-	Yes
1K	45	-	5	6	6	-	Yes
1M	35	-	25	-	-	4	Yes
1N	40	-	15	-	-	4	Yes
1L	45	-	5	-	-	4	Yes
2A	-	35	25	6	-	-	Yes
2B	-	40	15	6	-	-	Yes
2C	-	45	5	6	-	-	Yes
2D	-	35	25	-	6	-	Yes
2E	-	40	15	-	6	-	Yes
2F	-	45	5	-	6	-	Yes
2G	-	35	25	6	6	-	Yes
2H	-	40	15	6	6	-	Yes
2K	-	45	5	6	6	-	Yes
2M	-	35	25	-	-	4	Yes
2N	-	40	15	-	-	4	Yes
2L	-	45	5	-	-	4	Yes

Each of these batches will undergo rigorous testing to evaluate their compressive strength and overall structural performance. The testing will adhere to ASTM standards, particularly focusing on ASTM-C109 for determining compressive strength. The results from these tests will inform which mixture designs show the most promise in terms of structural integrity and sustainability, paving the way for the broader application of hempcrete in construction.

Table 3-4. Mixture Matrix 3

Mixture Design	Sand	Binder Types		Hemp	Additives			Compaction
		Lime	MgO		Metakaolin	Fly Ash	NanoSilica	
1BS	40	40	-	15	6	-	-	Yes
2BS	40	-	40	15	6	-	-	Yes
2ES (3BS)	40	-	40	15	-	6	-	Yes
2NS (4BS)	40	-	40	15	-	-	4	Yes
1ES	40	40	-	15	-	6	-	Yes
1FS	40	45	-	5	-	6	-	Yes
1GMF20	-	35	-	25	20	20	-	Yes
1HMF20S	40	40	-	15	20	20	-	Yes
1HMF50	-	40	-	15	50	50	-	Yes
1HMF50S40	40	40	-	15	50	50	-	Yes
1KMFS	40	45	-	5	6	6	-	Yes
1NS	40	40	-	15	-	-	4	Yes
2CS40	40	-	45	5	6	-	-	Yes
2FS40	40	-	45	5	-	6	-	Yes
2KMF50	-	-	45	5	50	50	-	Yes
2GMF50	-	-	35	25	50	50	-	Yes
2HMF50	-	-	40	15	50	50	-	Yes
2HMF50S40	40	-	40	15	50	50	-	Yes
2LS20	20	-	45	5	-	-	4	Yes

2LS40	40	-	45	5	-	-	4	Yes
2LS40NS10	40	-	45	5	-	-	10	Yes
2LS60	60	-	45	5	-	-	4	Yes

Based on the provided table; Table 3-4., the specimen names in the modified mixture design series, which includes selections from Mixture Design 1 and 2 with alterations in ingredients and the addition of sand, are defined as follows:

- **1BS**: This specimen originates from Mixture Design 1 and includes 40% hydrated lime, 15% hemp, and 6% metakaolin (percentage of binder weight), with the addition of 40% sand (percentage of total weight).
- **2BS**: From Mixture Design 2, this specimen has 40% MgO, 15% hemp, and 6% metakaolin, with the inclusion of 40% sand.
- **2ES (3BS)**: Also from Mixture Design 2, replacing hydrated lime with MgO, this specimen contains 40% binder, 15% hemp, and 6% fly ash, with 40% sand.
- **2NS (4BS)**: A specimen from Mixture Design 2 with 40% MgO, 15% hemp, and 4% nano silica, supplemented with 40% sand.
- **1ES**: A Mixture Design 1 specimen with 40% hydrated lime, 15% hemp, and 6% metakaolin, plus 40% sand.
- **1FS**: Also from Mixture Design 1, this specimen contains 45% hydrated lime, 5% hemp, and 6% metakaolin, along with 40% sand.
- **1GMF20**: A unique specimen from Mixture Design 1 featuring 35% hydrated lime, 25% hemp, and a combined 20% of both metakaolin and fly ash, without sand.
- **1HMF20S**: This specimen is a variant of 1H from Mixture Design 1, which contains 40% hydrated lime, 15% hemp, and 20% of both metakaolin and fly ash, along with 40% sand.
- **1HMF50**: Another Mixture Design 1 specimen, it has 40% hydrated lime, 15% hemp, and a higher content of additives, at 50% of both fly ash and metakaolin, without sand.

- **1HMF50S40**: Similar to 1HMF50, this specimen includes 40% sand in its composition.
- **1KMFS**: This is a Mixture Design 1 specimen with 45% hydrated lime, 5% hemp, and 6% of both metakaolin and fly ash, with the addition of sand.
- **1NS**: A Mixture Design 1 specimen containing 40% hydrated lime, 15% hemp, and 4% nano silica, with 40% sand.
- **2CS40**: From Mixture Design 2, this specimen includes 45% MgO, 40% sand, and 5% hemp with 6% metakaolin.
- **2FS40**: Another Mixture Design 2 specimen, it has 45% MgO, 5% hemp, 40% sand, and 6% fly ash.
- **2KMF50**: This Mixture Design 2 specimen features 45% MgO, 5% hemp, and a total of 50% metakaolin and fly ash, without sand.
- **2GMF50**: Similar to 2KMF50, but with 35% MgO and 25% hemp, for a total of 50% additives; metakaolin and fly ash.
- **2HMF50**: Also from Mixture Design 2, containing 40% MgO, 15% hemp, and 50% fly ash and metakaolin, without sand.
- **2HMF50S40**: Like 2HMF50 but includes 40% sand in the mix.
- **2LS20**: A Mixture Design 2 specimen with 45% MgO, 5% hemp, 20% sand, and 4% nano silica.
- **2LS40**: This specimen has 45% MgO, 5% hemp, 40% sand, and 4% nano silica.
- **2LS40NS10**: Similar to 2LS40, but with an additional 10% nano silica of mgo weight.
- **2LS60**: From Mixture Design 2, this final specimen contains 45% MgO, 5% hemp, 60% sand (percentage of total weight), and with 4% nano silica (percentage of binder weight).

In this study, the inclusion of sand at 40% of the total weight was meticulously examined to assess its impact on hempcrete mixtures. Three samples of each specimen were prepared to ensure consistency and reliability. These were cured for 7 days and subjected to standardized compaction procedures as detailed in subsequent sections.

Expanding on initial findings, the research delved into the potential of sand to boost the compressive strength of selected hempcrete specimens. These specimens utilized binders such as lime and magnesium oxide, with additional pozzolans like fly ash, metakaolin, and nanosilica. This investigation aligns with the ongoing efforts in the construction industry to enhance the performance of sustainable materials beyond traditional standards.

Sand is recognized for its ability to significantly increase the compressive strength of composite materials. Serving as a fine aggregate, it fills gaps within the coarser structure of hemp hurds, creating a denser and more robust matrix. This study aimed to determine if sand could similarly enhance the structural integrity of hempcrete, potentially broadening its use in load-bearing applications.

The research specifically focused on the interaction between sand and the distinctive properties of hempcrete mixtures incorporating both conventional and innovative binders and additives. The dual objectives were to examine how sand affects the compressive strength when used alongside nanosilica and to understand its role within the mix.

This methodical approach ensured the generation of reliable and comparable data, providing insights into the efficacy of sand in improving hempcrete's mechanical properties. The findings from this comprehensive analysis could lead to significant advancements in green building materials, reinforcing hempcrete's role as a sustainable and structurally viable alternative to conventional concrete. Should the integration of sand prove to be beneficial, it would represent a crucial advancement in hempcrete technology, confirming its potential in sustainable construction practices.

3.5 Mixing, Molding and Curing of Hempcrete Specimens

This section details the meticulous preparation, casting, and curing processes undertaken for the hempcrete cube specimens, each measuring 2x2 inches. The experimental endeavor aimed to explore the impacts of various binders and additives on hempcrete's mechanical properties. The comprehensive methodology outlined below captures each step of the specimen preparation, from mixing to curing, ensuring consistency and reliability in the experimental results. Each of the mixtures indicated in Table 3-3. and 3-4. were mixed using the electrical mixer shown in Figure 3-9. each mixture were mixed until a homogeneous mixture was achieved.

Figure 3-9. Hobart Mixer used for preparing Hempcrete mixtures

3.6 Mixing Process

The process commenced with the preparation of the hempcrete mixture in a large pan mixer. Based on preliminary investigations and existing literature discrepancies regarding the mixing sequence of lime-hemp concrete (LHC), a standardized approach was adopted. The decision was influenced by findings that pre-wetting the hemp hurds before adding the binder could increase water demand without significantly benefiting the measured properties. Consequently, pre-wetting was omitted from the procedure.

Initially, hemp hurds were combined with dry binders—lime and magnesium oxide (MgO)—and mixed thoroughly for 3 minutes to ensure a homogeneous dry mix. This step was crucial for achieving an even distribution of the binders throughout the hemp hurd matrix. Following this, water was gradually added to the mixture to create a consistent slurry. The slurry was mixed for an additional 3 minutes, ensuring that the hemp hurds were fully saturated and the mixture achieved the desired consistency. As seen in Figure 3-10, the dry hemp hurds, binder agent and water are mixed together to get a consistent mixture paste, ready for the subsequent molding and curing processes integral to this study.

Figure 3-10. Mixture Paste of Hempcrete Specimens

3.7 Molding Process

After mixing, the slurry was carefully placed into diagonal cube molds. This was done in 3 to 4 layers to ensure uniform compaction throughout the cube. Each layer was tamped 15 to 20 times using a tamping rod, with particular attention given to the corners of the cubes. This meticulous compaction process was vital to eliminate voids within the cube and ensure that the corners were sufficiently compacted to withstand compression loads during testing, Figure 3-11.

Figure 3-11. Molds being used for casting hempcrete mixtures

3.8 Initial Curing

Immediately after casting, each mold was wrapped in a damp towel and sealed in plastic wrap. This setup was designed to retain moisture, enabling the initial hydration processes without significant moisture loss. The wrapped molds were stored at a consistent room temperature of 23°C and shielded from direct sunlight to maintain a stable curing environment for the first 24-48 hours, Figure 3-12.

Figure 3-12. Casted Hempcrete Paste in Molds being Wrap in Damp Cloths

3.9 Controlled Curing

Following the initial 24-48 hours curing period, the specimens were demolded with care and transferred to a curing chamber. This chamber was maintained at 100% relative humidity and a temperature of 23°C. The specimens remained in this controlled environment for 7 days, a duration determined to prevent surface drying and promote optimal, uniform curing across all samples. Figure 3-13 shows hempcrete specimens in Curing Chamber.

Figure 3-13. Demolded Specimens in Curing Chamber

3.10 Post-Curing and Preparation for Testing

After a controlled 7-day curing phase, the hempcrete cubes were removed from the humidity chamber and allowed to air dry at room temperature for 24-48 hours, reaching a surface-dry state. Each specimen was subsequently weighed and its volume calculated, with any loose material on the surfaces being brushed off to prepare for mechanical testing. This process ensured that all specimens were in the optimal condition for compressive strength assessment, thus providing reliable data for further analysis.

The focus of this research was to evaluate the early-age strength development of hempcrete blocks that included various binders and additives such as hydrated lime, magnesium oxide, metakaolin, Class F fly ash, and nano silica, with sand added as a structural filler in some specimens of Mixture Design 3. The aim was to determine the compressive strength of these compounds at the end of a week-long curing period.

The decision to use a 7-day curing period was based on technical considerations and supported by existing research. This period is crucial for enabling the rapid chemical reactions required for the setting of binders like lime and magnesium oxide, which are fundamental for initial strength gains via the formation of calcium silicate hydrate (C-S-H) and magnesium hydroxide ($Mg(OH)_2$). The pozzolanic activity of the additives used was expected to further enhance the hempcrete's strength and durability.

This interval also helped maintain optimal moisture levels, necessary for ongoing hydration and pozzolanic reactions, and prevented the material from drying too quickly, which could lead to strength loss and cracking. Additionally, the 7-day curing period was essential for developing a consistent microstructure, initiating the carbonation process, and establishing strong bonds between the hemp shives and the binder matrix, all vital for the structural integrity and longevity of the hempcrete.

Selecting a 7-day curing period balanced the need to assess early strength properties with practical construction timelines, providing a timely evaluation of the hempcrete's initial characteristics and facilitating informed decision-making in construction projects.

Overall, the selected curing period was crucial for investigating the immediate impact of the various binders, pozzolanic additives, and the structural role of sand, offering valuable insights into optimizing hempcrete mixtures for enhanced early load-bearing performance.

3.11 Compressive Strength Test of Hempcrete

The compressive strength of hempcrete, a critical indicator of its structural efficacy and longevity within the domain of sustainable construction, has been meticulously evaluated through the deployment of a MTS testing apparatus, as delineated in Figure 3-14. Absent a formal standard, the assessment procedures adopted were informed by the protocols established in EN 196-1. It was ascertained that a loading rate of 20 lb/s was optimal, substantiated by a series of comparative analyses across disparate rates, which confirmed the absence of significant discrepancies in mechanical behavior and strength.

Figure 3-14. MTS Compressive Strength Test Assembly and Hempcrete Cubes to be tested.

Hempcrete is characterized by its propensity to deform rather than fracture under duress, which stands in contrast to the brittle failure of conventional concrete. This distinctive response necessitated the cessation of tests at the cessation of linear stress/strain behavior. Yet, an exception was observed in specimens with a diminished ratio of hemp hurds, which exhibited a resemblance to the characteristic brittle fracture of conventional concrete and were thus crushed under compression.

Two primary approaches were employed to determine the compressive strength of hempcrete at the critical transition point between linear behavior and the plateau region. The first approach focused on identifying the inflection point where the behavioral alteration occurs. This method involves a thorough examination of the stress/strain or load/displacement curves for each specimen to pinpoint the exact moment when the material transitions from linear to non-linear behavior.

The second approach relied on the stress corresponding to a deformation of 0.1 - 0.4 inches (2.5 - 10 mm), which is commonly associated with ultimate strength values. This method takes into account the practical considerations of material deformation and provides a standardized range for determining the compressive strength.

In this research, the ultimate strength is considered to be the point at which the mechanical behavior departs from a linear stress/strain curve, aligning with the first approach mentioned above.

Conforming to ASTM C-109, the evaluation of compressive strength was executed on trios of cubes from each mix design after a septennial period of curing, with the findings exhibited in Figure 3-15. This protocol, traditionally reserved for concrete exceeding a density of 50 lb/ft3, was meticulously followed until the manifestation of specimen failure, evidenced by observable cracking, excessive deformation, or fragmentation.

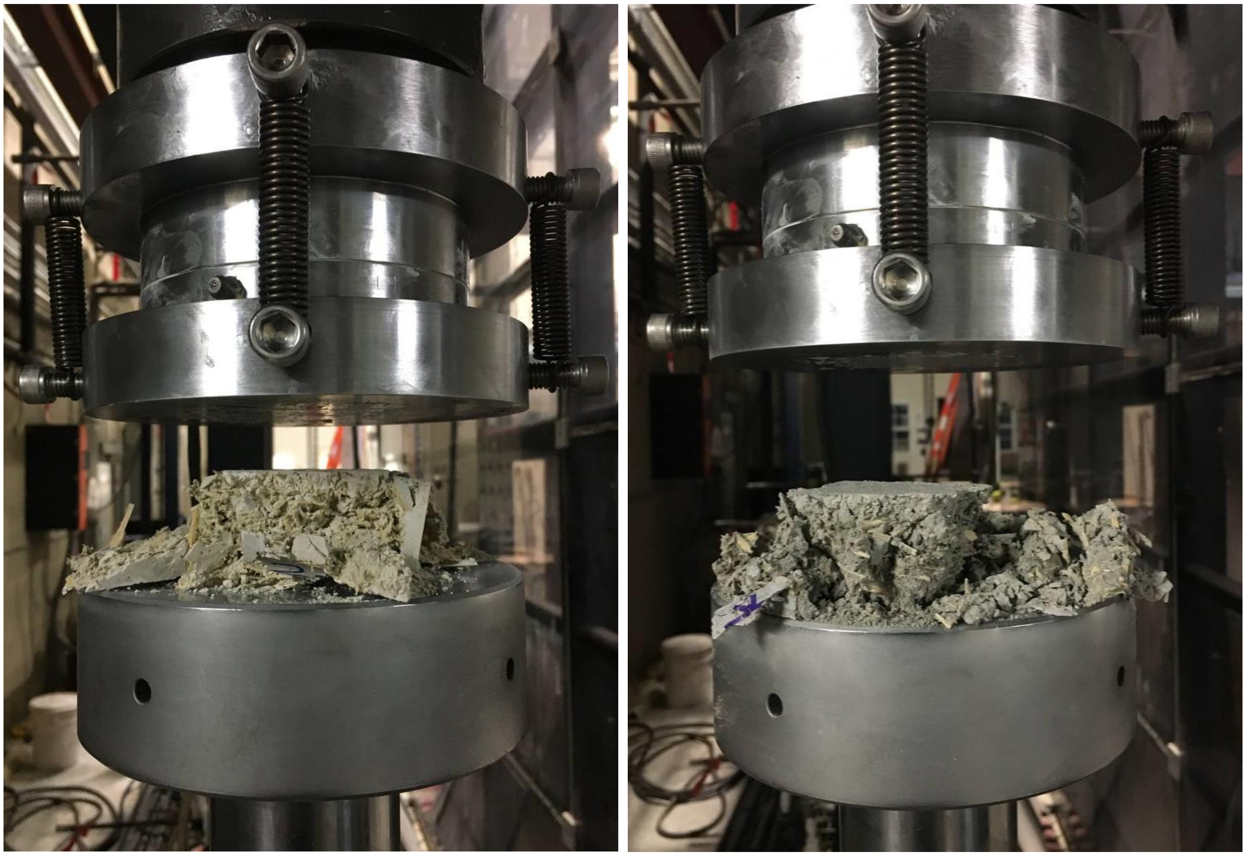


Figure 3-15. Hempcrete Cube under Compresstion Test Load

Samples of hempcrete, a composition of hydrated lime, magnesium oxide, and densely packed hemp shives, were prepared and subjected to a rigorous curing regime at 23°C with saturated humidity, guaranteeing the cultivation of optimal testing conditions. Targeted densities ranged from 600-1200 kg/m3, ensuring an equilibrium between structural fortitude and homogeneity of the mixture.

A range of compressive strength for hempcrete, typically spanning from 0.1 to 1 MPa, was revealed through initial analyses. This strength is largely dependent on the specific composition of the mixture and the conditions under which the curing process took place. The relationship between the binder and hemp content was given special attention in the study, with the hypothesis that increasing the proportion of binder would lead to a corresponding increase in compressive strength.

Furthermore, it was theorized that by incorporating alternative binders and additives, such as magnesium oxide, Metakaolin, Fly Ash, NanoSilica, and sand, while simultaneously employing enhanced compaction techniques, the compressive strength of hempcrete could be significantly improved. The interplay between these components and the optimization of their ratios were thought to be key factors in achieving superior mechanical properties.

Figure 3-16. illustrates the two distinct failure modes observed during the compression testing of hempcrete cubes: strain densification and brittle failure. The left image in Figure 3-16 depicts a specimen that underwent strain densification, where the hempcrete cube was compressed and deformed without exhibiting any signs of brittle failure. This type of failure is characterized by the specimen being squeezed or flattened, resembling a pancake-like shape. Strain densification is a unique characteristic of hempcrete, which allows the material to absorb energy through compression without experiencing sudden or catastrophic failure.

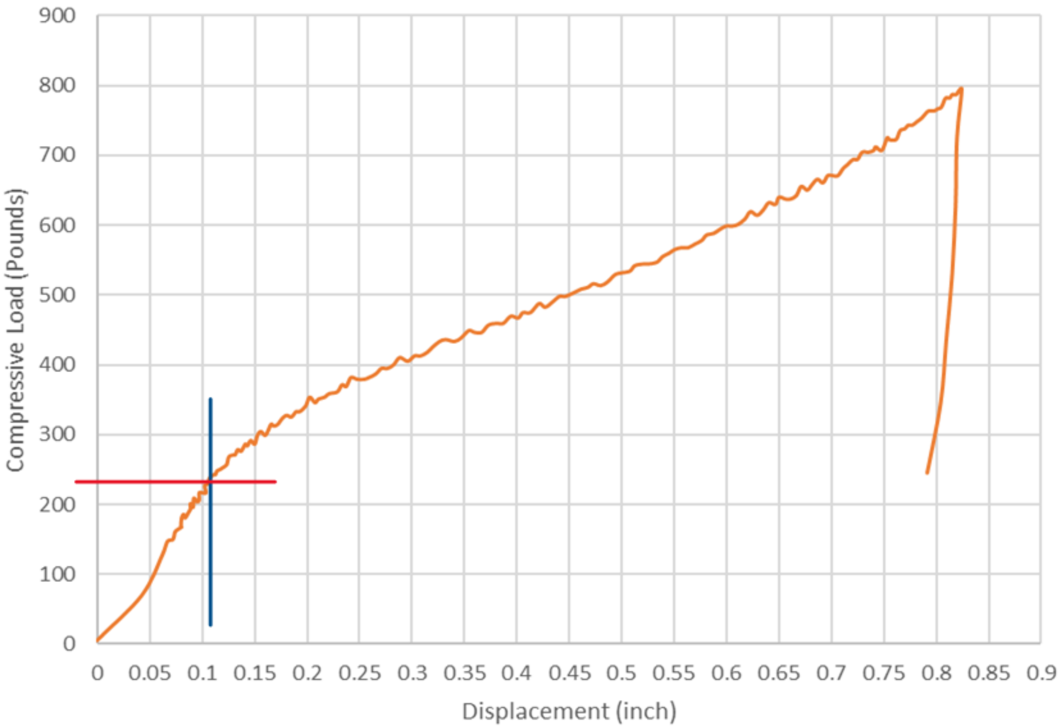
In contrast, the right image in Figure 3-16. presents a specimen that demonstrated brittle failure, akin to the behavior of regular concrete. Brittle failure in hempcrete is characterized by sudden fractures and a semi-explosive or explosive mode of failure. This type of failure occurs when the applied compressive stress exceeds the material's strength, leading to rapid crack propagation and a complete loss of structural integrity. Brittle failure is typically associated with materials that have limited ability to deform plastically and absorb energy before reaching their ultimate strength.

The load/displacement curves for two failure modes, as depicted, provide insightful data on the behavior of the hempcrete under compression testing. The last curve from the top, in particular, highlights the brittle failure characteristics. Initially, the curve exhibits a very shallow slope, representing the preliminary adjustment phase of the testing device. This initial segment, extending to approximately 0.08 inches displacement, represents the compressive testing device settling as the load actuators make contact with the surface of the specimen . This early segment, up to about 0.08 inches displacement, reflects the device's calibration rather than the hempcrete’s actual compressive behavior.Following the settling region, the curve transitions into a steep, nearly linear slope. This linear portion of the curve represents the elastic deformation of the specimen under increasing compressive load. The slope of this section is directly related to the specimen's stiffness or elastic modulus. The linearity of this region indicates that the specimen is undergoing uniform compression without significant damage or plasticity.

The linear elastic region continues until the curve reaches a peak load value of approximately 2147 Pounds at a displacement of around 0.25 inches. This peak represents the ultimate compressive strength of the 2KMF50-3 hempcrete specimen. At this point, the specimen has reached its maximum load-bearing capacity before experiencing critical failure.

Immediately following the peak load, the curve exhibits a sharp drop-off, indicating a sudden loss of load-bearing capacity. This rapid decrease in load is characteristic of a brittle failure mode, where the specimen fractures or collapses abruptly once its ultimate strength is exceeded. The steep decline suggests that the specimen does not exhibit significant post-peak ductility or energy absorption.

The comparison of these two failure modes in Figure 3-16 highlights the significant influence of mixture composition and additives on the mechanical properties and failure behavior of hempcrete. The incorporation of various binders, such as lime and magnesium oxide, along with additives like metakaolin, fly ash, and nano-silica, can substantially alter the failure characteristics of hempcrete.


Compressive Load (Pounds)
0
100
200
300
400
500
600
700
800
900
Displacement (inch)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9

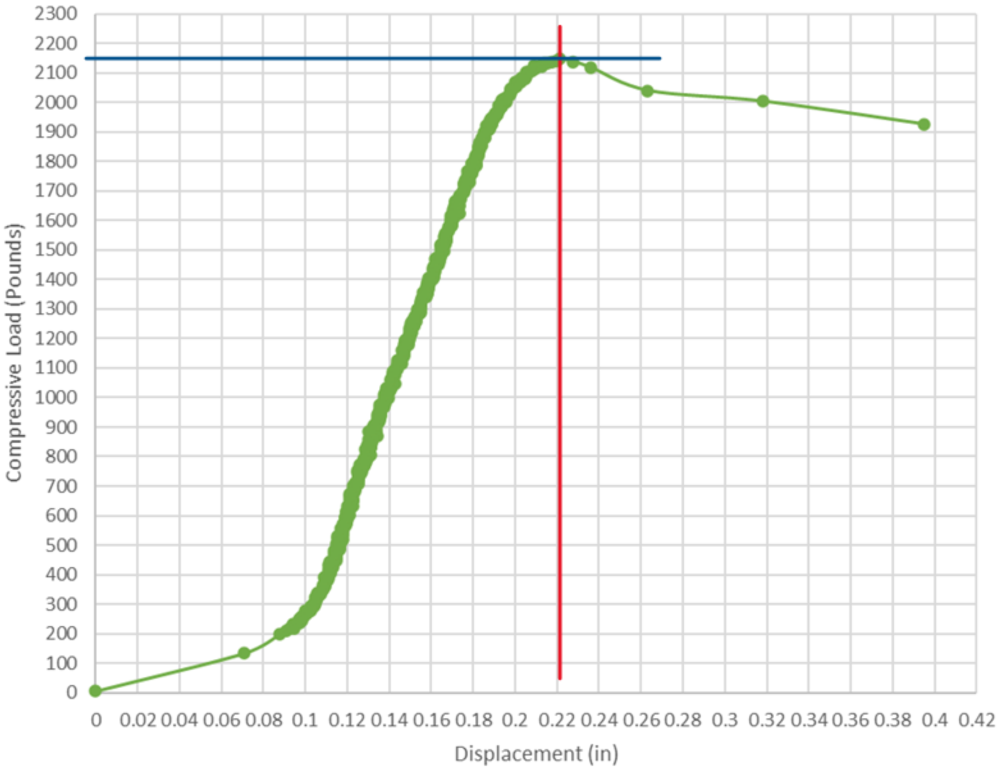


Figure 3-16. Post-Compression Test Comparison of Hempcrete Cubes; Deformed and Crushed.

The consequences of this study are twofold. Firstly, the potential for significantly expanding the use of hempcrete in load-bearing applications is presented, posing a challenge to traditional concrete use. Secondly, it aligns with the growing demand for environmentally friendly materials in the construction industry, marking a significant step towards sustainable building practices and possibly broadening the scope of hempcrete's use in the structural aspects of contemporary architecture.

Summary

This research aimed to enhance the compressive strength of hempcrete, a sustainable building material, through a comprehensive experimental program that investigates the effects of various binders, additives, and mixture proportions. The study has addressed the need for eco-friendly construction materials that can reduce the environmental impact of the building sector while providing adequate mechanical properties for load-bearing applications.

The experimental plan involved the preparation of hempcrete mixtures using two primary binders: hydrated lime and magnesium oxide (MgO). The mixtures incorporate different proportions of hemp hurds, water, and additives such as metakaolin, fly ash, and nanosilica. Some mixtures also include sand as a fine aggregate to increase density and strength. The study consists of three main mixture designs, with a total of 24 different formulations that systematically vary the binder type, hemp content, additive type, and additive content.

The specimens were prepared by mixing the dry ingredients, followed by the gradual addition of water to create a homogeneous slurry. The mixtures were then cast into 2-inch cubic molds, compacted in layers, and subjected to a controlled curing process. The curing involved an initial 24-48 hours period of sealed curing at room temperature, followed by a 7-day curing period in a humidity chamber maintained at 100% relative humidity and 23°C.

After curing, the specimens were tested for compressive strength using a standardized testing procedure adapted from EN 196-1. The tests were conducted using an MTS testing apparatus, with a loading rate of 20 lb/s. The compressive strength was determined at the transition point between linear elastic behavior and the onset of plastic deformation or failure. The results have been analyzed to identify the most promising mixture designs that achieve significant improvements in compressive strength.

The expected outcomes of this research include the following:

1. Identification of optimal binder types, additives, and mixture proportions that result in substantial enhancements in the compressive strength of hempcrete.
2. Improved understanding of the mechanisms underlying strength development in hempcrete, particularly the role of pozzolanic reactions and the interaction between binders, additives, and hemp hurds.

The findings of this study have the potential to advance the use of hempcrete as a load-bearing composite material in construction applications. By achieving significant improvements in compressive strength, the results of this research can help overcome one of the main barriers to the widespread adoption of hempcrete, thereby promoting sustainable building practices and reducing the environmental footprint of the construction industry.

Chapter 4

Results and Analysis

4.1 Introduction

This chapter explores the results of our experimental investigation into the density and compressive strength of hempcrete samples. The research employs a variety of materials, ranging from traditional binders like hydrated lime to innovative options such as magnesium oxide-cement, and includes both common additives like fly ash and metakaolin and new introductions like nano-silica, with sand used as a filler. The objective is to evaluate how these components, in their varied proportions, affect the mechanical properties of hempcrete. The analysis aims to demonstrate how enhancements in compressive strength could position hempcrete as a feasible material for load-bearing applications, thereby potentially transforming its use in sustainable construction practices. This could lead to greater adoption of hempcrete as a fundamental building material, markedly influencing the construction industry's commitment to environmentally sustainable practices.

4.2 Density of Hempcrete Specimens

4.2.1 Mixture Design Group 1

In the exploration of hempcrete's performance, the density of the material plays a crucial role, impacting both its mechanical properties and thermal conductivity. The focus of this section is on the density characteristics of Hempcrete Mixture Design 1, a composite comprising hydrated lime as the primary binder, hemp hurds as the aggregate, and water. The mixture is enhanced with additives like metakaolin, Class F fly ash, and nano silica to boost its mechanical properties and sustainability.

Hydrated lime, employed as the foundational binder, reacts with silica and other components to establish a robust matrix. The lightweight and insulating properties of hemp hurds introduce porosity and texture to the mix, while water facilitates the chemical reactions essential for the hempcrete's setting and curing. To further refine the mixture, carefully selected additives are incorporated.

Metakaolin, serving as a pozzolanic material, reacts with the lime to produce additional cementitious compounds that enhance the mixture’s strength and durability. Class F fly ash, a byproduct of coal combustion, is used to improve workability and strength over time, simultaneously reducing the mixture's carbon footprint. Additionally, nano silica, recognized for its highly reactive surface area, is utilized to significantly boost the density and strength of the mixture, even when added in small quantities.

Table 4-1. Measured Weight and Density of Mixture Design 1

Mixture Names	Cube	Weight (grams)	Avg	SD	Average Density (kg/m3)	Average Density (lb/ft3)
1A	1	89	87.80	2.89	669.73	41.81
	2	84.5				
	3	89.9				
1B	1	94.8	96.97	2.49	739.66	46.17
	2	99.7				
	3	96.4				
1C	1	119.2	118.43	1.24	903.40	56.39
	2	119.1				
	3	117				
1D	1	96.4	92.87	3.07	708.38	44.22
	2	91.4				
	3	90.8				
1E	1	119.4	119.67	1.81	912.81	56.98
	2	118				
	3	121.6				
1F	1	124.6	125.63	1.16	958.33	59.82
	2	126.9				
	3	125.4				
1G	1	100.8	98.43	2.69	750.84	46.87
	2	95.5				
	3	99				
1H	1	128.6	122.87	4.98	937.22	58.51
	2	120.4				
	3	119.6				
1K	1	130.7	130.90	0.20	998.50	62.33
	2	130.9				
	3	131.1				
1M	1	90.2	90.70	0.781	691.85	43.19
	2	90.3				
	3	91.6				
1N	1	124.1	127.20	2.78	970.28	60.57
	2	129.5				

	3	128				
1L	1	124.4	123.30	2.72	940.53	58.71
	2	120.2				
	3	125.3				

4.2.1.1 Weights and Densities of Mixture Design 1

The given weights for each cube are a direct measure of the mass of the specimens are shown in Table 4-1. These values are used to calculate the average density, which is the mass per unit volume (kg/m^3 or lb/ft^3). The density is influenced by the composition of the mix and the distribution and reaction of the additives within the matrix.

Influence of Hydrated Lime:

An increasing proportion of hydrated lime from specimens 1A to 1C and 1D to 1F correlates with an increase in average density. This is consistent with the fact that hydrated lime has a higher density than hemp shives. Lime also reacts with additives to form a denser matrix, as seen with metakaolin in 1A-1C and with fly ash in 1D-1F.

Role of Hemp Shives:

The decrease in hemp shiv content corresponds to increased density, likely due to the fact that hemp shives are less dense than the lime and additive mixture. This explains the higher densities in specimens 1C, 1F, and 1L, which have the lowest content of hemp shives.

Additives and Their Impact:

1. **Metakaolin (1A-1C):** Metakaolin's small particle size and high reactivity lead to a denser microstructure through the pozzolanic reaction, filling voids and increasing the weight and density of the specimens.
2. **Fly Ash (1D-1F):** The larger, spherical particles of fly ash likely result in a less dense matrix than metakaolin, but still contribute to increased density compared to the base lime and hemp shives mix due to pozzolanic reactions.

3. **Combined Metakaolin and Fly Ash (1G-1K):** The combination of both additives should theoretically offer a balance between the reactivity of metakaolin and the filler effect of fly ash, potentially leading to intermediate densities as observed in the table.
4. **Nano Silica (1M-1L):** Nano silica, due to its nano-scale particle size and high surface area, would be expected to significantly increase the density by filling microscopic voids and reacting rapidly with the lime. However, the expected trend is not consistent across the specimens. The increase in density is evident in 1M and 1N but not in 1L, possibly due to excessive water content leading to increased porosity as previously discussed.

Specimen Consistency:

Insights into the uniformity of each specimen are provided by the standard deviation (SD) values, with lower SD values indicating a more consistent density across the tested cubes. Specimens 1K and 1M exhibit the least variability, implying a highly uniform mix attributed to the effective distribution and reactivity of additives within the mixture.

The process of compaction is instrumental in influencing the density of hempcrete, impacting the distribution of hemp shives, the level of air entrapment, and the effectiveness of the binder in occupying the voids between aggregates. By reducing void spaces, compaction aims to enhance the density, which in turn, may improve key mechanical properties like compressive strength and thermal performance.

The densities of the specimens outlined in the table range from 669.738 to 998.504 kg/m^3, surpassing the densities reported in prior studies. For instance, Nguyen et al. (2009) documented a density range of 670-850 kg/m^3, Walker et al. (2014) reported significantly lower densities between 360-400 kg/m^3, and Tronet et al. (2016) observed densities ranging from 580-843 kg/m^3. These discrepancies in reported densities reflect variations in mixture compositions, the types and amounts of binders and additives used, the size and treatment of hemp shives, and compaction methodologies.

In contrast to these previously reported ranges:

- Specimens 1A, 1D, and 1M, with average densities of 669.738, 708.386, and 691.859 kg/m^3 respectively, align with or slightly under Nguyen et al.'s lower threshold. These specimens suggest lighter mixes which could prove advantageous in applications where reduced weight is beneficial.

- The specimen with the lowest density from your dataset, 1A, significantly surpasses the maximum density noted by Walker et al., which may result from higher levels of compaction and greater binder proportions used in your experiments.
- Several specimens, notably 1B, 1C, 1E, 1F, 1H, and 1K, exceed the maximum density limits set by Nguyen et al. and Tronet et al., suggesting these samples could be representative of a more compact material with a denser binder matrix, possibly enhanced by the addition of reactive additives such as metakaolin, fly ash, and notably nano-silica.
- Specimens 1N and 1L approach the upper density limit observed by Tronet et al., hinting that their mixture designs, combined with the application of nano-silica and a higher level of compaction, may yield a hempcrete of relatively higher density than typically seen.

4.2.2 Mixture Design Group 2

This section offers an in-depth analysis of Hempcrete Mixture Design 2, examining the use of magnesium oxide (MgO) as a substitute for traditional hydrated lime as a binder. MgO is celebrated for its rapid carbonation capabilities and potential to achieve higher early strength, signifying a significant shift in hempcrete technology. In this formulation, MgO is mixed with hemp hurds and water, laying the foundation for an innovative hempcrete matrix. To optimize its characteristics and improve performance, additives like metakaolin, Class F fly ash, and nano-silica are incorporated.

Compaction plays a pivotal role in the methodology of this study. It is performed by tamping with a rod, a technique that effectively minimizes void spaces while enhancing the homogeneity and density of the hempcrete. This standard approach to compaction is crucial for accurately evaluating the material's properties.

In Mixture Design 2, specimens labeled 2A through 2L are meticulously prepared, each varying in the proportions of MgO, hemp shives, and water, and are enhanced with differing percentages of selected additives. The density measurements obtained from the empirical weights of these compacted specimens are instrumental in evaluating the effectiveness of MgO as a binder.

These results are set to be juxtaposed against the established density ranges found in existing literature, thereby exploring the viability of MgO-enhanced hempcrete in diverse construction scenarios.

Table 4-2. Measured Weight and Density of Mixture Design 2

Mixture Names	Cube	Weight (grams)	Avg	SD	Average Density (kg/m3)	Average Density (lb/ft3)
2A	1	105.6	106.80	1.37	814.67	50.85
	2	108.3				
	3	106.5				
2B	1	132.8	131.93	2.13	1006.38	62.82
	2	129.5				
	3	133.5				
2C	1	149.9	149.53	3.06	1140.63	71.21
	2	146.3				
	3	152.4				
2D	1	105.1	104.10	1.17	794.07	49.57
	2	102.8				
	3	104.4				
2E	1	136.2	137.77	1.46	1050.88	65.60
	2	139.1				
	3	138				
2F	1	152.5	148.20	5.42	1130.46	70.57
	2	150				
	3	142.1				
2G	1	115.9	116.27	0.40	886.88	55.36
	2	116.2				
	3	116.7				
2H	1	148.5	143.73	4.37	1096.39	68.44
	2	142.8				
	3	139.9				
2K	1	157.2	159.10	1.73	1213.61	75.76
	2	160.6				
	3	159.5				
2M	1	98.3	102.83	4.20	784.41	48.97
	2	103.6				
	3	106.6				
2N	1	125.4	124.30	2.081	948.16	59.19
	2	125.6				
	3	121.9				
2L	1	151.8	148.77	3.213	1134.79	70.84

	2	149.1				
	3	145.4				

Table 4-2 provides empirical data on the weights and densities of hempcrete specimens incorporating magnesium oxide (MgO) as a binder, with varying contents of hemp shives, water, and additives such as metakaolin, Class F fly ash, and nano silica. Each specimen has been compacted to reduce void spaces and increase uniformity within the matrix. The following analysis explores the technical implications of this data within the context of the material's design and performance.

4.2.2.1 Weights and Densities of Mixture Design 2

The provided weights are used to calculate the average densities, reflecting the mass-to-volume ratio. These densities are a critical measure of the material's suitability for construction, affecting both the structural and thermal performance.

Influence of MgO:

The replacement of hydrated lime with MgO could potentially result in different reactivity and binding characteristics. MgO is known for its rapid rate of carbonation and ability to gain strength quickly, which could contribute to the variation in densities observed:

- **Specimens 2A to 2C (with Metakaolin):** These show an increase in density with increasing MgO content. Metakaolin's fine particle size and its pozzolanic reaction with MgO likely contribute to a denser matrix compared to specimens with lower MgO content, as evidenced by the increasing average density from 814.67 to 1140.64 kg/m^3.

- **Specimens 2D to 2F (with Class F Fly Ash):** Class F fly ash has a lower reactivity compared to metakaolin, which may result in a less dense matrix initially; however, long-term strength gains are expected. The average density increases with MgO content, ranging from 794.07 to 1130.47 kg/m^3, which aligns with the pozzolanic activity and the filling effect of fly ash particles.

- **Specimens 2G to 2K (Combined Additives):** The combination of metakaolin and fly ash results in a significant density increase, likely due to the synergistic effects of the two additives, as seen in the high density of 1213.61 kg/m^3 for specimen 2K.

- **Specimens 2M to 2L (with Nano Silica):** Nano silica's high reactivity with MgO should result in the highest densities due to the enhanced pozzolanic reaction and the effective filling of voids. However, the density for specimen 2M is lower than expected at 784.41 kg/m³, which could be attributed to factors such as the water-to-binder ratio, the efficiency of compaction, and the nano silica dispersion within the matrix.

Compaction Effect:

Compaction through tamping is employed to achieve a uniform and dense packing within the hempcrete mixtures, with the consistency of this process reflected by lower standard deviation (SD) values. These values are indicative of the effectiveness of the compaction method used. However, higher SD values in certain specimens, like 2F, indicate potential inconsistencies in compaction or uneven material distribution.

The in-depth examination of hempcrete mixture designs 1 and 2 has highlighted how different binders, additives, and compaction methods influence the density and, consequently, the structural and thermal properties of the material. A thorough comparative analysis with prior studies shows considerable variations in density, which are crucial for understanding the material's performance characteristics.

In Mixture Design 1, hydrated lime is used as the binder, supplemented with additives such as metakaolin, Class F fly ash, and nano silica. The densities achieved range from 669.738 kg/m³ to 998.504 kg/m³, covering and exceeding typical density values cited in the literature. Metakaolin reacts with lime to enhance density significantly, whereas fly ash provides a more gradual increase due to its lower reactivity. Nano silica, known for its high pozzolanic activity, greatly increases the density, particularly in mixtures with a higher binder ratio.

Mixture Design 2 introduces MgO as a binder in place of hydrated lime, capitalizing on MgO's quick carbonation and potential for early strength development. This mixture achieves densities ranging from 784.412 kg/m³ to 1213.614 kg/m³, surpassing previously reported ranges. Each additive—metakaolin, Class F fly ash, and nano silica—contributes to creating a denser matrix when used with MgO, enhancing the material's overall properties compared to those achieved with hydrated lime.

4.3 Compressive Strength Testing of Hempcrete Specimens

In this section, the outcomes from compressive strength tests conducted on hempcrete specimens are detailed, exploring their suitability for structural applications. The specimens comprised varying ratios of hemp hurds and binders—namely hydrated lime and magnesium oxide (MgO), enhanced with additives like metakaolin, fly ash, and nano-silica. Additionally, sand was included in certain samples, constituting 40% of the total weight, to evaluate its impact on enhancing compressive strength.

The uniform hempcrete cubes, each measuring 2 inches in every dimension, underwent rigorous manufacturing protocols. Initially, the samples were wrapped in damp towels and sealed in plastic to minimize moisture loss, a process visually depicted in Figure 3-11. They were then demolded after 24 to 48 hours and placed in a curing chamber maintained at a constant 23°C and 100% relative humidity, as shown in Figures 3-12 and 3-13, to establish a standardized curing regimen aligned with ASTM C109 procedures.

After curing, the specimens were conditioned to reach a state suitable for testing, involving an acclimation period at room temperature until a surface-dry condition was achieved. Each specimen was then weighed and its volume measured before testing. The compressive strength was assessed using a standardized testing apparatus, illustrated in Figure 3-14, where each sample underwent axial loading until failure.

Table 4-3 underscores hempcrete's potential as a viable load-bearing material, illustrating how the strategic incorporation of magnesium oxide, nano-silica, hydrated lime, and especially sand, substantially modifies its structural properties. The addition of sand, in particular, plays a critical role in enhancing compressive strength by replacing the material's natural porosity with a denser, stronger filler.

The analysis reveals a distinct correlation between mixture composition and compressive strength, demonstrating that innovative adjustments not only enhance strength but also position hempcrete as a revolutionary building material. The findings from these tests advocate for a sophisticated application of hempcrete, suggesting it can meet, if not surpass, the demands of traditional construction materials.

These insights are invaluable for future research and application in structural engineering, showing that hempcrete is not just an insulating material but a viable, eco-friendly option for load-bearing structures. This shift towards sustainable, structurally robust building practices is documented not just through numerical data but as a vision for a sustainable construction future.

Table 4-3. Measured and Calculated Compressive Load & Stress of Mixture Design 1

Specimen	Cube	Compressive Load (Pounds)	Stress (Psi)	Stress (Mpa)	Avg (Stress-Psi)	SD
1A	1	234.8	58.7	0.40	57.84	0.98
	2	227.03	56.75	0.39		
	3	232.2	58.05	0.40		
1B	1	446.45	111.61	0.76	115.61	3.46
	2	469.68	117.42	0.80		
	3	471.2	117.8	0.81		
1C	1	402.94	100.73	0.69	101.10	1.33
	2	399.98	99.99	0.68		
	3	410.31	102.57	0.70		
1D	1	290.65	72.66	0.50	74.53	2.81
	2	292.6	73.15	0.50		
	3	311.05	77.76	0.53		
1E	1	610.22	152.55	1.05	149.68	4.47
	2	578.1	144.52	0.99		
	3	607.85	151.96	1.04		
1F	1	281.3	70.32	0.48	71.18	0.97
	2	283.82	70.95	0.48		
	3	288.98	72.24	0.49		
1G	1	329.84	82.46	0.56	80.51	3.04
	2	308.03	77.00	0.53		
	3	328.26	82.06	0.56		
1H	1	634.9	158.72	1.09	163.54	4.65
	2	655.54	163.88	1.12		
	3	672.07	168.01	1.15		
1K	1	409.14	102.28	0.70	102.04	1.16
	2	403.06	100.76	0.69		
	3	412.22	103.05	0.71		
1M	1	356.1	89.02	0.61	94.62	5.48
	2	379.3	94.82	0.65		
	3	399.98	99.99	0.68		
1N	1	601.58	150.39	1.03	152.72	2.23
	2	611.66	152.91	1.05		
	3	619.4	154.85	1.06		

1L	1	393.05	98.26	0.67	98.48	1.41
	2	399.98	99.99	0.68		
	3	388.73	97.18	0.67		

Figure 4-1 provides a visual representation of the compressive loads for Mixture Design 1, offering a clear comparison as detailed in Table 8.

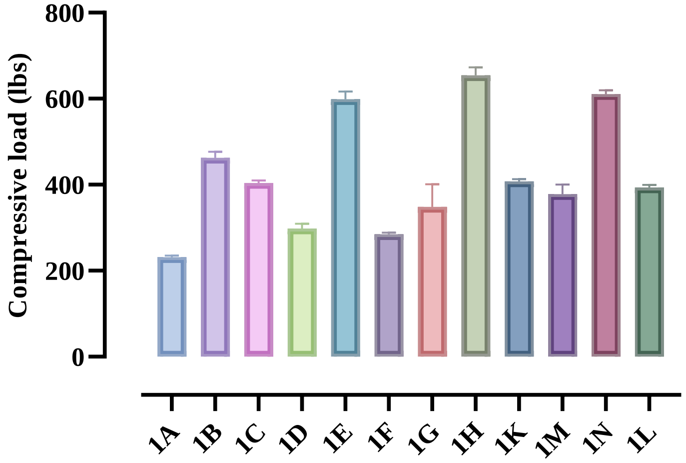


Figure 4-1. Comparison of Compressive Load of Mixture Design 1

4.3.1 Compressive Strength Analysis of Mixture Design 1

Specimens 1A-1C (Metakaolin Additive):

- The results show increasing compressive strength with increasing binder content and decreasing hemp shiv content. Specimen 1C, with the highest lime content, exhibits a compressive strength of 101.10 psi, indicating the role of metakaolin in providing a reactive pozzolanic action that enhances strength. The higher binder-to-shives ratio allows for a more cohesive matrix and better load distribution.

Specimens 1D-1F (Class F Fly Ash Additive):

- These specimens exhibit a higher compressive strength compared to 1A-1C, with 1E reaching the peak at 149.68 psi. The Class F Fly Ash contributes to the long-term strength due to its pozzolanic reaction, forming additional cementitious materials over time. The gradual increase in strength suggests that fly ash continues to react, potentially leading to durability.

Specimens 1G-1K (Metakaolin and Class F Fly Ash Additives):

- The combination of metakaolin and fly ash in these specimens seems to synergistically enhance compressive strength, with 1H displaying the highest strength at 163.54 psi. The dual additive approach benefits from the immediate reactivity of metakaolin and the long-term strength gains from fly ash, leading to a robust and durable matrix.

Specimens 1M-1L (Nano Silica Additive):

- Specimens with nano silica have varied strengths, with 1N reaching a high of 152.72 psi. Nano silica, due to its ultrafine particles, is highly reactive and fills the voids effectively, leading to a denser and stronger matrix. The increased strength with higher binder content and nano silica indicates a strong pozzolanic reaction and efficient particle packing.

An extensive study was undertaken to elevate the load-bearing capabilities of hempcrete, transitioning its use from non-structural to structural applications. The standard specimen, H1, featuring an equal hemp-binder-water ratio of 1:1:1 (33% Hemp, 33% Hydrated Lime, 33% Water), initially registered a compressive strength of 29.43 psi following a 7-day curing period. Efforts to enhance this baseline strength focused on altering material compositions to overcome hempcrete's traditional limitations for structural use.

Specimens augmented with a 6% metakaolin additive (Specimens 1A-1C) demonstrated significant strength improvements. Notably, Specimen 1B revealed an increase in strength by nearly threefold (292.83%) compared to the benchmark. This substantial boost is credited to the high pozzolanic activity of metakaolin, which improves the microstructure and facilitates early strength development. Nonetheless, it was observed that an excessive increase in binder content coupled with a reduction in hemp shives (as seen in 1C) led to a minor decrease in strength gain, pointing to an ideal ratio that optimizes compressive strength.

Figure 4-2 illustrates the varied failure modes of hempcrete specimens 1A, 1E, 1H, and 1L, ranging from strain densification to brittle fracture. These differences reflect the distinct compositions and structural responses of the specimens under load, highlighting the influence of mixture variations on the mechanical properties of hempcrete.

Figure 4-2. Post-Compression Test Form of 1A, 1E, 1H and 1L Hempcrete Specimens; Deformed & Crushed

In the study, specimens enriched with a 6% Class F Fly Ash additive (1D-1F) were observed to exhibit an incremental rise in compressive strength. Notably, specimen 1E registered an increase of 408.60%, the highest in this group. This enhancement is attributed to the slow-reacting pozzolanic nature of fly ash, which is crucial for boosting long-term durability in hempcrete.

The Integration of both metakaolin and Class F fly ash additives (1G-1K) showcased a notably effective synergy, with specimen 1H achieving a 455.69% increase in compressive strength. This suggests a complementary effect that maximizes the immediate and extended benefits of the additives used.

Additionally, the inclusion of 4% nano silica (1M-1L) markedly improved compressive strengths, with specimen 1N demonstrating a 418.93% uplift from the baseline. The ultrafine particles of nano silica densely pack the matrix and significantly fill voids, enhancing the strength of the cementitious bonds considerably.

These results collectively affirm the potential of hempcrete as a viable load-bearing material, given optimal formulation. The application of reactive pozzolanic additives such as metakaolin, Class F fly ash, and particularly nano silica, has proven to significantly enhance hempcrete's compressive strength early in the curing process. The careful adjustment of hemp-binder ratios and the strategic selection of additives are key factors in improving hempcrete's mechanical properties. This technical evaluation lays a solid groundwork for hempcrete's incorporation as a sustainable structural material, marking an important advancement towards eco-friendly construction practices.

Table 4-4 in Mixture Design 2 provides comprehensive data on compressive load and stress, reflecting the differences across various specimens and emphasizing the effects of mixture composition on the performance of hempcrete.

Table 4-4. Measured and Calculated Compressive Load & Stress of Mixture Design 2

Specimen	Cube	Compressive Load (Pounds)	Stress (Psi)	Stress (Mpa)	Avg (Stress-Psi)	SD
2A	1	252.8	63.2	0.43	62.35	0.98
	2	245.1	61.275	0.42		
	3	250.26	62.565	0.43		
2B	1	634.88	158.72	1.09	156.65	11.63
	2	668.44	167.11	1.15		
	3	576.5	144.125	0.99		
2C	1	1042.75	260.68	1.79	257.68	12.53
	2	975.63	243.90	1.68		
	3	1073.73	268.43	1.85		
2D	1	299.67	74.91	0.51	77.17	2.01
	2	315.27	78.81	0.54		
	3	311.1	77.77	0.53		
2E	1	661.31	165.32	1.13	166.79	1.97
	2	663.97	165.99	1.14		
	3	676.15	169.03	1.16		
2F	1	363.84	90.96	0.62	89.67	3.41
	2	343.2	85.8	0.59		
	3	369.00	92.25	0.63		
2G	1	347.34	86.83	0.59	83.57	4.06
	2	316.05	79.01	0.54		
	3	339.49	84.87	0.58		
2H	1	717.5	179.37	1.23	165.60	12.36
	2	621.9	155.47	1.07		
	3	647.8	161.95	1.11		
2K	1	725.24	181.31	1.25	180.66	0.57
	2	721.9	180.47	1.24		
	3	720.8	180.2	1.24		

2M	1	425.6	106.4	0.73	111.92	6.95
	2	478.9	119.72	0.82		
	3	438.5	109.62	0.75		
2N	1	725.24	181.31	1.25	186.90	7.56
	2	735.56	183.89	1.26		
	3	782.03	195.50	1.34		
2L	1	1491.9	372.97	2.57	387.60	12.93
	2	1590	397.5	2.74		
	3	1569.35	392.33	2.70		

4.3.2 Compressive Strength Analysis of Mixture Design 2

Mixture Design 2 experiments with varying ratios of magnesium oxide (MgO) as a binder, hemp shives, and water, along with different percentages of metakaolin, Class F fly ash, and nano silica additives. These specimens underwent a 7-day curing period, and their compressive strengths were evaluated to determine the potential of hempcrete in load-bearing applications.

Specimen Analysis

- **2A-2C (Metakaolin Additive):**
    - Specimens with metakaolin showcase a progressive increase in compressive strength as the MgO content rises from 35% to 45%. The highest average stress is observed in 2C (257.68 psi), which indicates the beneficial effect of metakaolin's pozzolanic reaction with MgO. This series presents an increase in the binder-to-shiv ratio, which appears to contribute positively to compressive strength.
- **2D-2F (Class F Fly Ash Additive):**
    - These specimens display an increasing trend in strength with higher MgO content, with 2E reaching the highest average stress (166.79 psi). Class F fly ash, a slower reacting pozzolan compared to metakaolin, offers a gradual development of strength, suggesting improvements in the long-term durability of hempcrete.
- **2G-2K (Combined Metakaolin and Class F Fly Ash Additives):**
    - The combination of metakaolin and Class F fly ash provides a synergistic effect that enhances compressive strength, as seen in 2H (165.60 psi). However, an

optimal balance seems necessary, as the highest MgO content in 2K does not yield the strongest specimen, which may be due to excessive water creating a more porous structure.

- **2M-2L (Nano Silica Additive):**
    - The inclusion of nano silica demonstrates a remarkable increase in strength, particularly for 2N (186.90 psi). Nano silica's ultrafine particles and high reactivity lead to significant densification and strength gains, underscoring its effectiveness in improving the compressive strength of MgO-based hempcrete.

Technical Considerations

The increased compressive strength across Mixture Design 2 can be technically analyzed based on:

- **Particle Interactions**: Fine particles in metakaolin and nano silica fill voids within the matrix, leading to denser packing and higher strength. Conversely, the spherical particles of fly ash improve workability, potentially affecting compaction and the resulting strength.
- **Chemical Reactions**: The pozzolanic reactions between MgO and the additives contribute to the formation of additional cementitious materials, enhancing the matrix's strength. Notably, the reaction with nano silica is rapid and effective, providing considerable early strength gains.
- **Hydration and Curing**: The water content in the mixtures influences the hydration process. While necessary for chemical reactions, excessive water can increase porosity and reduce strength, a balance that must be carefully managed.
- **Standard Deviation**: Variability in compressive strength within specimen sets, indicated by the standard deviation, highlights the importance of consistent mixing, compaction, and curing processes to ensure uniformity in hempcrete's structural properties.

In conclusion, the utilization of magnesium oxide (MgO) as a binder within Mixture Design 2, coupled with the strategic employment of pozzolanic additives, has proven to be a promising strategy for amplifying the compressive strength of hempcrete. The findings indicate that certain formulations significantly surpass the baseline strength needed for structural applications, signifying a pivotal development in the functional capabilities of hempcrete. Particularly, nano silica stands out as a highly effective additive, markedly boosting compressive strength and supporting hempcrete's advancement as a viable structural material.

The initial benchmark for this research was set by Specimen H1, which displayed a compressive strength of 29.43 psi after a curing period of one week, with a formulation comprising equal parts hemp hurds, hydrated lime, and water. This baseline strength was pivotal in guiding subsequent enhancements aimed at bolstering hempcrete's inherent structural qualities.

Figure 4-3 captures the physical transformation of the H1 specimen, showcasing its undistorted shape before compression testing and its altered form after testing. This visual representation serves to highlight the effects of mixture formulation on the structural integrity of hempcrete, reinforcing the potential of meticulously crafted mixtures not only to meet environmental sustainability goals but also to satisfy structural demands in the construction industry.

Figure 4-3. Undeformed and Deformed Shape of H1 Specimen made from Hemp Hurds, Hydrated Lime and Water with Ratios of 1:1:1

In Mixture Design 2, magnesium oxide (MgO) was substituted for hydrated lime as the binder, complemented by additives such as metakaolin, Class F Fly Ash, and nano silica. These components were subjected to a standard 7-day curing process and rigorous compaction techniques. Specimens 2A-2C, which incorporated 6% metakaolin, experienced significant enhancements in compressive strength, with increases ranging from 111.85% to an impressive 775.55%. This marked improvement reflects the potent pozzolanic activity generated by the interaction between MgO and metakaolin. However, the gains showed diminishing returns as the binder proportion increased in specimen 2C, suggesting a delicate balance is required between material components to achieve optimal strength.

The integration of Class F Fly Ash in specimens 2D-2F illustrated a similar pattern, with strength gains varying from 162.21% to 466.72%. The enduring strengthening effects of fly ash's reactivity, when used in conjunction with MgO, highlight its potential to boost the durability and load-bearing capabilities of hempcrete.

Further strength enhancements were observed in specimens 2G-2K, which combined both metakaolin and Class F Fly Ash. Notably, specimen 2K demonstrated an exceptional increase of 513.87% in compressive strength. This result suggests that a strategic combination of reactive additives can be effectively orchestrated to exploit their individual benefits, culminating in a synergistic effect that significantly reinforces the hempcrete composite.

These findings underscore the transformative potential of using innovative material combinations in hempcrete formulations, thereby advancing its application in structural contexts and offering a more robust alternative within the construction industry.

Figure 4-4. Post-Compression Test Form of 2B, 2F, 2G and 2M Hempcrete Specimens; Deformed & Crushed

As depicted in Figure 4-4, the 2B, 2F, 2G, and 2M specimens from Mixture Design 2 showcase varied deformation and crushing patterns post-compression testing, which illustrate the distinct failure modes inherent to each formulation. The presence of nano silica in specimens 2M-2L, notably, has significantly augmented compressive strength, with specimen 2L demonstrating a striking increase of 1217.037% in strength. The capability of nano silica to efficiently pack micro-voids within the hempcrete matrix has proven to be a game-changer, substantially boosting the material's strength.

These enhancements collectively confirm the potential of hempcrete, when optimally formulated with the right additives and ratios, to serve as a structurally sound material. The strategic use of MgO as a binder, combined with pozzolanic additives such as metakaolin, Class F Fly Ash, and particularly nano silica, has been shown to considerably elevate hempcrete's compressive strength, even at early curing stages. This improvement is pivotal, as it facilitates the use of hempcrete in load-bearing applications within the construction industry, signaling a shift towards more sustainable and structurally robust building methods.

Figure 4-5 visually represents this advancement, summarizing the compressive load data from Table 4-4 and underscoring the enhanced performance across different hempcrete formulations within Mixture Design 2. This advancement not only supports the thesis's claim of hempcrete's viability as a structural material but also exemplifies a significant leap in combining environmental sustainability with the requisite mechanical properties for modern construction.

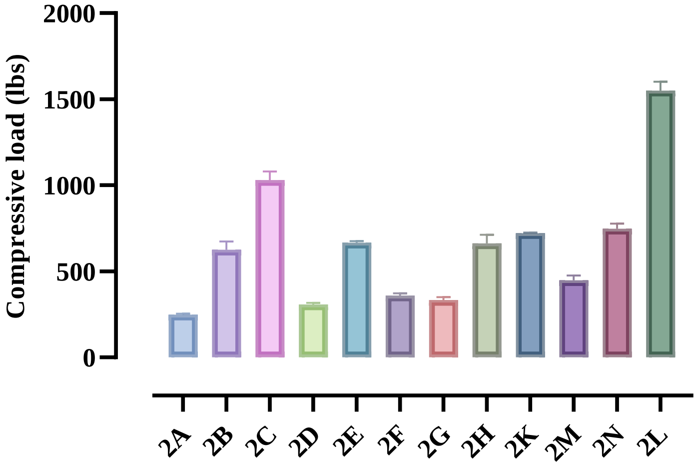


Figure 4-5. Comparison of Compressive Load of Mixture Design 2

4.3.3 Comparative Analysis of Hempcrete Compressive Strength: MgO versus Hydrated Lime Binders

A thorough evaluation was conducted to explore the advancement of hempcrete as a sustainable construction material, comparing Mixture Designs 1 and 2 to assess the effects of substituting magnesium oxide (MgO) for traditional hydrated lime as a binder. This assessment aimed to elucidate the impact of this binder change on hempcrete's compressive strength, particularly when combined with additives such as metakaolin, fly ash, and nano silica. The focus was to determine how these variations influence the material's capability to transition from non-load-bearing to load-bearing applications.

In the first batch comparison, Specimens 1A-1C were juxtaposed with 2A-2C, as depicted in Figure 4-6. This bar chart visually underscores the compressive load differences between the two mixture designs, with a particular emphasis on the specimens containing metakaolin.

Both sets, 1A-1C and 2A-2C, underwent a standardized 7-day curing period, during which the compressive strength was meticulously measured. These specimens were methodically altered, gradually increasing the binder percentage from 35% to 45%, while reducing the proportion of hemp shives, maintaining a consistent percentage of additives.

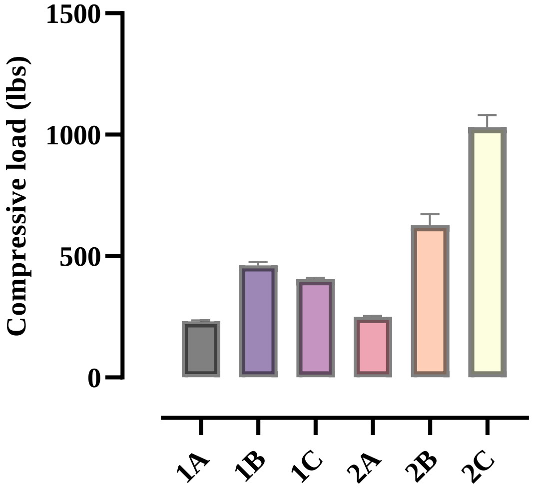


Figure 4-6. Comparison of Compressive Load of Mixture Design 1 and 2 Specimens with Metakaolin Additive

The transition from hydrated lime to MgO presented notable changes in the compressive strength values. The metakaolin series (1A-1C and 2A-2C) displayed a significant increase in strength with the inclusion of MgO, with specimen 2C reaching an increase of 775.55% over the H1 baseline (29.43 psi), compared to specimen 1C's 243.53% increase.

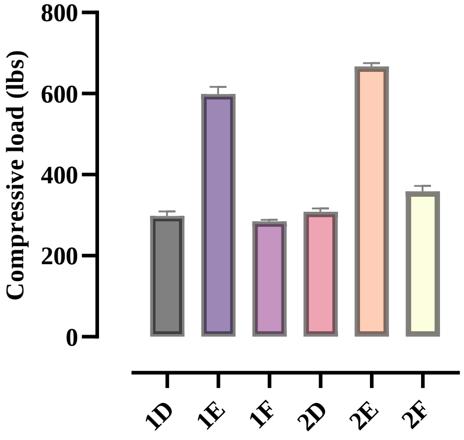


Figure 4-7. Comparison of Compressive Load of Mixture Design 1 and 2 Specimens with Class F Fly Ash Additive

Figure 4-7 illustrates the compressive load capacities of Mixture Design 1 and 2 specimens, specifically highlighting variations when Class F fly ash is used as an additive.

In a detailed comparative analysis of the compressive strength between Mixture Design 1 (1D, 1E, 1F) and Mixture Design 2 (2D, 2E, 2F), the effectiveness of magnesium oxide (MgO) as an alternative binder to hydrated lime is evaluated. This comparison is instrumental in assessing the potential of hempcrete to transition from non-load-bearing to load-bearing applications within the sustainable building sector.

Mixture Design 1: Hydrated Lime with Class F Fly Ash

- Specimen 1D achieved an average compressive strength of 74.53 psi.
- Specimen 1E displayed a notable increase with an average strength of 149.68 psi, the highest in this series.
- Specimen 1F showed an average strength of 71.18 psi, indicating some decrease from 1E.

Mixture Design 2: Magnesium Oxide with Class F Fly Ash

- Specimen 2D recorded an average strength of 77.17 psi, showing a slight improvement over its hydrated lime counterpart.
- Specimen 2E marked a substantial increase, reaching an average compressive strength of 166.79 psi, surpassing 1E by a significant margin.
- Specimen 2F exhibited an average strength of 89.67 psi, again an increase compared to the hydrated lime equivalent.

The average compressive strengths indicate that the MgO binder in Mixture Design 2 enhances the compressive strength of hempcrete when combined with Class F Fly Ash. Specifically, the increase from Specimens 1E to 2E (which possess the same hemp shives and water ratios but different binders) suggests that MgO's interaction with the fly ash additive is more effective in strengthening the matrix than the traditional lime-based approach. This is further supported by the improvement observed in 2D and 2F over their corresponding specimens from Mixture Design 1.

The higher compressive strength values in Mixture Design 2 can be attributed to the fundamental characteristics of MgO, which include a faster setting time and a stronger final set, compared to hydrated lime. The pozzolanic reactions between MgO and Class F Fly Ash appear to create a denser and more cohesive matrix.

Figure 4-8 presents a bar chart comparing the compressive loads of Mixture Design 1 and 2 specimens, showcasing the impact of fly ash and metakaolin additives on their structural performance.

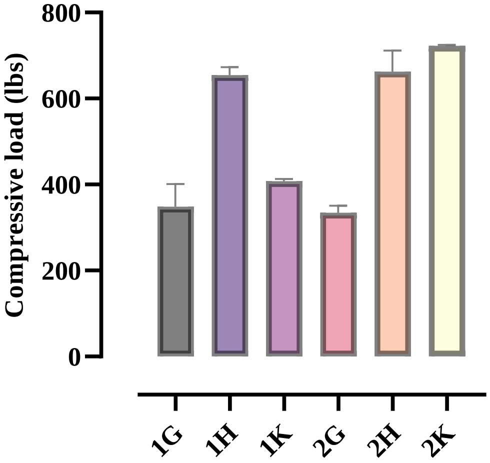


Figure 4-8. Comparison of Compressive Load of Mixture Design 1 and 2 Specimens With Fly Ash and Metakaolin

The bar chart and accompanying tables for Mixture Designs 1 and 2 present the compressive load test results for specimens 1G, 1H, 1K, which incorporate a blend of 6% metakaolin and 6% Class F fly ash, and specimens 2G, 2H, 2K, which utilize the same additives but with magnesium oxide (MgO) as the binder. This analysis aims to underscore the differences in compressive strength resulting from the type of binder used and its interaction with the additives.

In Mixture Design 1, the average compressive strengths of specimens 1G, 1H, and 1K are recorded at 80.51 psi, 163.54 psi, and 102.04 psi, respectively. These values reveal that the combination of metakaolin and fly ash can significantly bolster the compressive strength of hempcrete, although the effectiveness can vary depending on the ratio of binder to hemp shivs.

Conversely, in Mixture Design 2, where MgO serves as the binder, the compressive strengths are considerably enhanced, with averages of 83.57 psi for 2G, 165.60 psi for 2H, and 180.66 psi for 2K. This suggests that MgO's interaction with the pozzolanic additives leads to a more robust hempcrete composite. Notably, the strength enhancement from specimen 1H to 2H is approximately 1.24%, and from 1K to 2K, an impressive 77%. These increases are particularly significant against the backdrop of the baseline strength of 29.43 psi observed in the original H1 specimen, highlighting MgO's potential to elevate hempcrete to a viable structural material.

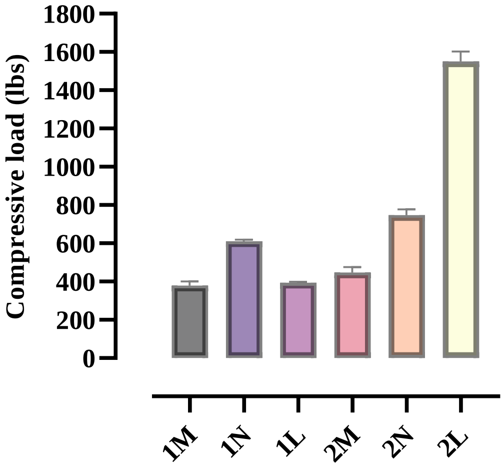


Figure 4-9. Comparison of Compressive Load of Mixture Design 1 and 2 Specimens With Nano-Silica

As depicted in Figure 4-9, a bar chart illustrates the differences in compressive load for Mixture Design 1 and 2 specimens when nano-silica is used as an additive.

The final batch of data presents a side-by-side comparison of compressive strength results for hempcrete specimens with nano silica as an additive—1M, 1N, and 1L from Mixture Design 1 using hydrated lime, versus 2M, 2N, and 2L from Mixture Design 2 using MgO as a binder. This analysis aims to highlight the improvements achieved in Mixture Design 2 and to evaluate the effect of the binder type in conjunction with the nano silica additive.

Mixture Design 1: Hydrated Lime with Nano Silica

- Specimen 1M has an average compressive strength of 94.62 psi.
- Specimen 1N shows an enhanced average strength of 152.72 psi.

- Specimen 1L demonstrates further strength improvement, with an average of 98.48 psi.

Mixture Design 2: MgO with Nano Silica

- Specimen 2M shows a notable increase to an average strength of 111.92 psi.
- Specimen 2N exhibits a significant jump to 186.90 psi, outperforming its hydrated lime counterpart.
- Specimen 2L achieves a remarkable average compressive strength of 387.60 psi, demonstrating a vast improvement over 1L.

The data reveals that substituting hydrated lime with MgO in the presence of nano silica results in substantial gains in compressive strength across all comparable specimens. The average strength increase from 1N to 2N is approximately 22.37%, and a striking increase of over 293.5% is seen from 1L to 2L, indicating that the MgO-nano silica combination produces a more robust hempcrete.

The interaction of MgO with nano silica yields a denser and more cohesive matrix due to the fine particle size and high reactivity of the additive, which effectively fills voids and promotes the pozzolanic reaction. This results in a significant improvement in the compressive strength of the material, making MgO-based hempcrete with nano silica an excellent candidate for higher load-bearing capacity hempcrete.

4.3.4 Mixture Design 3

The table below provides a thorough analysis of compressive strength test results for Mixture Design 3 (MD3), comparing it with results from previous Mixture Designs 1 (MD1) and 2 (MD2). MD3 features novel adjustments in the binder-to-additives ratios and incorporates sand into the hempcrete mix, enhancing its structural properties. Each specimen in MD3 is carefully formulated with varying percentages of magnesium oxide (MgO) as the binder, metakaolin, and Class F fly ash as additives. Some specimens also include sand, constituting 40% of the total weight, to assess its impact on compressive strength.

These specimens were all subjected to a standard 7-day curing period and compaction, ensuring consistency in the testing methodology. This controlled process guarantees that the test results accurately reflect the true performance potential of each modified formulation, facilitating a precise evaluation of how these compositional changes affect the material's properties.

Table 4-5 illustrates the compressive load and stress (psi) across three individual cubes for each hempcrete variant within MD3. These data are essential for evaluating hempcrete's load-bearing capabilities and for guiding further refinements in mixture design. The subsequent technical discussion will explore the detailed outcomes of these tests, focusing on the influence of each component on the hempcrete's overall compressive strength, underlining the advancements in using hempcrete as a sustainable and structurally sound building material.

Table 4-5. Measured and Calculated Compressive Load & Stress of Mixture Design 3

Specimens	Cube	Compressive Load (Pounds)	Stress (Psi)	Stress (Mpa)	Avg (Stress-Psi)	SD
1BS	1	682.95	170.73	1.17	169.38	1.50
	2	671.03	167.75	1.15		
	3	678.61	169.65	1.16		
2BS	1	659.35	164.83	1.13	163.02	2.82
	2	639.04	159.76	1.10		
	3	657.81	164.45	1.13		
2ES (3BS)	1	428.95	107.23	0.73	106.71	1.36
	2	430.96	107.74	0.74		
	3	420.63	105.15	0.72		
2NS (4BS)	1	572.93	143.23	0.98	145.26	4.42
	2	601.33	150.33	1.03		
	3	568.85	142.21	0.98		
1ES	1	845.06	211.26	1.45	210.48	4.18
	2	856.89	214.22	1.47		
	3	823.83	205.95	1.42		
1FS	1	397.4	99.35	0.68	97.86	1.33
	2	387.2	96.8	0.66		
	3	389.66	97.41	0.67		
1GMF20	1	508.4	127.1	0.87	125.38	1.62
	2	495.5	123.87	0.85		
	3	500.65	125.16	0.86		
1HMF20S	1	807.84	201.96	1.39	206.26	3.78
	2	836.24	209.06	1.44		
	3	831.07	207.76	1.43		
1HMF50	1	745.31	186.32	1.28	184.70	1.54
	2	732.98	183.24	1.26		

	3	738.14	184.53	1.27		
1HMF50S40	1	1056.56	264.14	1.82	264.29	3.03
	2	1045.33	261.33	1.80		
	3	1069.57	267.39	1.84		
1KMFS	1	588.42	147.10	1.01	146.82	0.56
	2	584.67	146.16	1.00		
	3	588.76	147.19	1.01		
1NS	1	942.16	235.54	1.62	236.97	3.84
	2	965.31	241.32	1.66		
	3	936.20	234.05	1.61		
2CS40	1	1021.83	255.45	1.76	256.03	0.51
	2	1025.84	256.46	1.76		
	3	1024.68	256.17	1.76		
2FS40	1	621.24	155.31	1.07	155.23	0.31
	2	619.56	154.89	1.06		
	3	621.98	155.49	1.07		
2KMF50	1	2135.26	533.81	3.68	532.68	4.87
	2	2109.35	527.33	3.63		
	3	2147.59	536.89	3.70		
2GMF50	1	360.15	90.03	0.62	87.84	3.33
	2	336.00	84.00	0.57		
	3	357.96	89.49	0.61		
2HMF50	1	647.42	161.85	1.11	167.48	4.97
	2	676.94	169.23	1.16		
	3	685.34	171.33	1.18		
2HMF50S40	1	553.89	138.47	0.95	142.41	3.85
	2	570.35	142.58	0.98		
	3	584.72	146.18	1.00		
2LS20	1	1466.1	366.52	2.52	364.57	4.37
	2	1438.25	359.56	2.47		
	3	1470.5	367.62	2.53		
2LS40	1	2361.84	590.46	4.07	586.54	4.63
	2	2325.7	581.42	4.00		
	3	2350.98	587.74	4.05		
2LS40NS10	1	2414.18	603.54	4.16	604.12	0.56
	2	2418.73	604.68	4.16		
	3	2416.53	604.13	4.16		
2LS60	1	2636.61	659.15	4.54	655.42	3.53
	2	2619.83	654.95	4.51		
	3	2608.54	652.13	4.49		

Figure 4-10 displays a bar chart comparing the compressive load of Mixture Design 1 and 2 against 3 specimens, highlighting the variations in the content of metakaolin, fly ash, nano-silica, and sand.

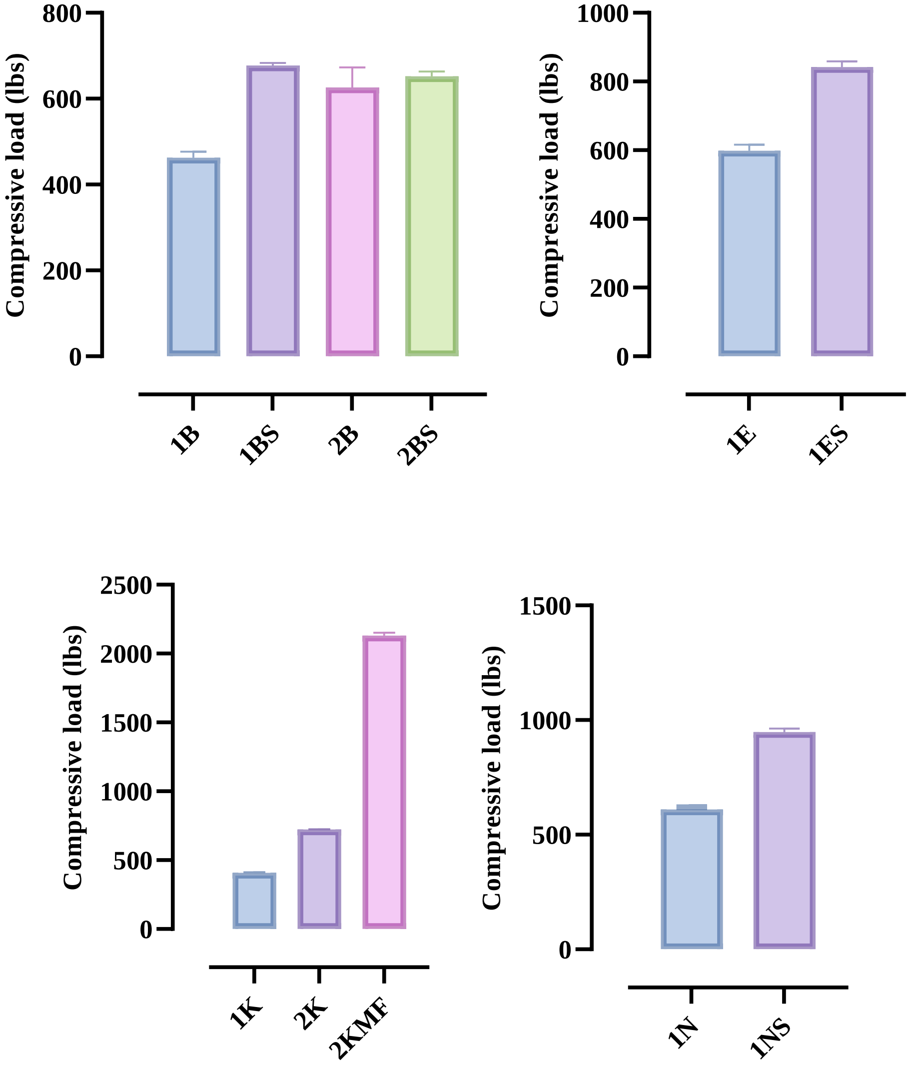


Figure 4-10. Comparison of Compressive Load of Mixture Design 1 and 2 against 3 Specimens With Metakaolin, Fly Ash, Nano-Silica and Sand

As we synthesize the data from Mixture Design 3 (MD3), our analysis endeavors to discern the mechanical fortitude of hempcrete, scrutinizing how innovative alterations in material constituents influence compressive strength. The specimens are meticulously compared against established formulations in Mixture Designs 1 (MD1) and 2 (MD2), revealing notable differences in performance.

Interpreting Compressive Strength Data:

In the study, the compressive stress values (in psi) for MD3 were compared to those from MD1 and MD2, illustrating how variations in material compositions affect performance. For example, the MD3 specimen 1BS, which contains 40% sand, demonstrates a compressive stress of 169.38 psi, noticeably higher than its MD1 counterpart, 1B, with a compressive stress of 115.61 psi. This comparison underscores the positive role of sand in enhancing compressive strength.

Moreover, when examining specimens like 2ES (3BS) and 2NS (4BS), which also include sand, stress values of 106.71 psi and 145.26 psi are recorded, respectively. These figures are in contrast to their sand-free counterparts, 2E and 2N, from MD2, which present higher values of 166.79 psi and 186.9 psi, respectively. The lower stress values observed in the sand-inclusive specimens may suggest a potential dilution of the binder matrix's effectiveness or could reflect a differential impact of varying additives when combined with sand. These results highlight the complexity of interactions within hempcrete mixtures and the need for careful optimization of material proportions to achieve desired structural properties.

Figure 4-11. Crushed Forms of 2KMF50 & 2LS60 Hempcrete Specimens Under Compression Test

As depicted in Figure 4-11, the 2KMF50 and 2LS60 hempcrete specimens exhibited a brittle failure pattern under compressive testing

Notably, 2KMF50, which combines a high percentage of MgO with metakaolin and fly ash, reaches an impressive stress value of 532.68 psi, highlighting the synergetic interaction between MgO and the pozzolanic materials.

Technical Discussion:

The technical analysis in this discussion delves into the impact of mixture design components on compressive strength, highlighting that mixtures in MD3 using magnesium oxide (MgO) as the binder—especially those combined with significant amounts of metakaolin and fly ash—typically exhibit superior compressive strength compared to traditional lime-based systems. This enhancement is likely attributable to the greater pozzolanic activity of these components, which effectively improves the microstructure of the hempcrete.

The behavior of specimens containing sand is varied; while some show a boost in strength, others do not. This variation may be related to the dual role of sand, which in some cases enhances the density as a filler and in others may interfere with the binder-aggregate interaction.

Specifically, specimens like 1HMF20S and 1HMF50S40, which carefully balance lime, metakaolin, fly ash, and sand, have achieved impressive strength values of 206.26 psi and 264.29

psi, respectively. These results suggest that precise adjustments in the proportions of binder to additives, coupled with the strategic inclusion of sand, are critical in creating durable, load-bearing hempcrete.

Furthermore, the use of nano silica, particularly in specimens such as 2LS40NS10 which reached a compressive strength of 604.12 psi, underscores the significant influence of this additive. Nano silica's contribution to denser particle packing and its role in enhancing pozzolanic reactions likely lead to a denser, stronger matrix, substantially elevating the compressive strength. This insight underlines the potential for engineered hempcrete formulations to meet and exceed traditional construction material standards, paving the way for broader structural applications in the construction industry.

4.3.5 Effects of Pozzolanic Additives and Sand Integration

An in-depth analysis of MD3 specimens demonstrates significant compressive strength gains when high percentages of metakaolin, fly ash, and nano-silica are used alongside sand. For instance, specimen 1ES, blending traditional lime binder with fly ash and sand, achieved a stress value of 210.48 psi, marking a notable improvement from its MD1 counterpart, 1E, which recorded 149.68 psi. This increase highlights the effectiveness of incorporating fly ash and sand into the hempcrete mix.

Similarly, the MD3 specimen 1HMF20S achieved a stress value of 206.26 psi, a substantial rise from the MD1 specimen 1H, which had a stress value of 163.54 psi. The combined use of metakaolin and fly ash, enhanced by sand, contributes synergistically to optimizing hempcrete's compressive strength.

Moreover, the MD3 variant 1HMF50S40, which includes a higher proportion of pozzolanic additives along with sand, recorded a stress value of 264.29 psi. This figure significantly surpasses the 184.70 psi noted in its MD1 precursor, 1HMF50, demonstrating the impactful role of these additives in improving hempcrete's microstructure.

Continuing this trend, the MD3 specimen 2KMF50, containing 50% each of metakaolin and fly ash combined with MgO, reached an impressive stress value of 532.68 psi, starkly contrasting with the MD2 specimen 2K, which registered 180.66 psi. The inclusion of sand in specimens such as 2LS40 further enhances compressive strength, evidenced by a stress value of

586.54 psi, a significant increase from 2L’s 387.6 psi. These substantial strength gains indicate that high-additive mixes paired with sand can not only meet but greatly exceed the performance standards of traditional construction materials.

4.4 Discussion and Limitations

The mix design analysis has revealed valuable insights into the relationship between the proportions of hydrated lime and hemp hurds, the compaction process, and the resulting compressive strength of hempcrete mixtures. The strongest mixtures achieved a compressive strength of approximately 600 lbs, with the best-performing design containing 40% hydrated lime and 15% hemp hurds. This specific combination of ingredients and proportions led to the optimal balance of strength and other desirable properties. However, the study also highlighted the challenges associated with compacting mixtures with higher hemp hurds content, such as those containing 25%. The high water absorption capacity of hemp hurds led to a moisture-rich matrix, which affected the compaction process and the final strength of the hempcrete. Specimens with 5% hemp hurds and 45% hydrated lime (e.g., 1C, 1F, 1K, 1L) presented particular challenges during compaction, resulting in porous regions, air voids, and premature failure during compression tests.

The inability to achieve proper compaction in certain mixtures underscores the importance of workability and the balance between the proportions of hemp hurds and binder. While a higher percentage of hemp hurds can contribute to the ductility and flexibility of the hempcrete, it also increases the water demand and hinders the compaction process. Conversely, a higher proportion of hydrated lime improves the binding properties but may lead to a sticky and difficult-to-compact mixture when combined with a low percentage of hemp hurds. These findings emphasize the need for further research and optimization of mixture designs to achieve the desired balance between strength, workability, and other performance characteristics. Future investigations should focus on finding the optimal range of hemp hurds content that allows for effective compaction while maintaining the desired mechanical properties, as well as exploring alternative compaction methods and the use of additives to improve the workability of hemp-lime mixtures.

The failure mode of hempcrete specimens is governed by a combination of factors, including the mixture design, binder type, hemp hurds content, and moisture levels. Mixture Design 1, which primarily utilized hydrated lime as the binder, exhibited the most ductile behavior among the three mixture designs, suggesting that the use of hydrated lime promotes a more flexible and less brittle failure mode. The presence of hydrated lime likely allows for better stress distribution and energy dissipation within the matrix, resulting in a more gradual failure process. In contrast, Mixture Design 2, which incorporated magnesium oxide (MgO) cement as the binder, generally displayed brittle failure, especially when higher MgO binder content was used in combination with lower hemp hurds content. The brittleness of MgO-based mixtures can be attributed to the strong bonding between the MgO particles and the formation of a dense matrix, which limits the ability of the material to deform plastically before failure.

The presence of a higher proportion of hemp hurds (typically around 25%) and increased moisture content contributed to more flexible and ductile failure modes. The fibrous nature of hemp hurds and their ability to bridge cracks and redistribute stresses may contribute to the improved ductility of the material. The relationship between moisture content and failure behavior highlights the importance of proper drying and curing conditions in the production of hempcrete, as adequate drying time is necessary to ensure that the specimens reach an appropriate moisture level before testing. Understanding these relationships can help in the development of hempcrete mixtures with desired mechanical properties and failure characteristics, enabling the optimization of the material for specific applications in the construction industry.

The analysis of the compressive strength results and failure behavior of hempcrete specimens from Mixture Design 1 and Mixture Design 2 provides valuable insights into the complex interactions between the various components of the mixture. In Mixture Design 1, specimens containing 15% hemp and 40% hydrated lime exhibited better compaction, consistent densification, and a combination of ductile and brittle behaviors, which is preferred for optimal performance. Conversely, in Mixture Design 2, specimens with 5% hemp hurds and 45% MgO binders achieved higher compressive strength, with their fresh paste being slurry and allowing for perfect and even compaction. These findings highlight the significance of the interaction between hemp hurds, binder agents, additives, and proper compaction in determining the mechanical properties and failure behavior of hempcrete. A combination of brittle and ductile behaviors is preferred, as it is believed that with optimum ratios of these components, higher compressive strength can be achieved without compromising other essential properties of hempcrete.

Based on the findings of this study and the questions posed, it is evident that while the compressive strength of hempcrete remains a significant barrier for its widespread use in structural applications, there are several other properties and opportunities that should be explored to fully realize the potential of this sustainable building material. The highest compressive strength achieved in this study, approximately 600 psi, is a promising starting point, but further research is needed to enhance this value to meet the requirements of a broader range of construction projects. Future studies should focus on optimizing mixture designs, investigating the effects of various constituents, and exploring innovative additives and manufacturing techniques to improve the mechanical properties of hempcrete.

In addition to compressive strength, other mechanical properties such as flexural strength, shear strength, and dynamic resistance should be examined to gain a comprehensive understanding of hempcrete's potential as a structural material. Conducting flexural strength tests and investigating the behavior of hempcrete under lateral or cyclic loading conditions could provide valuable insights into its ability to withstand bending, tensile stresses, and seismic events. Moreover, assessing the thermal properties of the proposed mixture designs, including thermal insulation (R-values) and fire resistance, is crucial for evaluating their energy efficiency and safety in building applications. These investigations will help to identify the most promising hempcrete formulations for specific structural applications and guide the development of design guidelines and construction techniques.

However, it is essential to acknowledge the limitations of the current study, particularly regarding the moisture content of the specimens and the curing duration. The presence of excess moisture within the mixture can significantly impact the material's ability to withstand compressive loads, leading to lower strength values and premature failure during testing. Future research should carefully control and monitor the moisture content of the specimens, ensuring that they are thoroughly dried before subjecting them to compressive loads. Additionally, investigating the effects of different moisture levels on the compressive behavior of hempcrete could offer valuable insights into the material's sensitivity to moisture and help establish optimal moisture content ranges for desired performance. Furthermore, increasing the curing duration to 28 days or more could potentially lead to improved compressive strength values and provide a better understanding of the material's long-term performance. By addressing these limitations and conducting more comprehensive investigations, future studies can contribute to the development of high-performance hempcrete mixtures that can be successfully implemented in the construction industry while promoting sustainability and reducing the environmental impact of building materials.

Chapter 5

Conclusion

5.1 Introduction

In this detailed study, the viability of hempcrete as a structural material was assessed, focusing on its mechanical properties and the environmental advantages of hemp-based alternatives. The research examined how variations in the proportions of hemp hurds, binders—hydrated lime for Mixture Design 1 and magnesium oxide (MgO) for Mixture Design 2—and additives such as metakaolin, fly ash, and nano silica affect the material's performance, especially when sand is added to specific formulas.

Experimental results and subsequent analyses have shown that while hemp enhances the environmental credentials of hempcrete, its amount within the mixture inversely affects compressive strength. Decreasing the hemp content typically increased strength, underscoring the need to carefully balance environmental considerations with structural demands.

The addition of sand as a fine aggregate was identified as a crucial factor in boosting compressive strength. Sand's presence improved packing density and facilitated stronger bonding between particles, enhancing the microstructure and mechanical properties of the mixtures. This was particularly evident in the superior compressive strength values observed.

Mixture Design 3 demonstrated the potential benefits of integrating sand, especially when combined with higher proportions of binders and additives. This advanced strategy adjusted critical components such as sand content, which varied from 20% to 60%, and explored binder ratios of 35%, 40%, and 45% alongside significant additions of metakaolin and fly ash. The impact of these components was further augmented by incorporating nano-silica at concentrations of 4% and 10% relative to binder weight.

The choice of binder and its proportion crucially influenced hempcrete's compressive strength. Transitioning from hydrated lime to MgO and augmenting the mix with pozzolanic additives substantially enhanced the material’s structural capacity. Mixture Design 3 highlighted this improvement by experimenting with different binder ratios and increased additive levels. The integration of metakaolin and fly ash at 20% and 50% relative to binder weight, along with nano-silica at 10%, demonstrated significant potential to boost compressive strength.

Compaction was shown to be vital, improving density and reducing voids within the mix, which resulted in stronger, more durable hempcrete. This aligns with previous research, emphasizing the role of compaction in preparing hempcrete for structural applications.

These findings emphasize the critical role of material composition in optimizing the structural properties of hempcrete. By adjusting the hemp to binder ratio, adding high-performance additives, and employing effective compaction techniques, hempcrete can evolve from an insulating material to a structurally viable alternative. While each component is essential, their combined interaction ultimately determines the overall performance of the hempcrete mix, paving the way for its use in sustainable and structurally sound building practices.

5.2 Conslusions

The experimental study aimed to enhance the compressive strength of hempcrete by investigating the effects of various binders (hydrated lime and magnesium oxide), hemp hurd content, water content, additives (metakaolin, fly ash, and nano silica), and the inclusion of sand. The results demonstrate that the compressive strength of hempcrete can be significantly improved through the optimization of mixture proportions and the incorporation of additives and sand.

The compressive strength of the original hempcrete specimen, made from hemp hurds, water, and hydrated lime without any additives or sand, was 29.43 psi. The results of this study show that the compressive strength can be significantly increased, with values ranging from 57.84 psi to 655.42 psi, depending on the mixture design.

Comparing similar specimens from Mixture Design 1, 2, and 3 with different ratios highlights the impact of binder type, hemp hurd content, and the inclusion of sand on compressive strength. For instance, specimen 1B from Mixture Design 1, containing 40% hydrated lime, 15% hemp, and 6% metakaolin, achieved a compressive strength of 115.61 psi. In comparison, specimen 2B from Mixture Design 2, with the same proportions but using MgO as the binder, reached a higher compressive strength of 156.65 psi, a 35% increase (41.04 psi). Furthermore, specimen 1BS from Mixture Design 3, which included 40% sand in addition to the same proportions as 1B, attained a compressive strength of 169.38 psi, a 46% increase (53.77 psi) compared to 1B and a 8% increase (12.73 psi) compared to 2B.

Another example is the comparison between specimens 1E, 2E, and 1ES. Specimen 1E from Mixture Design 1, containing 40% hydrated lime, 15% hemp, and 6% fly ash, achieved a compressive strength of 149.68 psi. Specimen 2E from Mixture Design 2, with the same proportions but using MgO as the binder, reached a higher compressive strength of 166.79 psi, an 11% increase (17.11 psi). Specimen 1ES from Mixture Design 3, which included 40% sand in addition to the same proportions as 1E, attained a compressive strength of 210.48 psi, a 41% increase (60.80 psi) compared to 1E and a 26% increase (43.69 psi) compared to 2E.

The incorporation of additives, such as metakaolin, fly ash, and nano silica, had a positive impact on the compressive strength of hempcrete. Specimens containing these additives exhibited improved compressive strength compared to the original hempcrete specimen. For example, specimen 1N from Mixture Design 1, containing 40% hydrated lime, 15% hemp, and 4% nano silica, achieved a compressive strength of 152.72 psi, a 419% increase (123.29 psi) compared to the original hempcrete specimen. Specimen 2N from Mixture Design 2, with the same proportions but using MgO as the binder, reached an even higher compressive strength of 186.90 psi, a 535% increase (157.47 psi) compared to the original hempcrete specimen and a 22% increase (34.18 psi) compared to 1N.

The inclusion of sand as a fine aggregate in Mixture Design 3 further enhanced the compressive strength of hempcrete. For example, specimen 2LS40 from Mixture Design 3, containing 45% MgO, 5% hemp, 40% sand, and 4% nano silica, achieved a compressive strength of 586.54 psi, a staggering 1,892% increase (557.11 psi) compared to the original hempcrete specimen. In comparison, specimen 2L from Mixture Design 2, with the same binder, hemp, and nano silica content but without sand, reached a compressive strength of 387.60 psi, a 1,217% increase (358.17 psi) compared to the original hempcrete specimen but a 34% decrease (198.94 psi) compared to 2LS40, highlighting the significant impact of sand on compressive strength.

The combination of metakaolin and fly ash in specimens like 1HMF50 from Mixture Design 1 (184.70 psi) and 2KMF50 from Mixture Design 2 (532.68 psi) resulted in significant strength gains of 527% (155.27 psi) and 1,710% (503.25 psi), respectively, compared to the original hempcrete specimen. When sand was added to a similar specimen, 1HMF50S40 from

Mixture Design 3, the compressive strength further increased to 264.29 psi, a 798% increase (234.86 psi) compared to the original hempcrete specimen, a 43% increase (79.59 psi) compared to 1HMF50, but a 50% decrease (268.39 psi) compared to 2KMF50, indicating the complex interactions between binders, additives, and sand in determining the compressive strength of hempcrete.

While the second set of hemp design mixtures, which incorporated a reduced hemp content of 5% in combination with MgO and other additives, demonstrated an increase in compressive strength, it is crucial to approach the optimization of hempcrete mixtures with a multi-faceted perspective. Excessively reducing the hemp content may undermine one of the primary objectives of using hempcrete as a sustainable building material: its ability to sequester CO2. Hemp hurds play a vital role in the carbon sequestration process, absorbing and storing atmospheric CO2 during the curing, hydration, and throughout the lifetime of the material. Therefore, the pursuit of higher compressive strength should not overshadow the environmental benefits that hemp brings to the material. Future research should focus on finding the optimal balance between hemp content, binder proportions, and additives that maximize both the mechanical properties and the CO2 sequestration potential of hempcrete.

A holistic approach to hempcrete optimization is necessary, considering not only compressive strength but also other properties such as thermal insulation, moisture regulation, fire resistance, and acoustic performance. By adopting a multi-performance optimization approach and evaluating the material's performance across various criteria, researchers can develop hempcrete mixtures that align with the goals of creating sustainable, low-carbon building solutions. This study serves as a foundation for further exploration and refinement of hempcrete mixtures, highlighting the importance of striking a balance between mechanical properties and environmental benefits. Future studies should aim to find the optimal combination of ingredients and manufacturing techniques that maximize the potential of hempcrete as a truly green and high-performance building material, contributing to the development of sustainable construction practices.

In conclusion, this study demonstrates that the compressive strength of hempcrete can be significantly enhanced through the optimization of mixture proportions, the use of alternative binders like magnesium oxide, the incorporation of additives such as metakaolin, fly ash, and nano silica, and the inclusion of sand as a fine aggregate. The comparative analysis of similar specimens from Mixture Design 1, 2, and 3 with different ratios provides valuable insights into the individual and synergistic effects of various components on the mechanical properties of hempcrete. The findings of this research pave the way for the development of high-performance hempcrete mixtures that can be utilized in load-bearing applications, promoting the use of sustainable building materials and reducing the environmental impact of the construction industry.

5.3 Recommendations

In pursuit of developing hempcrete as a viable structural material with a compressive strength comparable to conventional concrete (around 2000 psi), future research should focus on exploring innovative approaches, materials, and techniques. This includes investigating the incorporation of nano-particles (e.g., nano-silica, nano-clay, or nano-cellulose), high-potential materials (e.g., expanded perlite, expanded graphite, and natural or synthetic fibers), and advanced compaction methods (e.g., pressure compaction, external vibration, and ultrasonic energy) to enhance the mechanical properties, durability, and homogeneity of the hempcrete matrix. Additionally, pre-treatment methods for hemp hurds and various curing techniques should be studied to improve the compatibility between the binder and hemp hurds, accelerate strength development, and produce a more resilient hempcrete. To further advance the understanding of hempcrete performance, future research should also explore a wider range of mixture ratios, incorporate new additives, and investigate the flexural strength, thermal properties (e.g., R-values), and acoustic properties of the proposed mixtures. Analyzing the moisture content and its impact on mechanical, thermal, and acoustic properties would provide valuable insights for developing optimal moisture management strategies and curing techniques.

To enhance the robustness and applicability of the findings, future studies should extend the testing duration beyond the current 7-day period, evaluating the strength development of hempcrete mixtures at longer intervals, such as 14 and 28 days. This would provide a better understanding of the long-term performance and strength gain profile of hempcrete, enabling informed decisions about construction timelines and load-bearing capacities. Furthermore, clearly stating the assumptions made during the research process, including those related to material properties, testing conditions, and data analysis, would allow for a better understanding of the study's limitations and facilitate future research efforts in addressing potential gaps or uncertainties. By continually refining and optimizing mixture designs, testing methodologies, and exploring new avenues for improvement while maintaining a focus on sustainability, researchers can push the boundaries of hempcrete performance and pave the way for its successful integration into modern, sustainable building practices. The ultimate goal is to develop a structural-grade hempcrete with a compressive strength of 2000 psi, making it a viable and eco-friendly alternative to conventional concrete in the construction industry.

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