EFFECTS OF MIX DESIGN PARAMETERS ON PHYSICAL PROPERTIES, STRENGTH, AND IMPACT BEHAVIOR OF HEMPCRETE

A Thesis Submitted to
the Graduate School of
İzmir Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY

in Civil Engineering

by
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December 2024
IZMIR

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ACKNOWLEDGMENTS

I would like to express my gratitude to all those who allowed me to complete this thesis. I wish to thank my advisors, Assoc. Prof. Dr. Selçuk SAATCİ and Prof. Dr. Tahir Kemal ERDEM for their support, guidance, and assistance.

The members of the thesis monitoring committee, Prof. Dr. Gökmen TAYFUR, and Assoc. Prof. Dr. Çağlar YALÇINKAYA also helped with their valuable recommendations and reviews.

I sincerely thank Mr. Haldun BABACAN for supplying the hemp shives used in this study. I am also grateful to the administration of OYAK Çimento and the İskenderun cement plant for providing the GGBFS. Special thanks go to the staff of the İYTE Integrated Research Centers, particularly Dr. Ebru HANCIOĞLU, for their invaluable assistance in conducting the thermal conductivity tests, and Mr. Mutlu Devran YAMAN for his support with the compressive strength tests.

I would also like to thank Mr. Ercüment DEGIDIBEN for organizing a workshop on hemp in Zonguldak.

I would like to express my sincere gratitude to Professor Dr. Alyaa AL-ATTAR, President of the Northern Technical University in Mosul, Iraq, for her support. Her encouragement, valuable insights, and leadership have been instrumental in shaping my academic journey and the success of this work.

Finally, I would like to express my heartfelt thanks to my family for their endless love and patience throughout my life. My father, mother, siblings, wife, and son have helped me overcome all difficulties with their encouragement, financial support, and love. I dedicate this thesis to them.

ABSTRACT

EFFECTS OF MIX DESIGN PARAMETERS ON PHYSICAL PROPERTIES, STRENGTH, AND IMPACT BEHAVIOR OF HEMPCRETE

The building and construction sector increasingly adopt sustainable materials to lower emissions of carbon. One of these materials is hempcrete. However, optimizing hempcrete's performance characteristics to be used for different applications remains a challenge. This research aims to evaluate the effects of replacing hydrated lime with natural hydraulic lime and various cementitious materials like fly ash and ground granulated blast furnace slag on hempcrete's density, compressive strength in both directions parallel and perpendicular to hemp shives orientation, thermal conductivity, and capillary water absorption. Moreover, the study investigates the ability of hempcrete to absorb and dissipate energy by performing an impact test. The research involved testing different binder compositions, hemp shive particle sizes (coarse, medium, and fine), and hemp : binder and hemp : water ratios to analyze their impact on hempcrete performance. Results show that these parameters influence hempcrete's density, compressive strength, thermal conductivity, and capillary water absorption, with some parameters having a more significant impact than others. It was also observed that the compression in the perpendicular direction also reflected the performance of the specimens if they were compared at a specific strain ratio. The impact test results demonstrate that hempcrete significantly reduces impact forces and beam displacements. Lower binder content enhanced the cushioning effect, offering better energy dissipation, although specimens with lower binder content were more prone to crumbling after testing. These findings highlight hempcrete’s potential for protecting reinforced concrete structures under impact. The tested properties and findings are expected to expand the use of hempcrete in various applications in the upcoming years.

ÖZET

KARIŞIM TASARIM PARAMETRELERİNİN KENEVİR BETONUN FİZİKSEL ÖZELLİKLERİ, DAYANIMI VE DARBE DAVRANIŞI ÜZERİNE ETKİLERİ

Yapı ve inşaat sektörü, karbon emisyonlarını düşürmek için giderek daha fazla sürdürülebilir malzeme kullanmaya başlamaktadır. Bu malzemelerden biri de kenevir betonudur. Ancak, kenevir betonun farklı uygulamalar için kullanılabilirliğini artıracak performans özelliklerinin optimize edilmesi hala bir zorluk teşkil etmektedir. Bu araştırma, sönmüş kireç yerine doğal hidrolik kireç, uçucu kül ve öğütülmüş granüle yüksek fırını cürufu gibi çeşitli bağlayıcı malzemelerin kenevir betonun yoğunluğu, kenevir kıtığı yönelimine paralel ve dik yöndeki, basınç dayanımı, ısıl iletkenlik ve kapiler su emilimi üzerindeki etkilerini değerlendirmeyi amaçlamaktadır. Ayrıca, araştırma, hempcrete'in enerji emme ve dağıtma kapasitesini bir darbe testi ile incelemektedir. Araştırma, farklı bağlayıcı bileşimlerini, kenevir kıtığı parçacık boyutlarını (kaba, orta ve ince), kıtık : bağlayıcı oranlarını, ve kıtık : su oranlarını deneyerek bu parametrelerin kenevir betonu performansı üzerindeki etkilerini analiz etmektedir. Sonuçlar, bu parametrelerin kenevir betonun yoğunluğu, basınç dayanımı, ısıl iletkenlik ve kapiler su emilimi üzerinde etkili olduğunu, bazı parametrelerin ise diğerlerinden daha belirgin bir etki sağladığını göstermektedir. Ayrıca, kıtık yönelimine dik yöndeki basıncın, belirli bir birim deformasyon oranı için numunelerin performansını arttırdığı gözlemlenmiştir. Darbe testi sonuçları, kenevir betonun darbe kuvvetlerini ve kiriş yer sehimlerini önemli ölçüde azalttığını göstermektedir. Daha düşük bağlayıcı içeriği, şok emme etkisini artırarak daha iyi enerji dağılımı sağladı; ancak, bağlayıcı içeriğe daha düşük olan numuneler test sonrası kırılmaya daha yatkındı. Bu bulgular, kenevir betonun darbeye maruz betonarme yapıları koruma potansiyelini öne çıkarmıştır. Test edilen özellikler ve bulguların, önümüzdeki yıllarda kenevir betonun çeşitli uygulamalarda kullanımını genişletmesi beklenmektedir.

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ABBREVIATIONS

Abbreviation	**Definition**
NHL	Natural Hydraulic Lime
HL	Hydrated Lime
FAF	Fly Ash Type F
FAC	Fly Ash Type C
GGBFS	Ground Granulated Blast Furnace Slag.
THC	Delta-9-Tetrahydrocannabinol
TÜİK	Turkish Statistical Institute
LCA	Life Cycle Assessment
MIP	Mercury Intrusion Porosimetry
CT	Computed Tomography
CO_2	Carbon Dioxide
SEM	Scanning Electron Microscope
GHG	Greenhouse Gas
ITZ	Interfacial Transition Zone
LRC	Lime Rice Husk Concrete
LHC	Lime Hemp Concrete
VMA	Viscosity Modifying Agent
CSH	Calcium Silicate Hydrate
CAH	Calcium Aluminate Hydrates
CASH	Calcium Alumino-Silicate Hydrates
LVDT	Linear Variable Differential Transformer
BET	The Brunauer-Emmett-Teller
XRF	X-ray Fluorescence
W/B	Water Binder Ratio
ECC	Engineered Cementitious Composites
PVA	Polyvinyl Alcohol

CHAPTER 1

INTRODUCTION

1.1. Background of the Study

Hempcrete, a bio-composite material made from the hemp plant's woody core (shive) and a lime-based binder, has gained attention in sustainable construction. Its unique properties, such as low density, thermal insulation, and moisture regulation, make it attractive for non-load-bearing walls. However, optimizing its performance, particularly in density, compressive strength, thermal conductivity, and water absorption, remains a challenge. The presented research aims to optimize hempcrete for wall construction by altering some key parameters: hemp shive size, hemp-to-binder ratio, water-to-binder ratio, and binder type.

1.2. Problem Statement

While hempcrete has many advantages, such as sustainability, lightweight, and excellent thermal and acoustical insulation, its compressive strength is much lower than that of conventional building materials. In addition to compressive strength, the performance of hempcrete is affected by other parameters like density, thermal conductivity, and water absorption. A systematic investigation is needed to understand how variables like different binder compositions, hemp shive sizes, hemp-binder ratios, and hemp-water ratios can influence the performance of hempcrete in modern construction.

Moreover, the impact test of hempcrete, a subject not studied in previous studies, should also be investigated to further understand hempcrete's capacity for energy absorption. By considering these aspects, the potential for hempcrete's use in construction may be broadened to compete with conventional building materials except in terms of mechanical performance.

1.3. Significance of the Study

This is a vital study to advance the application of green construction materials. Accordingly, this research is focused on optimizing the formulation to enhance the mechanical strength and thermal performance of hempcrete while retaining its ecological benefits. Research of this nature could certainly enable better incorporation of hempcrete into the building industry and support the reduction of carbon emissions from buildings. It will also provide practical recommendations for appropriate hempcrete mixture designs that satisfy specific performance requirements.

The novelty of the present study concerns the investigation of hempcrete's resistance to the impact load. Previous studies have not focused on testing the energy absorption and dissipation ability of hempcrete under sudden impact forces. This constitutes a significant development for research in this area, especially regarding the behavior of hempcrete under dynamic loads, and can be expected to increase its potential uses in construction applications.

By performing an impact assessment on the hempcrete samples, the current study identifies a significant gap in the existing literature and provides new insights into the performance of hempcrete when it is subjected to incidental impacts or used in earthquake-prone areas. This makes the material more suitable for use in modern sustainable construction methods.

1.4. Research Objectives

The first objective of this research is to optimize hempcrete for use in building walls by studying the effects of:

Four different binder compositions include Natural Hydraulic Lime (NHL), Hydrated Lime (HL), Fly Ash type C (FAC), Fly Ash type F (FAF), and Ground Granulated Blast Furnace Slag (GGBFS).

- Three different hemp shive sizes (coarse, medium, fine),
- Three hemp : binder ratios (1:2, 1:3, 1:4)
- Three hemp : water ratios (1:2, 1:2.5, 1:3), and

Specifically, the study aims to:

- Determine how these factors influence density,

- Examine their effect on compressive strength at 28 and 180 days, in both parallel and perpendicular to the hemp shives orientation,
- Evaluate their impact on thermal conductivity, and
- Analyze their role in capillary water absorption.
- Determine the absorbed energy of each mixture at 28 and 180 days, in both parallel and perpendicular directions to the hemp shives.

The second objective is to test hempcrete's ability to absorb and dissipate energy when subjected to impact load, which is critical for assessing its potential use in structures exposed to dynamic forces or accidental impacts.

1.5. Scope and Limitations

This study focuses on using hempcrete as a non-load-bearing material for building walls. The research covers five key performance metrics: density, compressive strength, thermal conductivity, capillary water absorption, and absorbed energy. The hempcrete mixtures are varied by four binder compositions, three different hemp shive sizes, hemp-binder ratios, and three water-binder ratios. However, the research does not concern durability in the long term in harsh weather conditions, nor does it apply hempcrete to load-bearing structures.

1.6. Structure of the Thesis

This thesis is organized into five chapters, each focusing on a specific aspect of the study to ensure a clear and logical progression of ideas. :

1.6.1. Chapter 1: Introduction

This chapter briefly presents this study's background, problem statement, objectives, scope, and limitations.

1.6.2. Chapter 2: Literature Review

This chapter reviews the recent literature on hempcrete, focusing on the material's density and compressive, thermal, and water absorption properties. The review starts with an overview of hemp, its traditional uses, cultivation practices, and processing. The following literature discusses the composition of hemp shive and its interactions with binders while focusing on the chemical properties of the bio-aggregate and the effect of porosity in hemp shive on the overall performance of hempcrete. Moreover, this chapter explores the characteristics of hempcrete, detailing its benefits and drawbacks as a building material, with a particular focus on its environmental benefits.

It also discusses the binder selection process, discussing the roles of lime and hydraulic lime in forming hempcrete and carbonation to assist in its setting. Another section is dedicated to studying the effects of porosity in hempcrete, which is responsible for its thermal properties and mechanical behavior. Also, in this chapter, the mechanical properties of hempcrete were investigated in detail, including testing for compressive strength, direction of testing, and size of the specimens used. Studies investigating ways of improving the mechanical strength of hempcrete are also reviewed, along with the various factors affecting compressive strength and results from previous studies related to the subject.

Further, the thermal properties of hempcrete are addressed, focusing on thermal conductivity and the ability of water absorption, with a particular emphasis on how these characteristics affect the efficiency of hempcrete as a building material.

1.6.3. Chapter 3: Materials and Methods

This chapter describes the materials used in this study, namely hemp shive and various binder types. It also describes the experimental methods and testing procedures adopted in the study. Water absorption, dry bulk density, and initial water content were tested on the hemp shive. In addition, compressive strength and flexural strength tests were conducted on different binder compositions to choose the binder for hempcrete. Moreover, the hempcrete samples were tested for density, compressive strength, thermal conductivity, water absorption capacity, and absorbed energy. Finally, an impact test, an aspect that has not been previously investigated, was carried out on the hempcrete specimens to evaluate its ability to absorb and dissipate energy.

1.6.4. Chapter 4: Results and Discussion

This chapter details the analysis of the test results from the experimental investigation, pointing out the factors that most contributed to the variation in hempcrete performance. The test results are thus presented in an organized manner to show the effect of various parameters: binder composition, hemp shive size, hemp-to-binder ratio, and water-to-binder ratio. The results will also be compared with those of earlier studies. Moreover, the impact test of hempcrete is investigated to assess its ability to protect reinforced concrete by absorbing energy under applied loads.

1.6.5. Chapter 5: Conclusion and Recommendations

The results are summarized, and optimal formulations of hempcrete for wall construction are proposed. Moreover, recommendations on future research and possible industrial applications will be provided.

CHAPTER 2

LITERATURE REVIEW

2.1. What is Hemp?

Hemp is a versatile crop that provides stalks, seeds, and leaves, all of which have a wide range of applications. The plant has a woody core called a hurd or shive and fibrous tissue. Other plant parts are the seeds, flowers, and leaves. An image of the hemp plant is shown in Figure 1. Hemp is primarily grown for its valuable fiber extracted from the stem (Haapala 2024). Although hemp shives and seeds have commercial value, the plant's most valuable part is its fiber (Arrigoni, Pelosato, and Dotelli 2016).

There are two varieties of *Cannabis sativa*: hemp and marijuana. Marijuana is classified as a narcotic due to its psychoactive properties, while hemp, which does not have the psychoactive effects typically associated with drugs, is regulated as a controlled substance. On a dry-weight basis, the psychoactive component delta-9-tetrahydrocannabinol (THC) ranges from 3 to 15 percent in marijuana and less than 1 percent in industrial hemp. On the other hand, there is no visual difference between the two types (USDA 2011). Changes in laws governing the use and cultivation of the hemp plant have contributed to its resurgence, while research demonstrating its industrial and health benefits has increased demand for hemp-based products (Kaminski et al. 2024).

Figure 1. Hemp plant.

2.2. Hemp History

The hemp plant has been used since ancient times and has been grown for thousands of years. It has been a part of various cultures worldwide, serving multiple purposes such as food, medicine, cosmetics, animal beds, and clothing. It is believed that the plant originated in China and that cultivation of it progressively moved westward into India, the Middle East, Africa, and the Mediterranean. The importance of the hemp plant to the way of life, trade, and development of these major civilizations is demonstrated by documents that have survived from Egyptian, Greek, and Roman records (Stanwix and Sparrow 2014). Another evidence of its use can be seen in hemp fibers found in Taiwan pottery dating 10,000 years ago. In ancient China, the hemp plant was a significant crop grown mainly for its fibers, used to manufacture products such as clothes, rope, paper, oil, and sails. It was also one of the five staple grains commonly used in daily life (Karche and Singh 2019). The findings in Ellora caves suggest that hempcrete technology was known to ancient Indians as early as the 6th century A.D. (Singh, Vinodh Kumar, and Waghmare 2015).

Nowadays, hemp is produced in more than 30 countries worldwide. China has the largest production and exportation in the world. European countries and Canada also play key roles in the global hemp market (Crini et al. 2020). The leading hemp producers in Europe are France, followed by Germany, the UK, and the Netherlands (European Commission 2011).

2.3. Hemp in Türkiye

Hemp farming and the fiber industry have a long history in Türkiye, with Kastamonu being a province traditionally known for its hemp cultivation. In 1961, hemp production in Türkiye spanned 20,800 hectares, yielding 10,700 tons of fiber and 5,000 tons of seeds for fiber production. However, hemp production has steadily decreased due to several factors, including high labor demands, the lower cost of synthetic fibers, lack of mechanization, and its inability to compete with cotton.

Additionally, hemp must be grown under government-controlled conditions due to the presence of THC in its natural structure. With the global development of hemp usage and industry, the regulation issued in 2016 permitted 19 provinces in Türkiye to cultivate hemp plants under the framework of the hemp cultivation and control regulations. In 2017, hemp cultivation resumed on 12 hectares, producing 8 tons of fiber and 1 ton of seeds for fiber production (Gizlenci et al. 2019). The trend in hemp cultivation area and production in Türkiye from 1961 to 2017 is shown in Figure 2 (Gizlenci et al. 2019). This figure highlights the significant decline in hemp cultivation and production over the years.

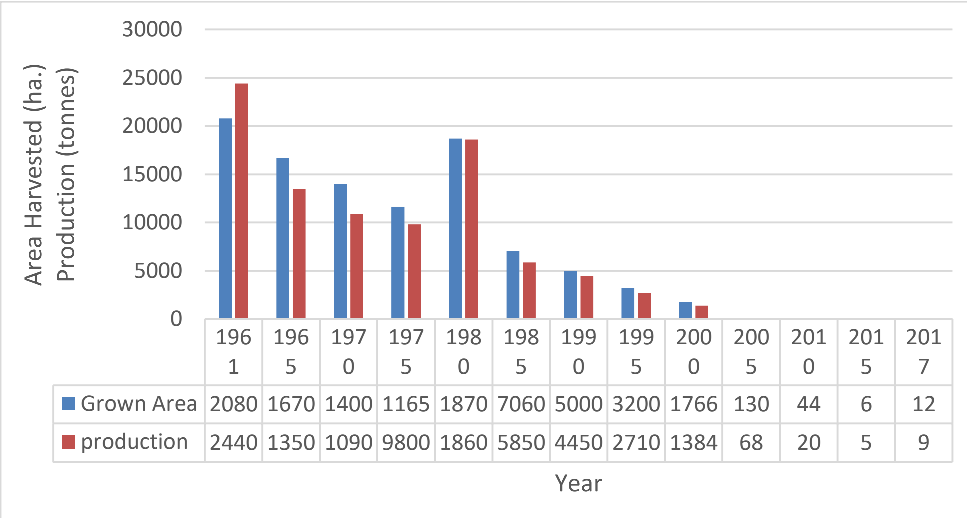


Figure 2. Area harvested and production of hemp in Türkiye (1961-2017).

According to Turkish Statistical Institute (TÜİK) data, production occurred on approximately 46 decares in 2017. By the end of 2018, it was reported that the cultivation area had reached around 20 hectares, but 20 hectares was hardly significant compared to the previously produced hectares. As a result, hemp became a prominent topic in Türkiye. Public interest grew, and those wanting to enter the industry began exploring their opportunities.

The revival of hemp farming in Türkiye was driven by a combination of factors, including the global interest in sustainable materials and growing awareness of hemp's versatility. In 2018, hemp was cultivated on ten decares, expanding to 100 hectares in 2019 and 450 hectares in 2020. In 2022, Hemp production increased to 230 hectares again, and 520 hectares again in 2023. The planned increase to 1600 hectares in 2024 is a testament to the promising future of the hemp industry. In March 2024, Konya became the 20th city permitted for hemp cultivation by the Turkish Ministry of Agriculture and Forestry. An image of a hemp farm in Türkiye is shown in Figure 3.

Figure 3. Hemp farms in Türkiye.

2.4. Applications of Hemp

The hemp plant's seeds, flowers, leaves, and stalks are used for various applications. Its uses span many industries, including construction materials, textiles, paper production, food and beverages, the automotive sector, furniture, the luxury market, and cosmetics and personal care products. Industrial hemp is the source of around 25,000 products (Crini et al. 2020).

Seeds are commonly used in food, beverages, cosmetics, and biofuel production. Flowers are valued in the pharmaceutical industry for THC-based drugs. Leaves are often used in cosmetics, medicine, animal bedding, and agrochemicals. Finally, stalks provide fiber and shives in biofuel, textiles, composites, paper, animal bedding, absorbent mulch, and construction materials. The applications and uses of hemp plant components are shown in Figure 4.

The versatility of the hemp plant lies in its ability to provide sustainable and renewable resources for a wide range of industries. Additionally, the by-products generated during hemp processing can often be repurposed, minimizing waste and contributing to a circular economy. All these diverse functions point to the growing importance of hemp in tackling global issues around sustainability and resource efficiency (Moscariello et al. 2021).

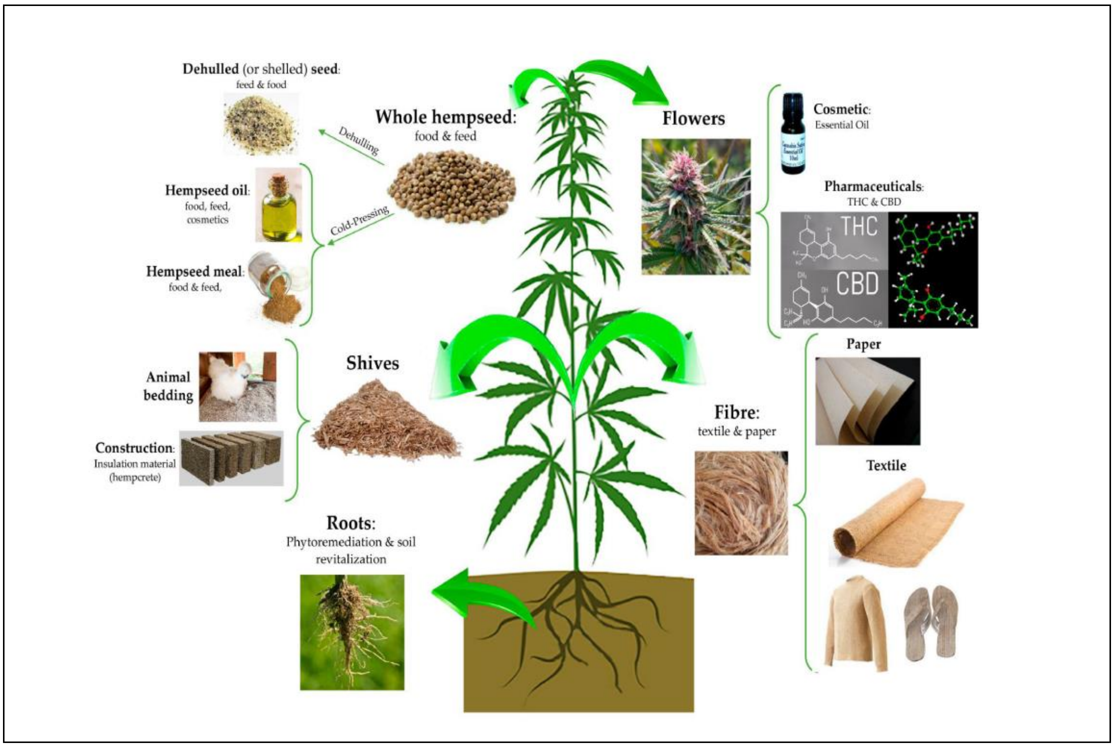


Figure 4. The applications of the hemp plant.
(Source: Farinon et al. 2020)

2.5. Hemp Growth and Processing

Hemp growth and processing involve several key stages: cultivation, retting, and separating fibers and shives. These steps are crucial for preparing hemp for various industrial applications, such as construction materials and textiles.

2.5.1. Hemp Cultivation

Hemp is well suited to growing in all environments except harsh deserts and high mountains. Warm climates with well-drained and nutrient-rich soil are the best hemp-growing conditions. Hemp needs a moderate amount of water, especially in the early stages of growth (Crini et al. 2020). Once established, it becomes relatively drought-resistant. As a result, hemp cultivation has the potential to expand dramatically and can be produced in wide areas of the world.

2.5.2. Hemp Retting

After harvesting, hemp stems typically undergo retting, separating the fibers from the woody core by breaking down the pectin that binds the fibers to the core. This is followed by mechanical defibration, which involves removing the hemp fibers from the shives. First, hemp plants are harvested after maturity using harvesters to cut hemp stems. Then, the retting process starts. It takes time depending on the retting methods: field, water, and dew retting. In this process, the moisture and microbes work together to break down pectins, which hold the fibers tightly to the woody core.

2.5.3. Fiber-Shive Separation

After retting, the stalks must be dried to make them less wet and easier to process. The dried stalks are then sent through a decorticator to separate the fibrous outer layer from the inner shive. The fibers get cleaned in scutching, which helps remove any leftover shive bits. Afterward, the fibers are combed or hacked to prepare them for spinning or other uses. While separated, shive is collected and used for various purposes (USDA 2011). Figure 5 illustrates the different components of the hemp plant.

Figure 5. Components of the hemp plant. (A) Hemp stem, (B) Hemp fiber, (C) Hemp shives.

The fibers obtained are raw materials in industries like textiles, insulation, paper, and biopolymers. The woody core, called hurds or shives, is used for animal bedding, garden mulch, or as a lightweight aggregate in concrete.

2.6. Hemp Shives

Hemp shives are generally elongated, malleable, and highly porous with low apparent density. As mentioned above, they are used as lightweight aggregates in concrete. Like other plant-based aggregates, hemp shives are very different from the traditional mineral aggregates typically used in concrete, which can be characterized using standardized instruments and methods (Sofiane Amziane and Sonebi 2016).

2.7. Composition of Hemp Shives

The composition of hemp shives, like other bio-aggregate materials, comprises three main structural biopolymers: cellulose, hemicellulose, and lignin, along with other organic and inorganic substances like pectin, waxes, fats, water-soluble compounds, and ash. The proportions of cellulose, hemicellulose, and lignin typically range between 34.5% to 52%, 9% to 34.5%, and 18% to 28%, respectively (Sofiane Amziane and Collet 2017).

Several factors contribute to this variation, including the geographical location, soil quality, the age of the plant, the location within the plant, climate conditions, plant variety, and the method of processing used to extract the aggregates (Sofiane Amziane and Collet 2017). Hemp shive is one of the most durable plant-based aggregates due to its high lignin content (Laborel-Préneron, Magniont, and Aubert 2018).

Generally, the compressive strengths of plant materials range from about 0.3 to 300 MPa. These wide variations result from the number of layers in the cell wall, its composition, the arrangement and volume fraction of cellulose fibers in those layers, and the cellular structure of the plant tissue (Gibson 2012).

2.8. The Effect of Chemical Composition of Hemp Shive on Hempcrete

Bio-based aggregates present characteristics that are very different from those of mineral aggregates typically used in concrete. The chemical compositions of bio-aggregates can affect their properties, such as compressibility, and their interactions with mineral binders. These properties, therefore, also affect the properties of the compounds that comprise them, including setting time, hydration mechanisms, and durability (Sofiane Amziane and Collet 2017).

One of the main reasons for the chemical characterization of bio particles is the risk of negative interactions with mineral binders. In the early stage, these interactions can interfere with the setting and hardening process of the binders, while in the hardened state, they may change the properties of the composite. In the long term, they can also affect the product. Future studies should build on the current results and provide a rapid and direct method to evaluate the compatibility of potential bio-aggregates with different types of binders. In cases where detrimental interactions are observed, corrective measures such as pre-treatment of plant particles or optimization of binder design will be necessary (Sofiane Amziane and Collet 2017).

The characteristics of hemp shives, such as physical properties (bulk density, particle size, and shape, moisture absorption), chemical composition (the ratio of cellulose, hemicellulose, and lignin), and porosity and pore structure, all affect hempcrete performance (Demir and Doğan 2020). The variability in hemp shive types and sources leads to differences in hempcrete performance. The dissolved compounds in the shives can influence the setting and hardening of the hempcrete. In contrast, the shives' porosity and chemical composition affect the material's overall performance (Niyigena, Amziane, and Chateauneuf 2018).

Many studies have shown the impact of these factors on practical applications. Arufe et al. (2021) studied the effect of the retting process on hemp shives. The retting process adjusts the physical and chemical properties of hemp shives by changing the color, porosity, and moisture content, making retted shives less dense and more porous than untreated ones and impacting the water absorption characteristics of the shive. They observed that a retted shive is better than an unretted shive for enhancing the setting properties and durability of the material.

Mostefai et al. (2015) found that the length and curing time of hemp shives and fibers positively correlate with the mechanical strength of modified mortars. In contrast, the hemp content shows a negative correlation. The flow table and maniabilimeter test findings indicate that the shive effect on mortar flow ability is less noticeable than that of hemp fibers.

Wang et al.(2021) investigated the impact of using four hemp shives from different resources in France. They found that hempcrete's properties can be influenced by factors like the origin of the hemp, the duration of retting, and the timing of the harvest etc. of the used hemp.

2.9. The Effect of Particle Size of Hemp Shives on Hempcrete

The anisotropic behavior of hempcrete is attributed to the elongated and flaky shape of the hemp shives. The shive particle size distribution and shape affect hempcrete's mechanical, thermal, and transport properties (Picandet et al. 2015).

Hempcrete's mechanical strength and thermal conductivity depend heavily on the size of hemp shive particles. According to a study by Williams et al. (2018), uniform particle sizes, where the particles are consistently similar in size, have a more beneficial impact on the mechanical properties of hemp-lime composites than mixed or varied particle sizes.

In contrast, a study by Sinka et al.(2015) found that the size of too many large or small particles negatively affects mechanical strength or thermal conductivity. Mixing large and small fractions of hemp shives can positively impact hempcrete properties.

The irregular shapes and low density of hemp shives lead to unequal compaction of the hempcrete, resulting in voids between the randomly placed shives. The large voids can negatively affect specific properties of the hempcrete. Brzyski and Widomski (2017) explored the potential benefits of filling these voids with loose, fine insulation materials. They partially replaced the hemp shives with the expanded perlite to improve the density, total porosity, thermal conductivity, and water absorption. A partial replacement of hemp shives with expanded perlite has improved the properties of hempcrete.

2.10. Porosity in Hemp Shives

The beneficial thermal and hydrophilic characteristics of hemp stem from its porosity and cell wall structure. Jiang et al. (2017) investigated the porosity of hemp shives using a combination of techniques: mercury intrusion porosimetry (MIP) and computed tomography (CT). They found that the average porosity of hemp shives was 77 ± 2.0 % by MIP and 50% to 75% by CT.

Mostefai et al. (2015) conducted a microstructural investigation using 3D μ-tomography shive-modified mortars and hemp fiber-modified mortars. The results reveal that shive-modified mortars have a higher porosity volume content (5.08%) compared to hemp fiber-modified mortars (3.54%). There are noticeable variations in the weight and volume of the hemp shive and fiber fillers. This variation leads to an uneven distribution of filler in the mortars. As a result, the porosity is affected because some parts of the mortar have a higher filler concentration while others have less. In addition, porosity analysis confirms that hemp shive introduces significantly more porosity than hemp fiber.

2.11. Hempcrete

"Hempcrete" refers to a construction material composed of hemp and lime, as shown in Figure 6. It is usually made by mixing a lime-based binder with hemp shive to produce a breathable, low-density, insulating material for new construction and restoration projects. The term breathable refers to the ability of hempcrete to absorb and release moisture. Furthermore, hempcrete is considered an effective insulator due to the large amount of air trapped inside it, both inside and within the hemp shive matrix in the cast material.

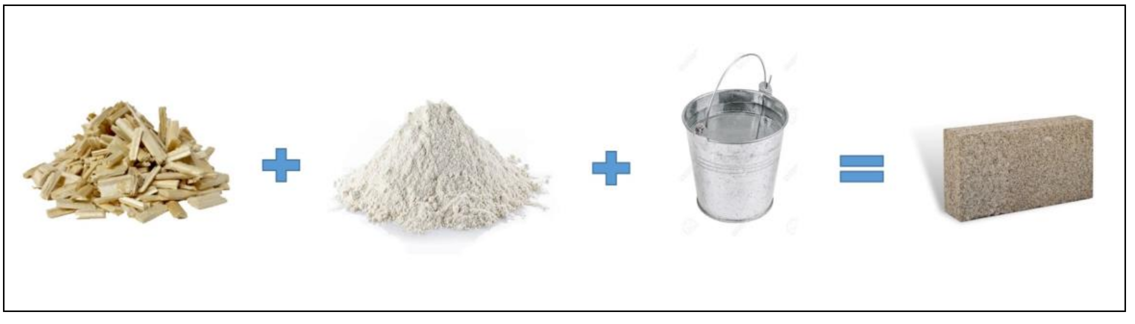


Figure 6. The components of hempcrete.

2.11.1. Hempcrete's Sustainable Properties

Hempcrete is a sustainable alternative to commonly used construction materials due to its natural origin and environmentally friendly characteristics, including a low carbon footprint throughout its lifecycle. Hemp plants grow quickly, reaching 4 meters in just four months, requiring minimal fertilizers and water. Additionally, hemp is more decay-resistant than many other plant-based materials. The hemp plant can absorb large amounts of CO_2 from the atmosphere during its growth and store it within the material, which makes hempcrete environmentally friendly. Hemp shive's low density and porous structure make them an effective thermal insulator and moisture regulators. Hempcrete absorbs moisture from the air when there is high humidity and releases it when it drops (Haapala 2024).

While hempcrete is unsuitable as a load-bearing material due to its mechanical properties, it is highly effective as an insulating material. It can be combined with wood, concrete, or masonry components and is often used to insulate existing walls, floors, and roofs or as a filler for single-layer walls with structural frames. Hempcrete can be utilized in various ways: compacted in formwork, applied by spraying, or formed into precast blocks and prefabricated wall units (Pietruszka, Gołębiewski, and Lisowski 2019). The type of binder, aggregate-to-binder ratio, aggregate size and porosity, and degree of compaction all affect the characteristics and range of hempcrete products (Haapala 2024).

2.11.2. Terminology of Hemp-Lime Composites

The terminology for hemp-lime composites varies across different studies and regions. Hempcrete was initially created to replace Wattle and clay infill for timber-frame construction in France, where it is known as 'Chaux-Chanvre'(Lawrence et al. 2012). The term "hempcrete" is the most commonly used and refers to a bio-composite material made of hemp shives mixed with a lime-based binder.

Some studies, however, refer to it as hemp-lime concrete, which emphasizes lime as the binder, which is critical for the material's binding and carbonation process. It is essentially the same as hempcrete but highlights the specific use of lime, which is crucial for the material's binding and carbonation process. The term "Hemp Concrete" is less commonly used but can refer to any composite material that uses hemp shives as an aggregate with various potential binders, including lime, cement, or other materials.

2.11.3. Hempcrete Advantages

1. Hempcrete is a renewable material mainly made of hemp shives and lime. The hemp plant grows 3-4 months faster than other crops. It does not need much pesticides or water. It can be grown in different climates in most parts of the world (Asghari and Memari 2024).
2. Hempcrete is an environmentally friendly material. The hemp plant absorbs large amounts of carbon dioxide (CO_2) from the atmosphere during its growth. When the hemp shives are used in concrete production, hempcrete continues to store this carbon, helping to reduce a building's overall carbon footprint (Asghari and Memari 2024).
3. Hempcrete has good insulation capabilities. It can maintain stable indoor temperatures for a long time, reducing the need for air conditioning. This, in turn, lowers energy consumption, resulting in substantial energy bill savings (Asghari and Memari 2024).
4. Hempcrete is an effective moisture regulator that absorbs moisture from the air when there is high humidity and releases it when it drops (Pietruszka, Gołębiewski, and Lisowski 2019).
5. Hempcrete is decay-resistant. The lime's alkalinity allows the material to resist mold and insects (Daly, Ronchetti, and Woolley 2010). Moreover, hemp shives are not attractive to insects and moths due to their low protein content; therefore, these pests are less likely to consume them (Arrigoni, Pelosato, and Dotelli 2016).
6. Hempcrete can be recycled differently at the end of a building's life. Recycled hemp shives can be blended with fresh lime to make new hempcrete. They can also be used as biofuel in a power plant material (Lawrence et al. 2012).
7. Hempcrete is a sustainable and renewable material. Hemp shives and lime can be added as soil amendments to enhance soil quality. These make (Lawrence et al. 2012).

2.11.4. Hempcrete Disadvantages

1. Although hempcrete has several advantages, such as viability, sustainability, and eco-friendliness, its mechanical properties, especially its low compressive strength, must be considered in construction projects (Shewalul et al. 2023).
2. The hempcrete specimens may show variation in results because of differences in density and mixing, which are naturally influenced by the properties of the hemp shives. However, this issue can be managed using proper mixing techniques to achieve consistent results (Shewalul et al. 2023).
3. A significant challenge is that designers and builders must work closely with experts with deep knowledge of hempcrete to ensure its correct application(Asghari and Memari 2024).
4. Hempcrete is applied in limited locations above the damp-proof due to low resistance to prolonged exposure to moisture, which weakens its structure (Asghari and Memari 2024).
5. The construction cost could be more expensive than for conventional concrete. Since hempcrete is not load-bearing, it can be used as filling material or precast blocks, usually integrated with a steel or wood frame (Asghari and Memari 2024).
6. The ideal time for hempcrete construction is in the summer because the warm weather helps the material dry faster. The ideal time for hempcrete construction is in the summer because the warm weather helps the material dry faster. In winter, the colder temperatures slow the drying process. In addition, the material should be protected from moisture (Asghari and Memari 2024).

2.11.5. Hempcrete and Environmental Impact

Different environmental concerns like waste management, climate change, energy efficiency, life cycle impact, and others more influence planning, development, and construction of buildings. Due to the ever-increasing pressure on natural resources and the environment, the demand for greener building techniques has been raised, resulting in new developments in construction materials for better, improved, energy-efficient homes. Special focus on energy-efficient construction techniques and raw materials available locally can be used to reduce the environmental impact of the building. Some of the best materials in this respect include hempcrete. Compared to conventional construction materials, hempcrete has a low environmental impact (Bedlivá and Isaacs 2014).

Hemp shive is one of the most extensively used environmentally friendly building materials in Europe (Sofiane Amziane and Sonebi 2016). Fast-growing bio-based materials like hemp offer a significant opportunity to lower buildings' carbon footprints. Unlike wood from forests, hemp does not need long growing cycles, and thanks to its rapid absorption of CO_2 during growth, its ability to store carbon increases when used as thick insulation in exterior walls (Pittau et al. 2018).

A study has shown that a hempcrete wall with dimensions of 1 square meter and 0.3 meters thick can sequester 82.71 kg of CO_2. This amount exceeds the 46.53 kg of CO_2 emitted during the hempcrete manufacturing process, leaving an additional 36.18 kg of CO_2 stored. Regarding greenhouse gas impact, hempcrete walls are more environmentally friendly than traditional wall construction methods (Ip and Miller 2012).

Furthermore, in another study, the continuous hardening of the lime binder in hempcrete allows the wall to absorb about 35 kg of CO_2 over 100 years while using up to 394 MJ of energy. However, a similar wall made from Portland cement-based concrete consumes 560 MJ of energy and emits 52.3 kg of CO_2 (Haapala 2024). It is much more environmentally friendly than traditional Portland cement-based concrete, which spends a lot on energy resources and emits higher CO_2 emissions.

Pretot et al. (2014) performed a life cycle assessment analysis on hempcrete walls and found that the binder has the highest environmental impact due to CO_2 emission. On the other hand, the absorption of CO_2 during the growing of hemp plants and the carbonation of binder during hempcrete curing were higher than the CO_2 emitted during binder production. As a result, hempcrete has a lower environmental impact than traditional concrete. This makes hempcrete highly efficient in terms of embodied carbon and energy, making it an excellent choice for sustainable construction.

The environmental advantages of hempcrete extend beyond its carbon sequestration abilities. Hempcrete regulates indoor humidity, helps reduce daily fluctuations in indoor humidity, and cuts energy use by 45% compared to foam concrete. Additionally, the material is recyclable at the end of a building's lifespan, and incinerating it after use can save more energy and lower greenhouse gas emissions (Haapala 2024).

One effective strategy to address climate change and reduce emissions of carbon dioxide is the use of industrial bio-based plant materials. When used as raw building and insulation materials, these sustainable and eco-friendly materials offer significant benefits. They contribute to a considerably smaller carbon footprint by retaining the photosynthetic carbon in plant-based products. They can create breathable walls by quickly absorbing and releasing moisture in response to changes in relative vapor pressure gradients and humidity in the environment. This hygric buffering effect helps lower the energy demands of air conditioning while enhancing indoor comfort for the building's occupants.

The main environmental impacts for the building and construction sector are greenhouse gas (GHG) emissions, energy consumption, natural resource depletion, and waste production. Given these observed impacts, a great interest in recent times has grown in the field of low environmental impact materials, normally called "eco-materials." Eco-materials do not affect the environment adversely during production, use, and disposal. They reduce GHG emissions, conserve energy, save natural resources, and decrease waste. The construction sector can adopt more environmentally friendly building materials such as hempcrete, known for its carbon sequestration properties, low embodied energy, and use of renewable resources.

Promoting plant-based materials in the construction industry and concerns over environmental issues have driven extensive research into eco-friendly alternatives. Achieving higher energy efficiency is possible, but innovative technologies are required to reduce industrial energy demands further. The most important factors are reducing energy consumption, lowering CO_2 emissions, and using plant-based raw materials as substitutes for mineral aggregates (Capros et al. 2016).

2.11.6. Binder Selection in Hempcrete

The combination of the high flexibility of the hemp shives aggregates and the rigidity of the binder matrix results in the non-fragile elastoplastic behavior of the hemp : binder composite. As a result, the composite exhibits higher deformability under stress, increased resistance to breaking, and notable ductility, allowing it to absorb strains even after reaching its maximum mechanical strength (Page, Sonebi, and Amziane 2015).

Various binders are used in hempcrete manufacturing. The choice of binder depends on the desired properties like mechanical strength and thermal insulation. It also depends on the manufacturing process, whether it's done on-site (through pouring into molds or shotcrete projection) or using pre-fabricated units. Also, factors like the location of construction (indoors or outdoors), environmental considerations (such as reducing CO_2 emissions), and financial considerations (such as availability of materials) (Dinh, Magniont, and Coutand 2012).

One study partially replaced hydrated lime with Portland cement, Meta-kaolin, Aluminum silicate, Silica fume, and Fly ash to increase the binder's hydraulicity (Stella Mary, Nithambigai, and Rameshwaran 2020). Other researchers used binders other than hydrated lime, such as clay (Fernea et al. 2019) or stabilized clay (Mazhoud et al. 2021), and different classes of natural hydraulic lime NHL3.5, NHL3.5Z, and NHL2 (Arnaud and Gourlay 2012) biopolymers (Collet et al. 2015).

2.11.7. Lime as a Binder in Hempcrete

Lime-based binders are the most commonly used hempcrete binders (Pietruszka, Gołębiewski, and Lisowski 2019). Lime is a binder made by heating limestone in a kiln at around 950°C, about 35% lower than the temperature required to produce cement (approximately 1450°C). Furthermore, as the lime hardens, most CO_2 released during production is reabsorbed during carbonation. As a result, its embodied carbon is much lower than that of cement. Also, the embodied energy of hempcrete is relatively low, while its embodied carbon is negative due to the carbon sequestration of the hemp during its growing phase (Pittau et al. 2018; Ip and Miller 2012; Zampori, Dotelli, and Vernelli 2013).The process that begins with limestone and ends again with limestone is called the lime cycle, as shown in Figure 7. The lime cycle enables lime to transform continuously, making it an ideal component for eco-friendly building materials like hempcrete.

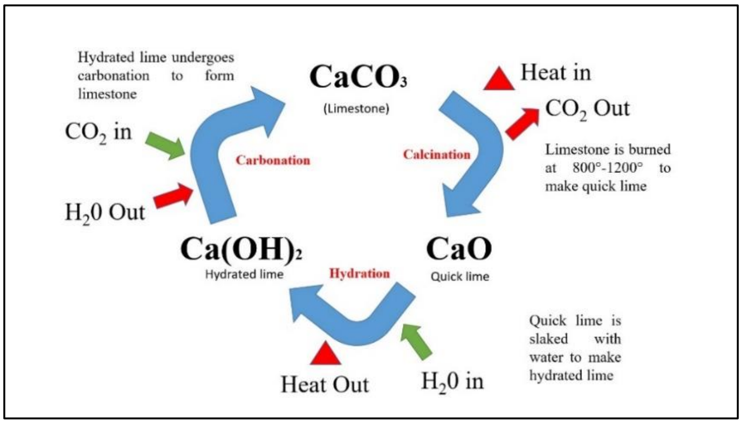


Figure 7. The life cycle of lime.

Woolley (2006) observed that lime gives masonry walls built with lime mortar a degree of flexibility, though it is relatively weak in compression and tension. Lime has good permeability and hardens by removing CO_2 from the environment, creating calcium carbonate $CaCO_3$. In contrast, cement is more rigid, resisting movement, and offers greater compressive and tensile strength. The cement hardens via hydration, which reacts with water to form a solid material.

According to Evrard and De Herde (2005), lime is a better binder for hempcrete than cement for several reasons:

1. The lime hardens through a slow carbonation process, which is more compatible with the hemp shives' fast water uptake than the reactions of a hydraulic binder such as cement.
2. The hemp shives are protected from mold and bacteria due to the high pH of lime.
3. Its thermal conductivity and density are lower than those of cement.
4. Its mechanical flexibility allows slight distortion without cracking.
5. Lime has a self-healing capacity through dissolution and re-precipitation of calcium compounds to heal cracks.

2.11.8. Hydraulic Lime as a Binder in Hempcrete

Hydraulic binders dry faster than lime-based binders at an early age. Hydraulic binders set and harden through hydration, forming hydrates that quickly reduce the amount of free water in the mix. The lime-based binder's slow drying at an early age can reach up to 2 weeks, depending on drying conditions. This is likely due to lime's reliance on carbonation, and the fine particle size of lime has high water retention. At later ages, the lime-based binder dries faster than the hydraulic binder due to the higher permeability of the lime, allowing it to release more retained moisture readily. Hydraulic binder has a denser structure due to the formation of hydrates, and it tends to retain moisture longer, making it slower to dry (Walker and Pavía 2012).

In the study of Arizzi et al. (2015), the hemp composites using natural hydraulic lime (NHL 3.5) demonstrated superior breathability, faster drying, and reduced water absorption by immersion and capillary action. They also showed greater resistance to bio-deterioration compared to composites made with hydrated lime. This indicates that natural hydraulic lime is the better choice when combining it with hemp shives, providing both durability and performance.

In the case of bio-composites with a hydraulic binder, the chemical characterization of plant aggregate is crucial since the composition of the plant aggregates might affect the aggregate characteristics and the composite properties, such as hydration reaction and setting time (Laborel-Préneron, Magniont, and Aubert 2018).

2.11.9. Influence of Hydraulic Additions on Hempcrete

The binder type influences the microstructure and properties of hempcrete. Increasing the binder's hydraulicity with hydraulic additions improves the compressive strength and lowers the capillary action of hempcrete due to the formation of hydrates. SEM analysis indicates that binders with hydraulic additions contain many hydrates in the hemp : binder transition zone and within the binder matrix. In contrast, the lime-based binder mainly contains carbonated lime because the lime-based binder is set through carbonation rather than hydration. Moreover, hydraulic additions speed up strength development and increase ultimate strength due to forming early hydrates (Walker and Pavía 2012).

The nature of the binder did not influence the compressive strength, thermal conductivity, moisture-absorbing properties, and acoustic performances of hempcrete due to the compounds in the hemp shive that affect the hydration process of the mineral binders (Delannoy et al. 2017).

2.11.10. Carbonation Process in Hempcrete

The research investigated the carbonation process in hempcrete specimens using different binders, such as lime, cement, metakaolin, alumino-silicate, silica fume, and fly ash, in various proportions. The specimens were placed in a carbonation chamber, and the change in weight before and after carbonation was measured. The results showed that the compressive strength of the carbonated specimens was higher than that of the non-carbonated specimens. This increase in strength is attributed to CO_2 filling the pores of the specimens during the carbonation process, leading to an increase in weight and density. Additionally, it was found that specimens containing lime and/or metakaolin absorbed more CO_2 than those with other binders (Stella Mary, Nithambigai, and Rameshwaran 2020).

All hydraulic lime mortars have a carbonation reaction in addition to their hydraulic set. In general, the carbonation decreases as the hydraulicity of the binder increases, and vice versa (Foster 2004). Dicalcium and tricalcium silicates in the hydraulic binder will react with water to form calcium silicate hydrates (C–S–H) and portlandite $Ca(OH)_2$. The pozzolanic binder will react with calcium hydroxide $Ca(OH)_2$ during the cement hydration and increase calcium silicate hydrate formation (Nozahic et al. 2012). The approximate ratio of the hydraulic set to the carbonation set in some popular binders is shown in Table 1 (Foster 2004).

Table 1. Approximate ratios of hydraulic set and carbonation set in common binders. (Source: Foster 2004)

Binder type	Degree of hydraulic set	Degree of carbonation set	Compressive strength
Non hydraulic lime	0%	100%	2-3 N/mm^2
NHL 2	45 - 50%	50-55%	2-7 N/mm^2
NHL 3.5	75-80%	20-55%	3.5-10 N/mm^2
NHL 5	80-85%	15-20%	5-15 N/mm^2
Portland cement	100%	0%	35 N/mm^2

2.11.11. Porosity in Hempcrete

The porosity of hempcrete is relatively high, mainly due to the intrinsic porosity of the hemp shive. The internal porosity of the hemp shive usually plays a decisive role in the overall porosity of hempcrete, affecting its density, mechanical strength, capillary water absorption, and thermal and acoustic properties. The Scanning Electron Microscope (SEM) Image in Figure 8 reveals the intricate pore structure of hempcrete (Collet et al. 2013). There are three main pore types existing in hempcrete (Laurent Arnaud and Gourlay 2012; Collet et al. 2008)

1. Macropores: These are found between the hemp shive particles, with diameters around 1 cm. They are largely influenced by compaction. A high ratio of macropores results from the imperfect arrangement of hemp shive particles within the material.
2. Mesopores: These pores exist within the shive and binder, as well as trapped air pockets and their diameters range from 0.1 mm to 1 mm.

3. Micropores: These occur between hydrates within the binder matrix and are determined by the binder's composition. Their diameters are less than 0.01 micrometers (µm).

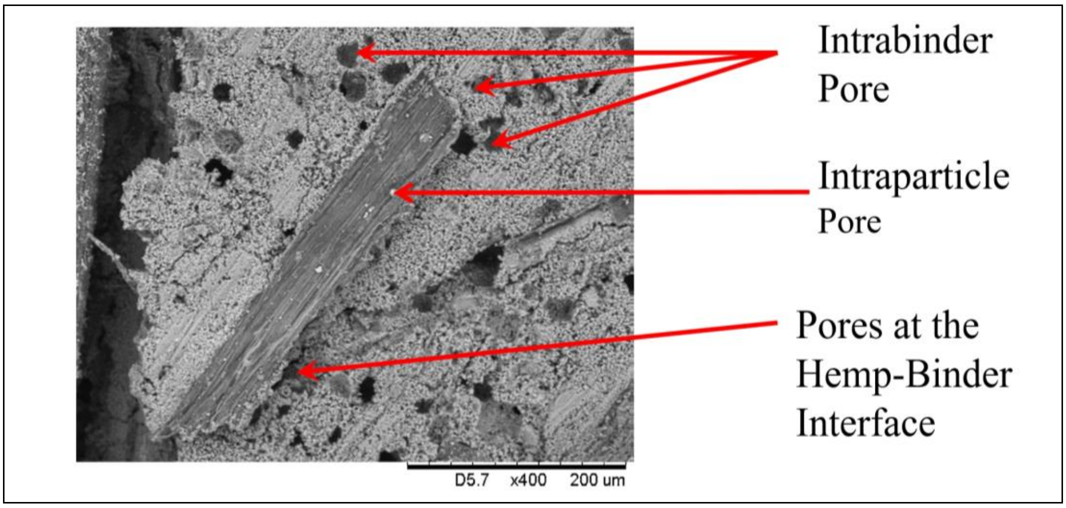


Figure 8. SEM image of hempcrete.
(Source: Collet et al. 2013)

2.11.12. Transition Zone of Hemp : Binder

The interfacial transition zone (ITZ) is a critical area in composite materials where the binder connects with the aggregate particles. One constraint of using hempcrete is the poor transition zone between the mineral binder and hemp shives, which affects the material's mechanical properties (Amziane, Nozahic, and Sonebi 2015).

Hempcrete's extremely low mechanical strength limits its use as a filler in load-bearing structures. Its limited mechanical qualities are caused, in part, by the lack of hydration in the interfacial transition zone around the shive. To improve the mechanical properties of this type of bio-based material, it is essential to identify the size and characteristics of this ITZ (Delhomme et al. 2022). Using optical microscope images, page et al. (2015) investigated the transition zone between hemp shives and the binder matrix. They found that gaps in the transition zone, caused by entrapped air, reduced the cohesion between the hemp shives and the binder matrix.

Many studies investigated plant-based concrete to evaluate the compatibility between plant particles and binders in producing plant-based concrete. For example, Chabannes et al. (2015) investigated and compared the behavior of lime rice husk concrete (LRC) and lime hemp concrete (LHC). They observed that the compressive strength, elastic modulus, and strength gain of LHC were higher than those of LRC, while similar rates of carbonation and hydration were observed in both concretes. The lower compressive strength and elastic modulus in LRC were attributed to a weak interface between the rice husk aggregates and the binder. This highlights the importance of the interfacial transition zone in plant-based concretes.

Other studies have employed distinct techniques and added multiple materials to enhance the transition zone between the binder and hemp shives (Amziane, Nozahic, and Sonebi 2015). Niyigena, Amziane, and Chateauneuf (2018) observed that smaller hemp shives generally have greater surface area and higher water absorption. Their inclusion in hempcrete can lead to lower mechanical properties due to weak binding at the interface between the binder matrix and hemp shives.

Other studies have used different binders to enhance the transition zone between the binder and hemp shives. Cement has been found to show better compatibility with plant particles, as seen by a notably reduced interfacial transition zone (Prud’Homme et al. 2024). In addition, lime has a high specific surface area, and its positive effects can be amplified. The increased surface area allows for better adhesion between the lime and hemp shives, resulting in stronger interfacial bonds (Diquélou et al. 2016). Moreover, the mass of plant particles and the sugar concentration impact the transition zone's size (Prud’Homme et al. 2024).

2.12. Mechanical Properties of Hempcrete

Hempcrete's mechanical properties are assessed via compressive strength tests, which consider the testing rate, specimen size, and direction of loading. The testing direction, parallel or perpendicular to the casting, affects the results due to material anisotropy.

2.12.1. Compressive Strength

Many research studies have been conducted on hempcrete's physical and mechanical properties. The density, compressive strength, and Young's modulus of hempcrete specimens can differ based on various factors, including the specific type of hemp shive being used, the amount of compaction energy applied, and the method used for measurement (Niyigena et al. 2016).

The results of Niyigena et al. (2018) have shown that its compressive strength typically ranges between 0.13 and 1.07 MPa for a density of 390–478kg/m^3. The compressive strength of hempcrete varies depending on several factors, including the type of binder, mix proportions, particle size, type of hemp shive, compaction, curing conditions, additives, and age.

The utilization of hempcrete for partitioning or enclosing walls depends upon its mechanical strength, surpassing the minimal value of 0.3 MPa, which is established for self-supporting construction materials (Gibson 2012). Hempcrete is a nonstructural insulating material generally used with load-bearing timber frames. Its increased strength enhances the structure's load-bearing capacity and stiffness. It can enhance the studs' load capacity by preventing buckling and resisting in-plane forces (Gross 2013). The compressive strength test has shown that hempcrete is an anisotropic material. Anisotropic means that the material has a different behavior when the load is applied in different directions.

Anisotropic behavior in hemp shives is due to their elongated particle size and the compaction process, which forces the particles to align in stratified planes perpendicular to the applied compressive force. In contrast, the particles are distributed randomly in the other two directions. This makes hempcrete a material with the same properties in two directions but different in the third (Williams, Lawrence, and Walker 2017). Another suggestion by Nguyen et al. (2010) regarding the anisotropic behavior is that hemp shive particles are anisotropic due to the capillary structure of the woody core from which they are cut.

2.12.2. Compressive Strength Testing

Different types of machines and techniques have been used in the literature to conduct the compressive strength test. Some studies used load control testing machines (Walker, Pavia, and Mitchell 2014), and some used displacement control testing machines to determine the compressive strength of hempcrete specimens.

2.12.3. Rates of Testing

Previous studies have applied different displacement rates to hempcrete specimens. Sonebi et al. (2015) used 0.4 mm/min, Ayati et al. (2024) used 2 mm/min, Williams et al. (2018) and Hirst et al. (2010) used 3 mm/min, Sassoni et al. (2014) used 3 and 5 mm/min, depending on the type of specimen, and Brzyski et al. (2020) and de Bruijn et al. (2009) used the rate of 5 mm/min.

According to Arnaud and Cerezo (L Arnaud and Cerezo 2002), applying different rates to hempcrete specimens has little effect on mechanical behavior. Mohamad et al. (2023) reported that controlling compressive strength results was challenging due to the high standard deviation attributed to the low cohesion between the hemp particles and the binder matrix.

2.12.4. Direction of Testing

The compressive strength test is applied in two directions depending on the specimen's shape, as reported in the literature. In cylinder specimens, the load is only applied perpendicular to the casting surface, or in other words, the orientation or arrangement of hemp shives. In cube specimens, the load is applied either parallel or perpendicular to the hemp shive orientation.

Some studies, like the study of (Collet et al., 2015), did not identify any significant effects or differences caused by the compression direction. Their findings suggest that the compressive strength of hempcrete might not be significantly influenced by the load direction, implying that other factors, such as mix composition or curing conditions, might have a more substantial effect.

In contrast, another study by Williams et al. (2017) found that Comparing the performance of the two directions is challenging due to differences in failure modes. Testing perpendicular to casting direction, the compressive strength can be identified from the peak stress on the stress-strain curve. However, in the parallel direction, the specimen continues to deform with increasing stress without a prominent peak as shown in Figure 9.

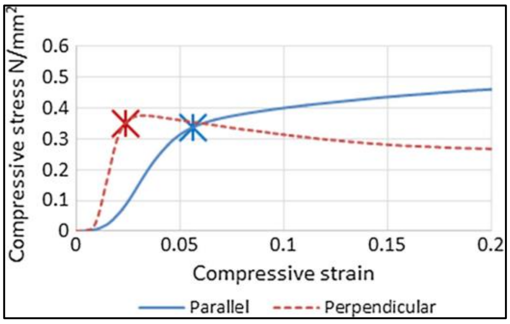


Figure 9. Stress-strain curve of the parallel and perpendicular direction.
(Source: Williams, Lawrence, and Walker 2017)

2.12.5. Size of Specimens

To test the mechanical properties, some authors used 40 × 40 × 160 mm prisms (Fernea et al. 2018), others 50×50×50 mm cubes, some 100×100×100 mm cubes (Sonebi et al. 2015), some 150×150×150 mm cubes, and others 100×200 mm cylinders (Williams, Lawrence, and Walker 2018).

The size of hempcrete specimens influences their compressive strength. Sonebi et al. (2015) found that 100 mm hempcrete cubes have lower compressive strength than 50 mm. They also found that the binder type, hemp : binder ratio, and density significantly influenced the compressive strengths. However, Collet et al. (2015) found no influence of specimen size on mechanical properties.

2.12.6. Compressive Strength Gain

Hempcrete strength gain is governed by the type of binder used, and hydration and carbonation processes. Knowing the differences in strength development can help in the optimization of the properties of hempcrete for different uses. Walker et al. (2014) found that the strength of hempcrete depends not only on binder hydration but also on other factors, such as binder carbonation, which contribute to strength at later ages.

At early ages, pozzolan binder-based hempcrete has a slower rate of strength gain. However, it achieves the highest compressive strength after one year. In contrast, hydraulic lime-based hempcrete gains strength quickly due to the early formation of hydrates, but its strength development slows after 28 days (Walker, Pavia, and Mitchell 2014).

2.13. The Factors Affecting Mechanical Strength of Hempcrete

Many researchers suggest different methods to improve the low mechanical strength. They attribute the reasons for the low strength of hempcrete to many reasons, such as the binder's hydraulicity, the ductile nature of hemp shives, their disordered arrangement, their high porosity (de Bruijn et al. 2009; Murphy et al. 2010), and their low apparent density (T.-T. Nguyen et al. 2009). Additionally, the hemp shive is surrounded by an interfacial transition zone that is not fully hydrated (Delhomme et al. 2022), and there is a weak interaction between the hemp shives and the binder (Niyigena, Amziane, and Chateauneuf 2017; Hirst et al. 2010).

Optimizing the hemp shives-to-binder ratio, compaction during casting, and adding fibers and additives to the matrix are the principal paths to improve compressive strength.

2.13.1. Optimizing the Hemp Shives-to-Binder Ratio

The mechanical properties of the hempcrete can be improved by adjusting the hemp shives binder ratio. A higher binder content may increase compressive strength; a higher hemp shive content may decrease it, affecting load-bearing capacity. Chamoin et al. (2014) found that the binder used in hempcrete affects the compressive strength of hemp concrete. Moreover, optimizing the binder dose can improve the compressive strength of hempcrete. Formisano, Dessì, and Landolfo (2017) found that adding 2% hemp shives by weight, or 35%-40% by volume, to the production of lime-based bricks reduces their density but decreases their compressive strength by 30%. Including hemp shives in various binders created gaps in the samples, making them lighter but reducing hempcrete strength. The use of hemp shives did not significantly improve the flexural strength of hempcrete (Özodabaş 2023).

2.13.2. Effect of Compaction on Strength

The behavior of hempcrete most significantly depends on its composition and the compaction applied during manufacturing. The compacting process improves hempcrete's compressive strength and increases the material's density due to the reduced volume of entrapped air. Nguyen et al. (2009) investigated the effects of compaction on hempcrete. They observed that the heavy compaction improved compressive strength by 28 days up to 6 months. They also observed that compaction enhanced the specimens' deformation capacity by allowing them to maintain a unified structure throughout the test, even while undergoing high deformation.

Nguyen et al. (2010) found that the compaction of hempcrete increased the compressive strength and thermal conductivity. However, the increase in thermal conductivity was insignificant compared to the improvement in compressive strength. Tronet et al. (2016) Investigated the effect of compaction on hempcrete to reach stiffness and strength comparable to those of traditional concrete blocks or clay bricks. The process is conducted using a 250 KN press at a load rate of 1mm/s to achieve the required level of compaction. They observed that the compaction of a block is a suitable means to improve strength when decreasing the paste content and increasing the proportion of shive. The shive will contribute to strength when the compaction process reduces the volume of the particles. This reduction occurs as the particles are rearranged and become more compact, leading to a volume reduction of approximately two. Compressive strength is improved by high compaction pressure. The stiffness also depends on compactness but will be reduced by a high shive content because the shive particles are more flexible than the binder particles.

Tronet et al. (2014) applied various compaction models to wet and dry mixes in their fresh state. A dry mix is one in which water has been removed from the ingredients. Their research demonstrated that water softens the hemp shive particles, and dry mixes are more difficult to compact than wet mixes.

2.13.3. Use of Additives

Some studies have incorporated additives into hempcrete to enhance its mechanical properties and durability. Sheridan et al. investigated the effect of adding a viscosity modifying agent (VMA) on hempcrete's mechanical properties and water absorption. They found that the VMA improved both the modulus of elasticity and compressive strength and decreased the water absorption ability of hempcrete (Sheridan et al. 2017). Another study by Walker et al. (2014) found that using water retainers with lime-pozzolana binders in hempcrete production has improved its early strength. Water retainers help retain the water needed for hydration and prevent the hemp shives, which have high water absorption, from absorbing the water necessary for binder hydration.

2.13.4. Incorporation of Fibers

Some studies have examined the effect of blending hemp shives and fibers on compressive strength. According to Sinka et al. (2015), using both hemp shives and fibers may improve mechanical strength, eliminating the need for a fiber separation process. On the other hand, other study by De Bruijn et al. (2009) indicates that blending hemp shives with fibers without a fiber separation process did not significantly increase the compressive strength of hempcrete. They also found that mixing hemp shives and fibers in hempcrete may enhance its mechanical properties compared to hempcrete with only shives.

2.13.5. Curing Conditions

The mechanical behavior of hempcrete is significantly affected by the curing conditions. Arnaud and Gourlay (2012) investigated the effect of curing conditions on hempcrete specimens. They found that high (75% and 98%) and low (30%) relative humidity conditions unsuitable for hempcrete. High relative humidity decreases mechanical properties, while low relative humidity slows down the process of setting hempcrete. Hempcrete has low compressive strength and a strongly ductile behavior even though after two years of setting, these characteristics are different from conventional concrete and limit the use of hempcrete in construction. The higher the binder content, the higher the stress that hempcrete withstands, and the lower the strain the hempcrete exhibits.

Exposing the hempcrete to outdoor conditions, such as open air, rather than keeping it in a controlled indoor environment, improved its compressive strength. Outdoor conditions were also ideal for CO_2 diffusion and dissolution (Chabannes et al. 2015).

2.14. Studies on Compressive Strength

Pavía et al. (2015) investigated the impact of relative density, oven drying, mold retention, and specimen geometry on the compressive strength of hempcrete using two binders: one with hydrated lime and cement and the other with natural hydraulic lime NHL3.5. They found that curing hempcrete at high relative humidity (>95%) decreased compressive strength by 65.4%. Drying hempcrete at 50°C did not significantly improve its compressive strength. Retaining the hempcrete in molds during curing increased compressive strength by 23% due to the prolonged presence of moisture, which enhanced hydrate formation. Specimen geometry did not significantly impact the ultimate compressive strength of hempcrete but did affect its behavior. Initially, cylinders and cubes deformed similarly under load up to the yield point. Beyond this yield point, cylinders fractured, whereas cubes continued to crush, eventually experiencing additional stiffness due to mechanical bridges forming between opposing cell walls.

A study by Mazhoud et al. investigated the effect of different hemp-clay ratios (0.4, 0.455, 0.5, and 0.75) on hemp-clay concrete's density and mechanical behavior. They found that the hemp-clay ratio significantly affects density, compressive strength, and tensile strength.

The highest density, compressive, and tensile strength were for the 0.4 hemp clay ratio, while the lowest density, compressive, and tensile strength were for the 0.75 hemp clay ratio. They conclude that the density of hemp-clay concrete decreases with an increase in the hemp-clay ratio, while the compressive and tensile strengths increase with higher density and a lower hemp-clay ratio (Mazhoud, Collet, and Lanos 2017).

Sheridan et al. investigated the effects of replacing hydrated lime with metakaolin on hempcrete specimens' mechanical, and capillary properties. They found that partial replacement of hydrated lime with metakaolin increased the compressive strength and capillary water absorption of the hempcrete specimens (Sheridan et al. 2017).

Šadzevičius et al. (2023) studied the effect of different binders such as organic sapropel, composite Portland cement, and unslaked calcitic lime on hempcrete's compressive strength. They found that hempcrete is influenced by the composition and type of binder used. Mineral binders like unslaked calcitic lime and cement increase compressive strength, while organic sapropel decreases compressive strength (Šadzevičius, Gurskis, and Ramukevičius 2023).

Pretot et al. (2015) replaced 20% - 60% of the lime-based binder with calcium sulfates (gypsum) to obtain faster hardening of hempcrete at an early age without adversely affecting other hempcrete performances. Such replacement impacts the porous structure of hempcrete and thus its mechanical, thermal, and hydric properties. They found that optimum replacement is less than 33% to improve the mechanical properties and ensure faster hardening (Pretot et al. 2015).

Fernea et al. (2019) observed that the values obtained for the mechanical properties of hempcrete were low. They suggested stabilizing the hemp clay composite with other binders to improve hempcrete's compressive and flexural strength.

Some concrete, like hempcrete, made up of plant particles and mineral binders, may have poor mechanical strength due to incomplete hydration of the hydraulic binder. Compounds produced from the plant, such as phenolic compounds, lignin derivatives, and other free compounds present in plants, may interact with binders and slow down or prohibit the setting of the hydraulic binder in hempcrete (Delannoy et al. 2020).

Sonebi et al. (2015) found that the binder type, hemp : binder ratio and density significantly influenced the compressive strengths.

2.15. The Factors Affecting the Thermal Properties of Hempcrete

In general, the thermal conductivity of bio-aggregate building materials is directly linked to their density. However, it is also influenced by other factors, such as the formulation, including the type of binder and aggregate, the binder-to-aggregate ratio, and the water content (Sofiane Amziane and Collet 2017).

2.15.1. The Effect of Porosity

The excellent porosity of hemp shives' structure is primarily responsible for the good thermal and hygienic (moisture-regulating) qualities of hempcrete (Bourdot et al. 2017). Its high porosity is due to the many little air pockets with a poor heat conductor, which help to add to the material's exceptional thermal insulation characteristics. The open porosity of hempcrete allows air and moisture to move freely through the material. (Samri 2008)

2.15.2. The Effect of Density

Thermal conductivity depends on the density of the material (Collet et al. 2015). The results show that thermal conductivity primarily depends on density, with a linear correlation between thermal conductivity and hempcrete density. The low thermal conductivity of hempcrete can be attributed to its low density (Brahim Mazhoud et al. 2021). While Fernea et al. (2019) observed that the values obtained for the density of clay-based hempcrete were not linear with the thermal conductivity values.

Hempcrete specimens with higher density exhibits higher thermal conductivity (Gourlay et al. 2017). When the density of hempcrete increases, the proportion of solid material increase compare to air proportion. Consequently, the hemp shives and binder are packed more closely together, forming a more continuous network. Because of this, heat can travel more effectively through the solid parts of the material. With a greater density, there are more and better-connected pathways for heat to flow, which makes hempcrete a better conductor of heat (Latif et al. 2015).

Dhakal et al. (2017) investigated the effect of hemp : binder ratio on the thermal conductivity of hempcrete. They found that the thermal conductivity of the three studied hempcrete mixes (with hemp : binder ratios of 1:1, 1:1.5, and 1:2) is highly influenced by their density. The higher the binder content, the higher the density, leading to a higher thermal conductivity. This relationship follows a near linear trend.

2.15.3. The Effect of Microstructure

Micropores within the hemp shive particles, the binder matrix, and the larger interconnected macro pores between the hemp shive particles play a significant role in thermal insulation by reducing heat transfer (Delannoy et al. 2020). However, the presence of hydrates, formed during the hydration of hydraulic lime and pozzolanic reactions, affects permeability and thermal conductivity. When the hydrates fill the pores, they reduce air-filled pores and increase thermal conductivity. Therefore, thermal conductivity increases with increasing hydrate content (Walker and Pavía 2014).

Hygrothermal properties of hempcrete depend on its microstructure, which evolves with age. The aging of specimens increases the moisture absorption and release rate, the water vapor permeability, and the moisture storage capacity. It decreases the material's thermal conductivity and specific heat capacity (Bennai et al. 2018).

2.15.4. The Effect of Water Content

Hempcrete's water content affects its thermal conductivity. Studies show that the thermal conductivity of hempcrete tends to increase almost linearly with the water content across all specimens (Gourlay et al. 2017). Moreover, in another study, the thermal conductivity of hempcrete increases with water content, with a more pronounced effect at lower hemp content (Mazhoud et al. 2021). The thermal conductivity of hempcrete decreases with time. As the hempcrete dries gradually over time, the pore water evaporates and is filled with air, decreasing the thermal conductivity (Niyigena, Amziane, and Chateauneuf 2018).

The thermal conductivity depends on hempcrete's hygric status (water content within it). When hempcrete is wet, its ability to transfer heat (thermal conductivity) increases because water conducts heat better than air. Conversely, when the hempcrete is drier, its thermal conductivity decreases. Hygrothermal properties of hempcrete depend on its microstructure, which evolves with age. The aging of specimens increases the moisture absorption and release rate, the water vapor permeability, and the moisture storage capacity. It decreases the material's thermal conductivity and specific heat capacity (Bennai et al. 2018).

In the study by Collet and Pretot (2014), density had a more significant impact on thermal conductivity than moisture content. The results show that thermal conductivity increases by 54% when the density rises by two-thirds, while moisture content causes only a 15–20% increase from the dry state to 90% relative humidity (RH). Additionally, the thermal conductivity of high-density hempcrete can be more than double that of low-density hempcrete with the same formulation.

2.15.5. The Effect of Binder Type

Thermal conductivity is influenced by the type of binder used. (Collet et al. 2015) Various binders can have varying thermal conductivities and affect the microstructure of the composite material. For example, Mazhoud et al. (2017) found that hempcrete and foamed concrete have the same thermal conductivity for the same density.

Sheridan et al. (2017) investigated the effects of replacing hydrated lime with metakaolin on thermal hempcrete specimens. They found that partially replacing hydrated lime with metakaolin reduced the thermal conductivity.

Šadzevičius et al. (2023) studied the effect of different binders, such as organic sapropel, composite Portland cement, and unslaked calcitic lime, on hempcrete's thermal conductivity. They found that hempcrete is influenced by the composition and type of binder used. Mineral binders like unslaked calcitic lime and cement increase thermal conductivity, while organic sapropel decreases it.

2.15.6. The Effect of Compaction

The compacting process increases the material's thermal conductivity and density due to the reduced volume of entrapped air. However, some researchers found that the increase in thermal conductivity is not significant compared to the improvement in compressive strength (Nguyen et al. 2010).

2.16. Water Absorption of Hempcrete

Hempcrete has the ability to absorb water. The vessels in the porous hemp shive are responsible for capillarity. These vessels, with diameters ranging from 50 to 100 μm, act as channels that can facilitate the movement of fluids through capillary action. Consequently, hemp shive exhibits a high water absorption capacity (Jiang et al. 2017). The high porosity of plant-based concrete results from the complicated interplay between the microscopic porosity of shives and the macroscopic porosity from particle arrangement (Cerezo 2005). However, the water absorption of plant-based aggregates is a challenge for plant-based concretes (Page et al., 2015).

The primary drawback of utilizing organic building materials, such as plant-based aggregates, is their vulnerability to water's effects. The wall's material, whether blocks or filling, is subjected to rising groundwater levels. Capillary absorption is used as an indicator of the degradation of construction materials. Moreover, since capillary transport is an effective factor in the movement of sulfate and chloride ions, absorbed water can be a serious problem for durability (Page et al., 2015).

Some studies have been conducted to reduce capillary water absorption in hempcrete to enhance its durability. For example, Ruus et al. (2021) investigated the effect of carbonation and hemp shive particle size on the hygrothermal properties of hempcrete. They found that adding CO_2 to hempcrete stored in a plastic bucket induced carbonation. They observed that hempcrete made with fine hemp shives had higher water absorption than that produced with coarse shives. Further, carbonation affected fine and coarse specimens differently. Fine carbonated specimens exhibited higher water absorption, while coarse carbonated specimens became denser and less permeable, reducing their capacity for water absorption.

The presence of hydrates, formed during the hydration of hydraulic lime and pozzolanic reactions, affects permeability and capillary water absorption. When the hydrates fill the pores, they reduce air-filled pores and reduce capillary action. Therefore, capillary absorption decreases with increased hydrate content (Walker and Pavía 2014).

Brzyski and Suchorab (2020) investigated the partial substitutes of hemp shives with expanded perlite. They found that substitution reduced the composite specimens' capillary water absorption by 14.5%. They also observed that the ratio of binder to hemp shives had a more significant effect on limiting the capillary water absorption than the type of hemp shives.

Sheridan et al. (2017) investigated the effects of replacing hydrated lime with metakaolin on hempcrete specimens' capillary properties. They found that partial replacement of hydrated lime with metakaolin increased the capillary water absorption of the hempcrete specimens (Sheridan et al. 2017).

2.17. Technic to Better Use Hempcrete

Elfordy et al. (2008) developed a process to manufacture hempcrete blocks using projection. This method provides water just before the hose to prevent the hemp shives from absorbing large quantities, which could affect the setting and drying of the hempcrete. The process also provides sufficient compaction to increase the density of the hempcrete blocks. They found that the mechanical and thermal properties improve with increasing density. Two types of blocks can be produced depending on the type of construction: one with low density and compressive strength, which provides high thermal insulation for infill in frames, and another with high density and compressive strength, which offers lower thermal insulation for load-bearing walls.

2.18. The Impact of Hemp Shives Water Extracts on Hempcrete

Water extracts from hemp shives are substances or compounds that can leach or be extracted from hemp shives by soaking or mixing them with water. The extracts usually contain soluble organic and inorganic compounds naturally present in the plant material, such as sugars, tannins, phenolic compounds, pectins, and minerals (Delannoy et al. 2020).

Delannoy et al. (2019) demonstrated that the adverse effects of water extracts on the hydration of two types of binders might explain the weak mechanical properties observed in hempcrete. The low extent of hydration reactions observed via the XRD test on hempcrete specimens confirms this.

Diquélou et al. (2015) investigate the effect of water extracts, which are the solutions obtained by soaking hemp shives in water, of different hemp shives on cement's setting and mechanical properties. They demonstrated that these extracts reduce mechanical properties (compressive and flexural strength) by reducing the formation of hydrates (calcium silicate hydrates and portlandite). Moreover, they act as retarders by increasing the cement setting time. The researchers also found that the chemical compositions of water extract may vary depending on the source of hemp shives and retting process. The third observation is that the complete absence of setting around hemp shive particles is due to the degradation byproducts of shive by the alkaline cement medium and water extracts.

Sheridan et al. (2017) investigated the effects of pretreating hemp shives with linseed oil on hempcrete specimens' mechanical, thermal, and capillary properties. They found that the pretreatment of hemp shives with linseed oil increased compressive strength and thermal conductivity but reduced the hempcrete's capillary absorption.

Research has shown that the soluble components (e.g., organic acids, simple sugars, proteins) of the shive negatively influence the mechanical properties of hempcrete; it retard setting time and prevents the carbonation reactions of hempcrete. Wang et al. found that water treatment can effectively remove the soluble components responsible for retarding and subsequently enhance the compatibility between hemp shive and the lime matrix in hempcrete (Wang et al. 2021).

Narattha et al. (2022) investigated the effect of treated hemp shives in a hemp geopolymer composite. The ratio of treated hemp shive to fly ash was set at 0.05, 0.10, 0.15, and 0.20 by mass. They found that as the hemp shive to fly ash ratio increased, the density decreased from 1,654 kg/m³ to a range of 1,358 kg/m³ to 933 kg/m³ due to the porous structure of the hemp shives. Similarly, the compressive strength decreased from 28.40 MPa to 22.23 MPa, 11.59 MPa, 4.91 MPa, and 2.75 MPa for the respective ratios of 0.05, 0.10, 0.15, and 0.20. Additionally, the thermal conductivity of the geopolymer composites decreased as the hemp shive to fly ash ratio increased, dropping from 0.55 W/m·K to a range of 0.36–0.25 W/m·K.

Dinh et al. (2012) investigated the effect of the pretreatment of hemp shives with an innovative pozzolanic binder prior to its incorporation into the matrix on the mechanical and thermal properties of hemp concrete. The results demonstrate that the pretreatment of hemp shives significantly improves the compressive strength and modulus of elasticity of hempcrete compared with hempcrete without pretreatment. While the thermal conductivity of pretreatment was not considerably affected.

The inclusion of hydrated lime in hydraulic binders reduces the delay effect of hemp shive water extract on the setting and hydration of hempcrete. The presence of calcium hydroxide in hydrated lime plays a significant role in the protection process by forming a layer around the hemp shives and binder particles to ensure the proceed of hydration reaction (Diquélou et al. 2016).

2.19. Hempcrete Durability

Several studies have investigated the durability of hempcrete, focusing on its long-term performance in different environmental conditions. For instance, Zerrouki et al. (2022) investigated the effect of partially substituting a commercial binder consisting of 10% natural hydraulic lime, 15% pozzolan mixture, and 75% hydrated lime with metakaolin on hempcrete's long-term physical and mechanical properties. The tests were conducted after 0, 15, 25, and 50 cycles of wetting and drying exposure. They found that adding metakaolin increased the durability and bond between the hemp shive particles and the matrix by forming additional C-S-H gel. The wetting and drying cycles reduce the compressive strength of reference hempcrete samples by weakening the bond of hemp particles to the matrix due to swelling and shrinking under cyclic wetting and drying effects.

2.20. Drying of Hempcrete

The drying of hempcrete is the critical factor in its performance. The water retained by the porous hemp shives must be discharged to establish a state of moisture balance with the ambient environment. Several factors affect drying time (Magwood 2016):

1. The most significant factor is the moisture content of the hempcrete mixture when placed in the walls. It depends on the mix ratio and the mixture's effectiveness in distributing the water content to the binder before it can soak into the hemp hurds. Using as little water as possible to make a workable mix will help reduce drying time.
2. Relative humidity in that atmosphere. Dry air quickly draws moisture out of the walls, whereas high humidity can completely halt drying.
3. Airflow around the wall. If moving air contacts hempcrete, drying will be faster. Exposing both sides of the wall to air promotes faster drying than when one side is obstructed by permeable sheeting.

The binder will continue its hydraulic set for days or weeks; however, the degree to which the chemical set is completed is not crucial to the functionality. Additionally, hydrated lime begins the process of recarbonizing and absorbing atmospheric CO_2. It gains in strength as this happens, and the process can take years or even decades to approach completion. But the strength gained in this process is not essential for the functional properties of the hypocrite (Magwood 2016).

Dhakal et al. (2017) investigated the hempcrete drying period, when kept at a controlled room temperature and relative humidity, lasted around 26 days. The material gradually lost moisture during this time until its density no longer decreased.

2.21. Impact Test of Concrete

Designing structures to withstand low velocity impact loads has become an important topic due to the risks associated with accidental or natural hazards, such as vehicle collisions, ice or ship impacts, and falling heavy objects onto structures. Reinforced concrete structures have been widely used for centuries, but understanding their impact behavior under impact loads remains limited. The increasing demand for impact-resistant reinforced concrete structures has been followed by a surge of experimental research aimed at developing advanced analysis and design methods for such applications and investigating various materials that can be added to or applied to concrete to improve its ability to resist impact and absorb energy (Saatci and Vecchio 2009).

Under impact loading conditions, concrete exhibits distinct behaviors depending on its composition. Bentur et al. (1986) investigated the behavior of plain and reinforced concrete beams under impact loading. They found that plain concrete beams, characterized by their brittle nature, fail abruptly under dynamic loads, with the load peaking within milliseconds (~1 ms) and declining rapidly to zero. In contrast, reinforced concrete achieved a higher maximum velocity during impact (~2 m/s compared to ~1 m/s for plain concrete). Additionally, while plain and reinforced concrete reached comparable peak loads (~30 kN), the load in reinforced concrete beams decreased gradually over an extended period (~70 ms). This suggests that reinforcement enhanced energy absorption and redistribution of the reinforced concrete beams, making them ductile behavior. Subsequently, the momentum is more effectively transferred from the impact hammer to the beam in reinforced concrete beams than in plain concrete beams.

Pham and Hao (2017) investigated the impact behavior of reinforced concrete beams under varying impact velocity, projectile weight, and concrete strength conditions. They adjusted the impact velocity and projectile weight to achieve the same impact energy as a 203.5 kg projectile dropped from a height of 2 meters. Their study found that beams subjected to higher impact velocities experienced more localized damage and higher maximum impact forces, while slower velocities resulted in greater maximum and residual displacements. They also observed that increasing concrete strength from 20 MPa to 100 MPa led to a 30% rise in concrete modulus and beam stiffness. However, the impact force increased, and the displacement reduction with higher concrete strength was less than 5%. Lower-strength concrete, particularly at 20 MPa, suffered severe damage and fractured into portions. However, these beams dissipated more energy through plastic deformations, influencing the failure modes.

Banthia et al. (1987) performed impact tests on different types of concrete, high-strength concrete, normal-strength concrete, and fiber-reinforced concrete beams to assess their impact performance. They found that the impact strength of high-strength concrete is higher than that of normal-strength concrete. However, high-strength concrete appears to be more brittle than normal-strength concrete. Concrete is inherently a brittle material. To overcome this brittleness, materials like steel are often added. Ductility can also be improved by incorporating fibers into the concrete matrix.

Banthia et al. (1987) also found that adding fibers to concrete increased ductility and impact resistance rather than impact strength. Due to its brittleness, plain concrete failed suddenly under impact loads. In contrast, fiber-reinforced concrete beams carried some load even after cracks developed in the matrix, thanks to the bridging effect of fibers across the cracks. The addition of fibers significantly enhanced both impact strength and fracture energy. Moreover, fiber-reinforced concrete was more ductile and had higher impact resistance than normal-strength concrete, making it better suited for dynamic situations. Among the fibers studied, steel fibers performed much better than polypropylene fibers. The smaller improvement observed with polypropylene fibers may be attributed to their lower volume content or modulus of elasticity (Banthia, Mindess, and Bentur 1987).

Anil et al. (2016) used experimental and numerical methods to investigate the behavior of reinforced concrete beams made from various concrete types and the effect of beam size under dynamic impact loading. Twelve beams made from low-strength concrete, normal-strength concrete, and engineered cementitious composites (ECC) with polyvinyl alcohol (PVA) fibers were tested. Results show that material type significantly affects crack width, with ECC beams exhibiting the smallest cracks and low-strength concrete beams the largest. Beams made from low-strength concrete also demonstrated larger maximum displacements due to their lower mechanical properties, such as tensile strength and modulus of elasticity. As expected, larger beams showed smaller maximum displacements than smaller beams. Repeated impacts increased maximum displacement, though the rate of increase was lower for ECC beams, highlighting their improved damage resistance. ECC's enhanced tensile ductility effectively limited crack formation in many cases.

Esaker et al. (2023) reviewed the parameters influencing the impact resistance of concrete, focusing on concrete compressive strength, the type and ratio of fiber, and the type and size of aggregate. The findings suggest that increased compressive strength correlates with improved impact resistance. Adding fibers to concrete significantly enhances its resistance to impact, including spalling, scabbing, and penetration depth. Nevertheless, the current understanding of the effects of fiber properties, such as fiber length, type, and volume fraction, is minimal and often contradictory in available studies. Besides, aggregates' size in a concrete matrix greatly influences the impact resistance. The structures and materials must have high tensile strength and ductility to enhance impact resistance and energy absorption capacity.

Researchers have employed various solutions to enhance the impact resistance of reinforced concrete members. These include increasing the grade of concrete, incorporating fibers into the concrete mix, increasing the reinforcement of structural members, installing dampers, and applying protective layers. Different cushioning materials, such as rubberized concrete, substances derived from recycled tires, and polycarbonate foam, have been examined for their potential to reduce damage resulting from impact events. These cushioning agents are frequently utilized in structural applications to diminish impact forces, prolong the onset of damage, and reduce the acceleration structures undergo during impact tests (T. T. Pham, Kurihashi, and Masuya 2022).

While these materials offer some benefits, they also have significant drawbacks. Some are expensive to produce, environmentally harmful, and energy-intensive, resulting in high carbon emissions. Furthermore, many have higher density and poor thermal insulation properties and may not be compatible with sustainability goals. These disadvantages highlight the need for new materials to overcome these limitations while providing efficient impact protection.

With growing interest in sustainable and multifunctional materials, hempcrete-biocomposite made from hemp shiv, binding, and water is attracting tremendous attention. It is mainly known for its lightweight nature, thermal insulation capabilities, and carbon-negative production process. Hence, hempcrete is a viable environmental and sustainable alternative to traditional cushioning materials. However, the impact performance of the material has not been explored in detail.

2.22. The Aim of the Study

There are many studies on hempcrete, most focusing on specific parameters and selected properties of the material. However, further research is needed to comprehensively analyze and optimize the effects of binder composition, hemp shive particle size, hemp-to-binder ratio, and hemp-to-water ratio on hempcrete's physical, thermal, and mechanical properties. The hemp shives used in the study are of a different particle size and origin than those found in previous studies. The research suggests that composite material is intended to be used as a filler and insulator for timber frame walls or as a prefabricated hempcrete element such as insulation boards or blocks.

The research's main aim is to assess the differences in the properties of the hempcrete made according to 10 mix designs that differ in the binder composition, size of the hemp shives used, hemp : binder ratio, and hemp : water ratio. Additionally, this study aims to determine hempcrete's ability to absorb and dissipate impact energy. The research looks at its energy absorption characteristics, stress distribution characteristics, and ability to reduce peak loads at impact to see if hempcrete can be used as a feasible and sustainable cushioning material. The findings may help use hempcrete in protective structural applications to reconcile environmental sustainability principles with functional performance.

CHAPTER 3

MATERIALS AND METHODS

3.1. Materials Used in the Study

The materials used in the study include hemp shives as lightweight aggregate, hydrated lime, and natural hydraulic lime as binders. Pozzolanas were incorporated to enhance binder performance. Cement and Crushed stone aggregate were explicitly used for reinforced concrete beams.

3.1.1. Hemp Shives

The hemp, cultivated in Çileme village in the Menderes district of Izmir, was processed in the field by harvesting machinery, breaking the stalks into small pieces (hemp shives), and supplied in large bags. The hemp shives used in this research were obtained from a local supplier in Izmir. Then, the hemp shives were sieved using four different sieves in the laboratory to obtain coarse, medium, and fine particle sizes. The hemp shives used in the study are shown in Figure 10.

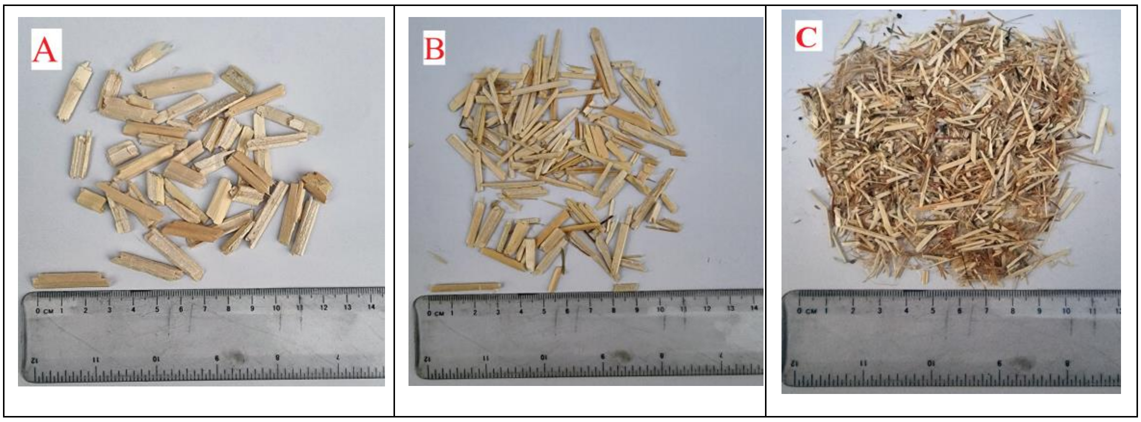


Figure 10. Hemp shives used in the study: A) Coarse, B) Medium, C) Fine.

3.1.2. Hydrated Lime

Hydrated lime (HL) is a type of lime that is produced by adding water to quicklime. According to TS EN 459-1 (Turkish Standards Institute 2011). , there are three European classifications according to their calcium oxide content: CL90 (>85%), CL80 (>75%), and CL70 (>65%). The hydrated lime used in this study was CL80 S, made by KİMTAŞ Company (Manisa, Türkiye). The HL's physical properties and chemical composition are given in Tables 2 and 3, respectively. The Brunauer-Emmett-Teller (BET) is a method used to measure the specific surface area of materials. X-ray Fluorescence (XRF) is a test used to determine the elemental composition of materials. The Bet surface area and XRF X-ray Fluorescence test were conducted in the Materials Research Center at Izmir Institute of Technology.

3.1.3. Natural Hydraulic Lime

Natural hydraulic lime (NHL) is a type of hydraulic lime produced by calcining limestone that contains impurities naturally. According to the European standards EN 459-1(Turkish Standards Institute 2011), there are three grades of NHL depending on the compressive strength of lime mortar at 28 days: NHL5, NHL3.5, and NHL2. The NHL used in this study was the NHL 3.5 grade made by TEKNO Company (Istanbul, Türkiye). The physical properties and the chemical composition of the NHL are given in Tables 2 and 3, respectively.

3.1.4. Fly Ash

Fly ash is a byproduct of the pulverized coal combustion process in electric power plants. Two types, type C (FAC) and type F (FAF), have been used. Fly ash reacts with calcium hydroxide ($Ca(OH)_2$) from lime in the presence of water to form additional cementitious compounds. Substituting a portion of lime or other binder with fly ash improves strength and provides some environmental benefits. As a waste product from coal combustion, fly ash reduces the demand for materials requiring more energy. FAC was obtained from a thermal power plant in (Muğla, Türkiye), while FAF was obtained from a thermal power plant in (Kütahya, Türkiye). The physical properties and the chemical composition of the FAC and FAF are given in Tables 2 and 3, respectively.

3.1.5. Ground Granulated Blast Furnace Slag.

Ground granulate blast furnace slag (GGBFS) is a byproduct of iron production. OYAK Company (Iskenderun, Türkiye) produced the slag used for the mixtures. Adding GGBFS to hempcrete also contributes to environmental benefits because it is an industrial by-product. GGBFS reduces reliance on more conventional and energy-intensive binders like lime, reducing the material's carbon footprint and significantly improving its performance. The physical properties and chemical composition of the GGBFS are given in Tables 2 and 3, respectively.

3.1.6. Cement

The cement used in the study was Portland calcareous cement CEM II/B-L 32.5 N produced by AKÇANSA (Çanakkale, Türkiye) complying with TS EN 197-1 standard (Turkish Standards Institute, 2002), consisting of Portland cement clinker, limestone, and gypsum. This cement was used to cast reinforced concrete beams for the impact test. The cement's physical properties and chemical composition are given in Tables 2 and 3, respectively. This specific cement type was selected based on its availability in the market and compatibility with local construction practices.

Table 2. Physical properties of the binder used.

Property	**Hydrated lime**	**Natural hydraulic lime**	**Fly ash type F**	**Fly ash type C**	**Ground blast furnace slag**	**Cement**
Bulk density (kg/m^3)	601	908	786	794	957	1352
BET Surface area (m^2/g)	11.0462	2.2029	1.7638	1.6933	2.3073	-
Blaine surface area (m^2/g)	-	-	-	-	-	0.49–0.55

Table 3. Chemical compositions of the used materials by XRF test.

Material	Compound content %									
	SiO_2	**Al_20_3**	**CaO**	**Na_2O**	**MgO**	**MnO**	**TiO_2**	**SO_3**	**K_2O**	**Fe_2O_3**
HL	0.0011	0.6959	84.39	10.92	2.702	0.031	0.00083	1.059	0.0012	0.0043
NHL	0.0011	11.59	78.67	5.68	2.525	0.032	0.0196	0.3796	0.0012	0.8337
GGBFS	34.45	15.23	36.07	2.23	7.701	0.945	1.393	0.4182	0.5083	0.7179
FAC	38.59	29.09	16.14	2.56	2.763	0.0516	0.8351	1.229	2.079	6.212
FAF	52.93	26.94	3.419	0.11	3.801	0.1149	1.004	0.2628	2.084	8.734
Cement	19.95	12.73	49.46	8.04	2.698	0.0512	0.2891	1.304	1.024	4.206

3.1.7. Aggregates

A well-graded crushed limestone aggregate, consisting of a mix of coarse aggregate and fine aggregate with a maximum aggregate size of 11.2 mm, was obtained from a local supplier. A sieve analysis was conducted on the aggregate using a mechanical sieve shaker according to TS 706 EN 12620 standards (Turkish Standards Institute 2009). A combination of coarse and fine aggregates was used to obtain a well-graded aggregate to obtain a well-graded aggregate. After several trials with different proportions of coarse and fine aggregates (e.g., 40:60, 55:45, 60:40, and 45:55), a 50:50 combination was selected as the optimal mix. The sieve analysis results are shown in Table 4, and Figure 11 illustrates the grading of the aggregate within the recommended limits by Turkish standards TS 706 EN 12620 (Turkish Standards Institute, 2009). The calculated fineness modulus is 5.86. The aggregates are used in the reinforced concrete mix for the impact testing of hempcrete.

Table 4. Sieve aggregate size of the combined aggregate used in this research.

Sieve	Coarse aggregate	Fine aggregate	Combination	Cumulative	Retained %	Passing %
16	0	0	0	0	0	100
11.2	196	0	98	98	9.8147	90.185
8	477	0	238.5	336.5	33.700	66.299
4	233	0	116.5	453	45.368	54.631
2	66	154	110	563	56.384	43.615
1	6	263	134.5	697.5	69.854	30.145
0.5	4	307	155.5	853	85.428	14.571
0.25	2	91	46.5	899.5	90.085	9.9148
0.125	3	135	69	968.5	96.995	3.0045
0.063	8	35	21.5	990	99.148	0.8512
Pan	6	11	8.5	998.5	100	0

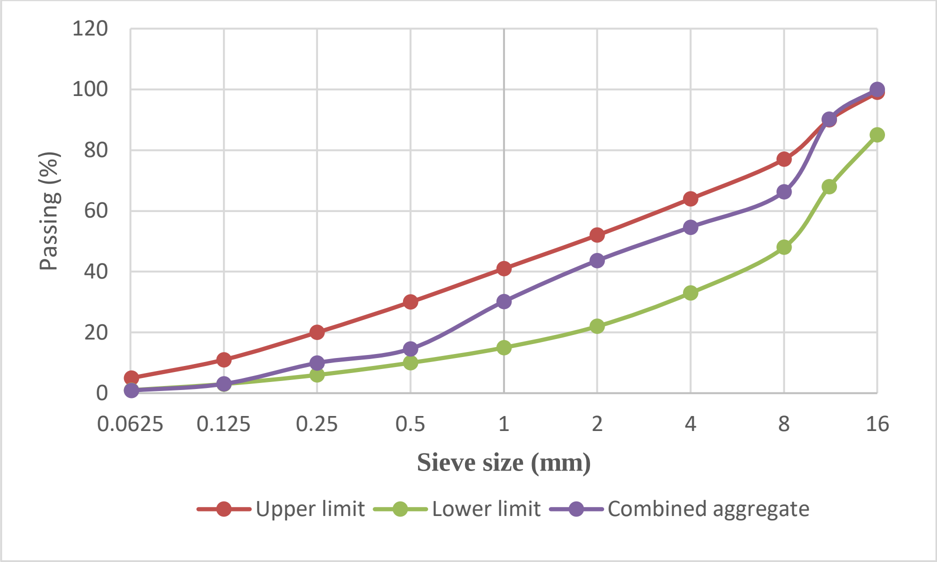


Figure 11. Gradation curve of combined aggregate.

3.2. Binder Preparation

In this study, various binders were explored in different proportions to identify those that yield the highest mechanical properties. The mixtures partially replaced lime and natural hydraulic lime with fly ash type F, fly ash type C, and GGBFS. To ensure a fair comparison, the consistency of the binder pastes was standardized. It is essential to highlight that materials with a low environmental impact were sought, so cement was not included in the studied binder compositions. The binder composition for the hempcrete mixtures is shown in Table 5.

The names of the binder mixtures are based on the weight ratios of their components. For example, Mixture 1 consists of 1 HL, indicating 100% hydrated lime by weight, while Mixture 2 consists of 1 NHL, indicating 100% natural hydraulic lime by weight. Mixture 3, on the other hand, consists of 0.25 NHL (25% natural hydraulic lime) and 0.75 HL (75% hydrated lime) by weight.

Fly ash (Type F and Type C) and GGBFS have amorphous structures that drive their pozzolanic activity. They react with calcium hydroxide ($Ca(OH)_2$) to form calcium silicate hydrate (C-S-H), calcium aluminate hydrates (C-A-H), and calcium alumino-silicate hydrates (C-A-S-H) gel, which are essential for strengthening and binding in concrete.

Table 5. Binder composition for hempcrete mixtures.

	Mixture
1	1 HL
2	1 NHL
3	0.25NHL 0.75HL
4	0.5NHL 0.5HL
5	0.75NHL 0.25HL
6	0.5NHL 0.5FAF
7	0.75NHL 0.25FAF
8	0.5HL 0.5 FAF
9	0.75 HL 0.25FAF
10	0.25 NHL 0.5 HL 0.25 FAF
11	0.5 NHL 0.25HL 0.25 FAF
12	0.75NHL 0.15HL 0.1 FAF
13	0.25 HL 0.75 GGBFS
14	0.5HL 0.5 GGBFS
15	0.75 HL 0.25 GGBFS
16	0.75NHL 0.25 GGBFS
17	0.5HL 0.5 FAC
18	0.75 HL 0.25 FAC
19	0.75NHL 0.25 FAC
20	0.25 NHL 0.5 HL 0.25 GGBFS

Natural hydraulic lime is used in hempcrete to enhance its setting time and strength gain. In addition to the benefits mentioned above, pozzolans like FAC, FAF, and GGBFS are added to reduce the amount of natural hydraulic lime required.

Three different reactions occur during the hardening of the hydraulic lime-based mix. The first is mainly the hydration of tricalcium silicate C_3S and dicalcium silicate C_2S to form calcium silicate hydrate C-S-H and calcium hydroxide ($Ca(OH)_2$), also called pure lime or Portlandite as shown in equations (3.1) and (3.2). The second is the pozzolanic reaction between pure lime and pozzolan, which forms additional calcium silicate hydrates, as shown in equation (3.3).

The last reaction consists of the carbonation of the pure lime to form calcium carbonates (Nozahic et al. 2012), as shown in equation (3.4). The hydration of the binder is responsible for the early setting time and hardening, while the carbonation reaction is a long-term process that takes several months to complete. The pozzolanic reaction is responsible for gaining strength in the long term.

$$\mathrm{C_3S} + \mathrm{H_2O} \rightarrow \mathrm{CSH} + \mathrm{Ca(OH)_2} \tag{3.1}$$

$$\mathrm{C_2S} + \mathrm{H_2O} \rightarrow \mathrm{CSH} + \mathrm{Ca(OH)_2} \tag{3.2}$$

$$\text{Pozzolan} + Ca(OH)_2 + H_2O \rightarrow CSH \tag{3.3}$$
$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \tag{3.4}$$

The amount of water needed to achieve standard consistency was determined for each binder mix using a flow table test, as shown in Figure 12A. The test consists of a table made of bronze with a diameter of 254 mm. The conical mold, made of brass, has a 100 mm base diameter, 70 mm top diameter, and 50 mm height. This test involves filling a conical mold with the binder mixture, compacting it into two layers with a tamper, and removing the mold, as shown in Figure 12B. The flow table is then dropped 25 times over 15 seconds to measure the spread of the mixture, as shown in Figure 12C. The flow was monitored by recording the percentage increase in diameter from the initial to the final measurements after compaction. The flow was fixed at 150 mm following the stringent requirements of TS EN 459-2 (Turkish Standards Institute 2011).

Figure 12. Flow table test: A) Flow table, B) Filling the mold with binder, C) Measuring the flow.

Each binder mix was then cast into steel prisms with dimensions of 40 × 40 × 160 mm, with three replicates for each mixture. The paste prisms were cured in the air at room temperature, about 20°C ± 5°C. The mechanical properties were assessed through compressive and flexural strength tests at 3, 7, 28, and 90 days. The flexural strength test was conducted first on the prisms, followed by compressive strength tests on the remaining portions. The binder that demonstrated the highest performance in these crucial tests was selected as the most suitable for producing hempcrete.

3.3. Hempcrete Specimen Preparation

Hempcrete specimens are prepared by proportioning hemp shiv, binder, and water, followed by sieving the shiv for uniformity and thorough mixing of the components. The mixture is then cast into molds and cured under controlled conditions to ensure proper hydration and carbonation.

3.3.1. Mixture Proportions

Ten different hempcrete mixtures were prepared, with three of these mixtures repeated for comparison purposes to explore the influence of binder composition, hemp shives particle size, hemp : binder ratio, and hemp : water ratio on the density, compressive strength, thermal conductivity, and capillary water absorption of hempcrete specimens. The mixture proportions used in this study are shown in Table 6.

The effect of binder composition was investigated on mixture numbers 1, 2, 3, and 4. For example, mixture 1 consists of 75% natural hydraulic lime, 15% hydrated lime, and 10% fly ash type F while keeping the hemp aggregate size, hemp : binder ratio, and hemp : water ratio constant to compare the effect of binder composition. Coarse hemp shives were used in these mixtures. The hemp : binder and hemp : water ratios were 1:3 and 1:2.5, respectively.

The effect of hemp shive aggregate size was investigated on mixture numbers 5, 6, and 7 produced using three different hemp shives: coarse, medium, and fine. The binder composition, hemp : binder ratio, and hemp : water ratio were kept constant to ensure a fair comparison of the effect of hemp shive particle size. The binder composition consists of 75% natural hydraulic lime, 15% hydrated lime, and 10% fly ash type F. The hemp : binder ratio and hemp : water ratio were 1:3 and 1:2.5, respectively.

The effect of the hemp : binder ratio was investigated on mixtures 8, 9, and 10 produced by using three hemp : binder ratios: 1:2, 1:3, and 1:4. The binder composition, hemp shive size, and hemp : water ratio were kept constant to ensure a fair comparison of the effect of the hemp : binder ratio. The binder composition consists of 75% natural hydraulic lime, 15% hydrated lime, and 10% fly ash type F. Medium hemp shives were used, and the hemp : water ratio was 1:2.5 in these mixtures.

The effect of hemp : water ratio was investigated on mixtures number 11, 12, and 13 produced by using three hemp : water ratios: 1:2, 1:2.5, and 1:3. The binder composition, hemp shive size, and hemp : binder ratio were kept constant to ensure a fair comparison of the effect of the hemp : water ratio. The binder composition consists of 75% natural hydraulic lime, 15% hydrated lime, and 10% fly ash type F. Coarse hemp shives were used, and the hemp : binder ratio was 1:3 in these mixtures.

Table 6. Mixtures used in this study.

Mix	**Binder composition**	**Hemp shive size**	**Hemp : Binder**	**Hemp : water**	**Explanation**
1	0.75NHL 0.15HL 0.1 FAF	coarse	1 : 3	1: 2	Effect of binder composition
2	0.75NHL0.25GGBFS				
3	0.75NHL0.25FAC				
4	0.75GGBFS 0.25HL				
5	0.75NHL 0.15HL 0.1 FAF	Coarse	1 : 3	1: 2.5	Effect of hemp shive size
6		Medium			
7		Fine			
8	0.75NHL 0.15HL 0.1 FAF	Medium	1 : 2	1: 2.5	Effect of hemp : binder
6			1 : 3		
9			1: 4		
1	0.75NHL 0.15HL 0.1 FAF	Coarse	1 : 3	1: 2	Effect of hemp : water
5				1: 2.5	
10				1 : 3	

3.3.2. Sieving

Most hemp shives show characteristics of flaky and elongated aggregates, which result from their fibrous structure. Compared with conventional aggregates with a relatively uniform and compact shape, hemp shives are irregular and slender, influencing their behavior and performance in composite mixes. Therefore, sieve analysis is only a preliminary or approximate method for classifying the shives. It provides an initial estimate of the particle size distribution; still, it does not take into proper account their specific shape and texture. This distinction is crucial in their application in composite materials since the geometry of the shives can significantly affect packing density, workability, and mechanical properties.

The hemp shives were sieved using four different-size sieves (1mm, 2mm, 4mm, and 8mm), as shown in Figure 13, and classified as fine, medium, or coarse. The hemp length ranges from 1 to 30mm, with a width of 1 to 8mm. The hemp that passed through the 8mm sieve but remained on 4mm is called coarse hemp shive. The hemp that passed through the 4mm sieve and remained on the 2mm sieve is called a medium hemp shive. Similarly, hemp that passed through the 2mm sieve and remained on the 1mm sieve is termed fine hemp shive. The remaining that passed the sieve 1mm is considered dust hemp resulting from the shredding process of the hemp stalk.

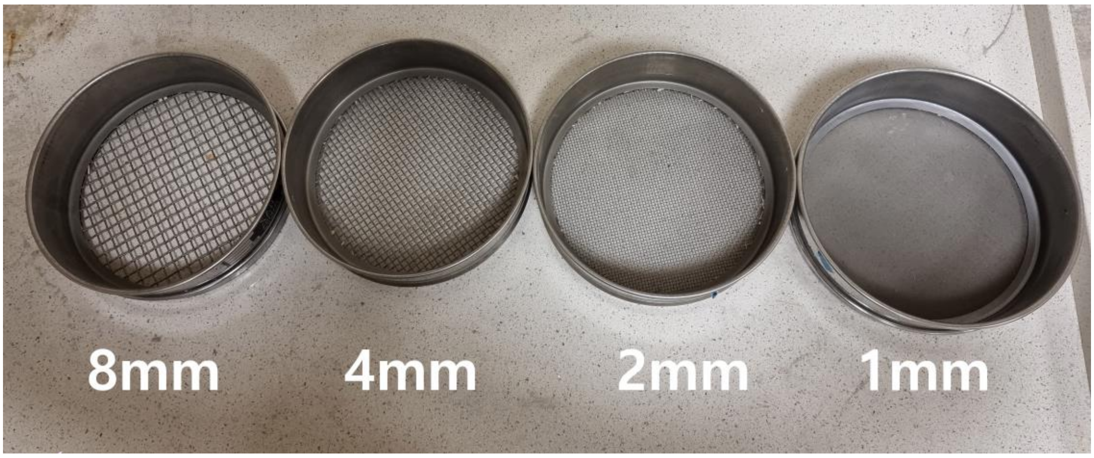


Figure 13. The sieves used in the research.

3.3.3. Mixing, Casting, and Curing

When the binder paste is added to the hemp shives during mixing, the shives absorb water, gradually reducing the mix's workability. Hemp shives compete with the binder for water during curing. This competition can affect the amount of water available for proper binder hydration, subsequently negatively impacting the hempcrete's performance (Walker and Pavia 2014). Hemp shives can absorb large amounts of water. As a result, the shives take up most of the water added to hempcrete, leading to excessively long settings and drying times (Elfordy et al. 2008).

The order of mixing hempcrete ingredients differs in the literature. Some researchers added water to hemp shives (pre-wetting) before adding a binder to the mixture (Cerezo 2005; T. T. Nguyen 2010), while others added water to the binder to create a slurry before adding the hemp shives to the mix (Hirst et al. 2010; Gourlay and Arnaud 2010; Williams, Lawrence, and Walker 2018). The purpose of pre-wetting the hemp shives is to ensure that they remain water-saturated throughout the compaction process, allowing the excess water released to be available for binder hydration (Picandet et al. 2015). Walker and Pavia (2014) found that prewetting hemp shives did not improve the properties of hempcrete. Moreover, it increased the water demand of the mixture. The slurry method was adopted in this study.

The mixtures were prepared using a pan-type concrete mixer to ensure a uniform blend of the hemp and binder, as shown in Figure 14. First, about 50 % of the mixing water was added to the binder and mixed for two minutes. Then, the hemp shives and the rest of the water were added to the bowl and mixed for five minutes. The ingredients were mixed thoroughly until a homogeneous mixture was obtained. Pre-mixing the binder with water before adding it to the hemp shives created a more workable and homogeneous material in hempcrete production (de Bruijn et al. 2009).

Figure 14. A pan-type concrete mixer used for mixing hempcrete.

The total duration of mixing was seven minutes. After mixing, the mixture was immediately cast into a wooden mold containing three 100 mm cubes, as shown in Figure 15, in three layers; each layer was tamped 25 times with a square steel rod.

Figure 15. The molds used for casting hempcrete specimens.

After casting the hempcrete specimens, they were covered with polyethylene sheets to prevent moisture loss. The specimens were de-molded after 48 hours to ensure a sufficient setting and prevent any damage that could occur when they were removed from the molds. Then, they were stored in the curing room, as shown in Figure 16 and subjected to ambient curing at 22±2 °C and relative humidity of 60±5 % for 28 days. Then, oven drying was performed because it is impossible to eliminate all the water in the specimens with open-air drying.

Figure 16. Hempcrete specimens in the curing room.

3.4. Tests on Binder

The binder was tested for compressive and flexural strength to evaluate its mechanical performance. Compressive strength tests indicated a binder's ability to resist axial loads, while flexural strength tests showed its ability to resist bending forces. This testing is crucial to determine whether the binder can be used with hempcrete mixtures.

3.4.1. Flexural Strength Test

The flexural strength was determined following TS EN 1015-11 standards (Turkish Standards Institute 2020) using the testing machine shown in Figure 17. A three-point bending test was conducted on three prisms from each mixture, with a loading rate of 50 N/s and a span of 100 mm. The load was applied until failure occurred, causing the specimen to fracture into two halves. These halves were then preserved for subsequent compressive strength testing.

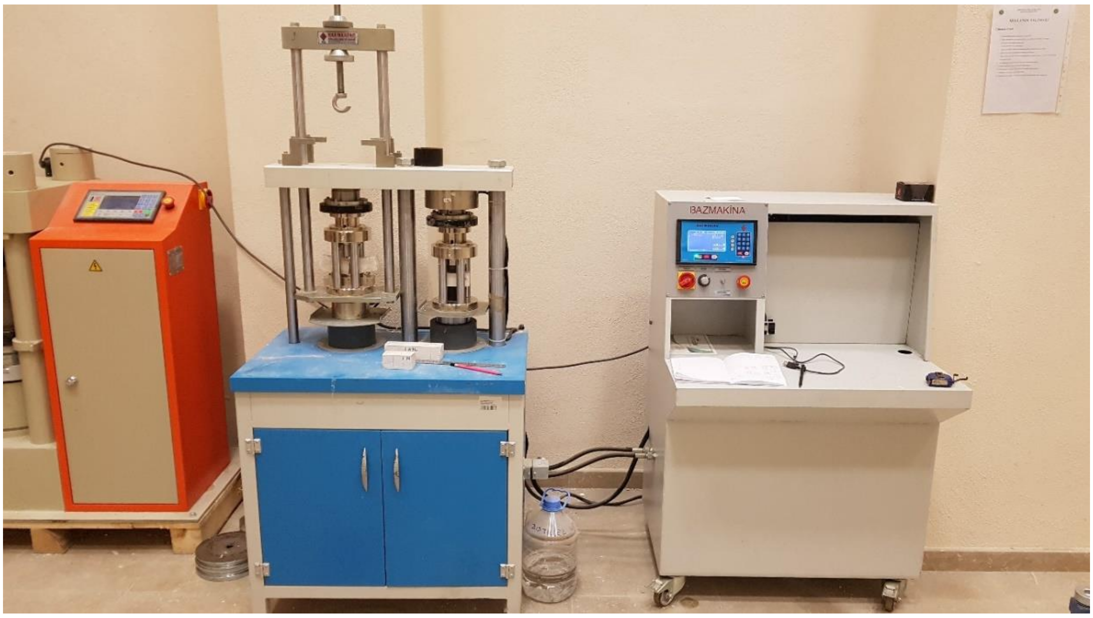


Figure 17.The testing machine used for evaluating the binder paste.

3.4.2. Compressive Strength Test

The compressive strength was also determined following EN 1015-11 standards (Turkish Standards Institute, 2020). The compressive strength test was conducted on the six half prisms remaining from the three-point bending flexural strength tests, as illustrated in Figure 18. The test was performed at a loading rate of 500 N/s, with the load applied at the center of each prism.

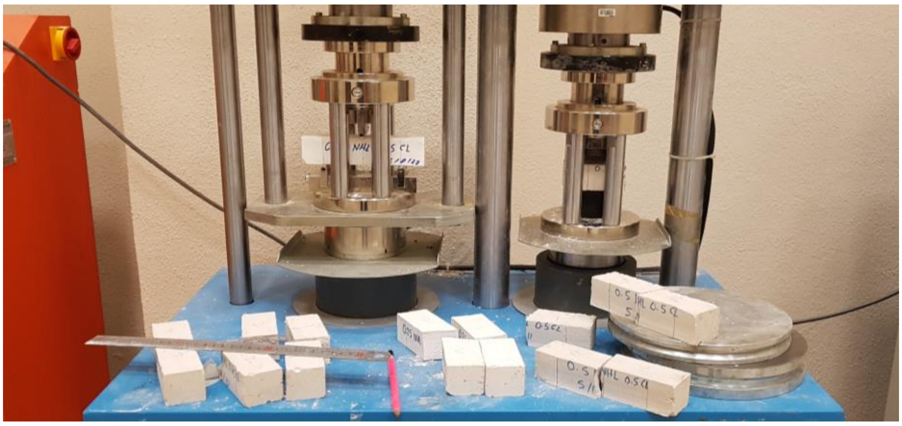


Figure 18. Testing the compressive strength of specimens remaining from the flexural strength test.

3.5. Tests on Hemp Shives

Characterization tests of hemp shives, such as bulk density, initial water content, and water absorption, were conducted to better understand the results obtained. The tests on hemp shive particles conform to RILEM recommendations for characterizing hemp shive (Sofiane Amziane et al. 2017). It is performed on the classified coarse, medium, and fine hemp shive to analyze the physical characteristics that affect the performance and workability of hempcrete. The tests are repeated three times for each particle size of hemp shive.

3.5.1. Initial Water Content

To determine the initial water content of aggregates, weigh them both before and after drying. First, the sampling procedure involves obtaining an equal amount of hemp shive in the opposite quadrant to obtain a sample. Then, a minimum of 50 grams of hemp shive is required to weigh the initial mass (Mo). The hemp is dried at 60°C until it reaches a consistent mass (less than 0.1% variation over 24 hours). The dry mass is measured after drying the hemp shive in the oven for at least 24 hours (Md). Finally, the initial water content is calculated using the equation (3.5):

$$W = \frac{Mo - Md}{Md} * 100 \tag{3.5}$$

3.5.2. Water Absorption

The water absorption is measured by drying hemp shives in an oven initially, and their water content is then determined at various immersion times to measure water absorption, as shown in Figure 19. First, the sample was divided into 4 quadrants for the sampling procedure. An equal amount of hemp shive is obtained from opposite quadrants to create a new sample. This ensures a representative sample that accounts for potential variations in the hemp shive. A sample of 200 grams of hemp shive is dried at 60°C until a constant mass is achieved, with a change of less than 0.1% observed over 24 hours. The dried hemp is then transferred to a sealed bag until it reaches equilibrium at room temperature.

A synthetic porous bag with perforations around 1 mm^2 is immersed in water, ensuring a thorough wetting process. The wet bag is placed into a "salad spinner" and rotated 100 times at approximately two rotations per second. The weight of the bag is then measured.

Next, 25 grams of hemp shive is weighed (M_0) and placed into the bag. The shive bag is immersed in water for 1 minute and then spun in the "salad spinner" 100 times at approximately two rotations per second. The bag is weighed again, and the value is recorded as M (1 min).

This process is repeated with the same sample at different immersion times: 15, 240, 1440, and 2880 minutes. Finally, the Initial Rate of Absorption (IRA) is determined for the specified immersion times. The slope of the curve is then plotted as a function of logarithmic time.

Figure 19. Water absorption test of hemp shives.

3.5.3. Dry Bulk Density

To measure the dry bulk density, the hemp shive is dried in an oven at 60°C for at least 24 hours until a constant mass is achieved. After drying, the hemp shive is transferred to a sealed bag to reach room temperature. A cylindrical container with a diameter of 10 cm and a height of 20 cm is used, following the RILEM recommendation (Sofiane Amziane et al. 2017), which states that the container's width should be at least 10 cm, ensuring the container is large enough compared to the particle size, and the height should be at least twice the container's width as shown in Figure 20.

This cylinder is half-filled with the dried hemp shive, and the weight of the hemp particles is recorded. After filling the cylinder with hemp shive, it should be shaken vertically ten times with precision. This step is crucial for achieving uniformity in the hemp shive. A cardboard disc is then used to level the surface horizontally. The new level of the hemp particles is marked.

The hemp shive is emptied from the cylinder, and then the cylinder is filled with water up to the marked level to determine the volume occupied by the hemp particles. The bulk density of the hemp shive is calculated using the equation (3.6):

$$\text{Bulk density} = \frac{\text{Mass of hemp particles}}{\text{The volume of hemp particles}} \tag{3.6}$$

Figure 20. Dry bulk density test of hemp shives.

3.6. Tests on Hempcrete

All tests on hempcrete were conducted in triplicate for each mixture, with the presented results representing the mean value. The tests were performed on 10 cm cube specimens at 28 days to ensure that the binder had reached a considerable degree of maturity, with much of the hydration and carbonation processes completed, as these processes influence the porosity of the hempcrete. However, compressive strength was tested at 28 days and 180 days. The specimens were dried in an oven at 60°C for 48 hours before testing. This was done to achieve a constant weight and dry specimen, a necessary condition before performing the dry density, compressive strength, thermal conductivity, and capillary water absorption tests. The oven-drying process minimizes the influence of moisture, which can distort these measurements. This sequence of testing was followed to ensure accurate and reliable results.

3.6.1. Dry Density

The dry weight is measured after drying the cubes for 48 hours in an oven at 60°C and divided by the volume of cubes, as shown in Equation (3.7). The test was conducted according to the TS EN 12390-7 standards (Turkish Standards Institute 2010).

$$\text{Bulk density} = \frac{\text{Mass of hempcrete speciemens}}{\text{The volume of hempcrete specimens}} \tag{3.7}$$

3.6.2. Mechanical Behavior

Before testing the compressive strength of hempcrete, the specimens were oven-dried at 60°C for 48 hours, as recommended in the study by Arnaud and Gourlay (2012) and Niyigena et al. (2016). This procedure was followed to prevent saturation water from disrupting the measurement of mechanical properties.

First, the compressive strength test was conducted on a load-controlled testing machine typically used for traditional concrete. However, the results were not precise because the load increased suddenly with the collapsed specimen, making it difficult to determine its failure. Moreover, the testing machine only provided a curve showing the increase in load over time. For these reasons, the specimens were subsequently tested on the displacement-controlled testing machine to give precise results and better analyze the specimens' behavior. Compressive tests are conducted using a Shimadzu AG-I 250kN testing machine in the Materials Research Center at Izmir Institute of Technology, as shown in Figure 21.

The Shimadzu AG-I 250kN is a displacement control device that applies load at a controlled rate. The tests are conducted to determine hempcrete's load-bearing capacity. The loads and displacements were measured during the testing of the specimens. The load is applied at a rate of 0.5 mm/min. The test was carried out according to TS EN 12390-3 standard (Turkish Standards Institute 2010).

Figure 21. Compressive strength test of hempcrete specimens.

During testing, the testing machine generated the load-displacement curve of hempcrete. Subsequently, the curves were smoothed using MATLAB software to enhance its clarity and accuracy.

Unlike conventional materials, hempcrete exhibits a progressive transition from elastic (reversible) behavior to plastic (irreversible) compaction under stress. The initial portion of the curve, where stress and strain are proportional. Then, when the material starts deviating from linearity, the onset of plastic deformation is indicated. Later, the plateau (in the case of load applied parallel to hemp shives orientation) or gradual slope increase (in the case of load applied perpendicular to hemp shives orientation) represents material densification.

To compare the compressive strength of the samples, the maximum stress recorded for each sample at a strain of 15% was used to determine the compressive strength values, as shown in Table 8. This strain value of 15% was chosen to align with previous studies on hempcrete, which used it as a benchmark for evaluating compressive stress. For example, in studies by Page et al. (2017), hempcrete's behavior and compressive strength were compared in parallel and perpendicular orientations to the hemp shives at 13% strain.

The study by Nguyen et al. (2010) mainly focused on the material's mechanical properties when under moderate strains, as high as 15%, which are most applicable for structural applications. While the strain magnitude is enormous for traditional building materials, it may be favorable for lightweight structures or special designs where a material's ductility may be advantageous. Similarly, another study by Nozahic et al. (2012), Sheridan et al. (2017), and Williams et al. (2018) used 20% strain to evaluate hempcrete's behavior and compressive strength in the same orientations. Sheridan et al. (2017) recorded the strength of the samples at 5% strain to determine serviceability limits. Hussain et al. (2019) analyzed the behavior of hempcrete composites at different strain levels (0%, 10%, 50%, and after testing). They observed that as the strain increased, the materials became more compact due to further densification. None of the composites failed at 60% strain, indicating strong interfacial bonding between the hemp shiva and the matrix.

Identifying compressive strength in the perpendicular direction, particularly concerning compacting behavior, is not universally agreed upon. In the wood industry, compressive strength is often defined as the stress corresponding to 10% strain. However, in Mazhoud, Collet, and Lanos (2017) study, compressive strength in the perpendicular direction is understood as where the material transitions from reversible to compacting behavior. This is identified as the stress at which a change in the slope occurs on the stress-strain curve.

Four sets of specimens were cast, each consisting of three specimens. One set was tested with the load applied parallel to the hemp shives orientation and another with the load applied perpendicular to them at 28 days as illustrated in Figure 22. The other two sets will be tested with the load applied parallel and perpendicular to the casting direction at 180 days.

When the load was applied perpendicular to the orientation of the hemp shives, it was directed onto the casting surface of the hempcrete cubes. To ensure flat, parallel end surfaces and promote even distribution of the applied load, rapid-hardening plaster was used to cap both the casting surface and the opposite surface of the hempcrete cubes, ensuring reliable compression testing results.

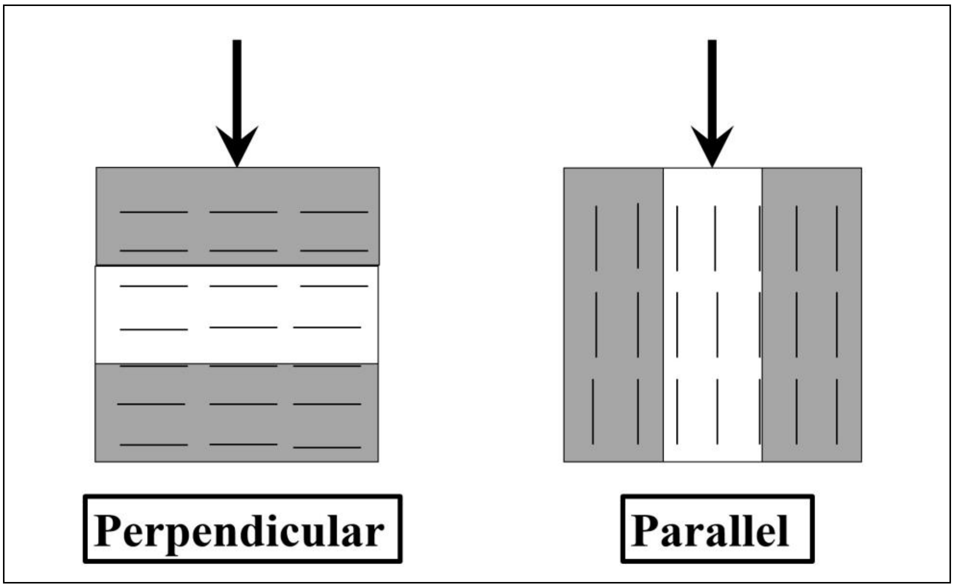


Figure 22. Application of load parallel and perpendicular to the hemp shives' orientation.

The energy absorption is calculated by determining the area under the stress-strain curve. After obtaining the force and displacement data from the testing machine, the force is converted to stress by dividing it by the specimen's cross-sectional area (10,000 mm^2). Similarly, the displacement is converted to strain by dividing it by the specimen's height (100 mm). The stress-strain curve is then plotted using MATLAB software, and the area under the curve is calculated.

3.6.3. Thermal Conductivity

The thermal conductivity test was conducted on three 100 mm cube hempcrete specimens for each mixture. It was performed using a KEM QTM 500-type thermal conductivity tester in the Materials Research Center at Izmir Institute of Technology, as shown in Figure 23. It quickly and easily measures the thermal conductivity of many materials, such as insulating materials, ceramics, bricks, plastic, concrete, etc. The device is based on the hot wire method as described in ASTM C1113/C1113M-09 (ASTM, 2013), which measures thermal conductivity based on the temperature rise in a wire heated by an electric current and the resulting heat flux into the material.

Compared to steady-state methods like the hot plate, the main advantage of this method is that it is a transient method, which limits or prevents water migration during testing (Hladik 1990). This makes it proper to study the impact of water content on thermal conductivity. However, the method has some limitations. It only provides local measurements and requires multiple measurements to ensure that the results represent the material's thermal conductivity well. Additionally, it does not consider geometric layouts of blocks with cavities or designed channels that will significantly impact heat transfer effectiveness. Therefore, it is appropriate only for the preliminary assessment of material but possibly does not sufficiently represent the thermal behavior of more geometrically complex blocks.

The specimens were tested three times from both sides of the specimens. This type of device measures between 0.023 and 12 W/mK with 5% precision. The measurements were performed in the laboratory's climatic room at a temperature of 25 ± 2 ◦C and a relative humidity of 50 ± 5 %. The specimen is placed on the test platform, and the sensor probe is placed on its top surface. The measurement results will appear on the display screen within one minute.

The device's rapid measurement capability allows for efficient testing of multiple specimens in a relatively short period, making it ideal for comparative studies. While the instrument has some limitations, its ability to provide quick and accurate results makes it a valuable tool for determining the thermal performance of eco-friendly building materials such as hempcrete.

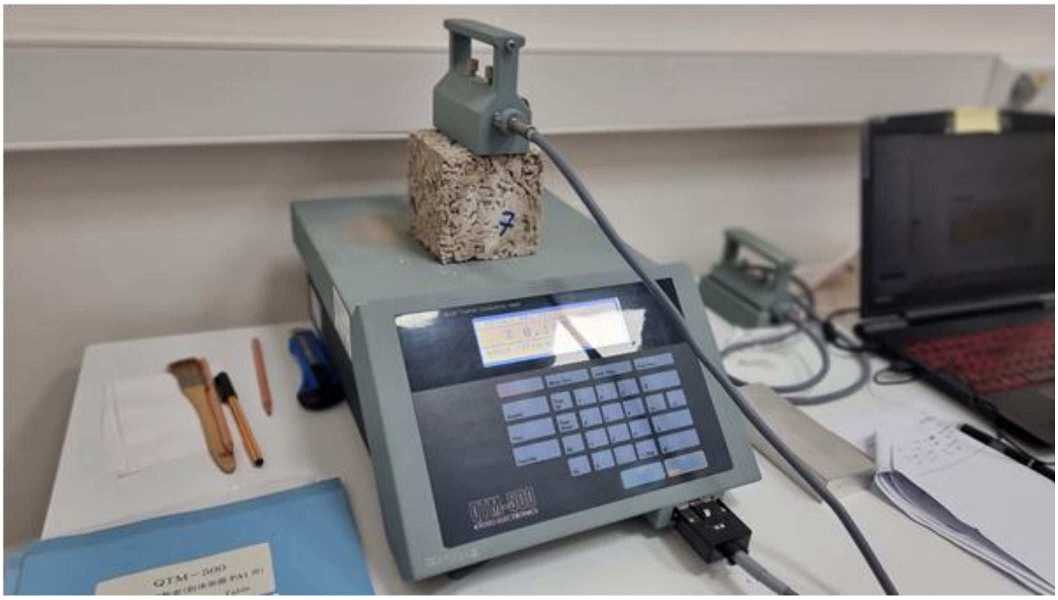


Figure 23. Thermal conductivity test of hempcrete specimens.

3.6.4. Capillary Water Absorption

This test aims to simulate water's movement through a hempcrete masonry wall, evaluating its resistance to water penetration and performance in moist environments. The test complied with the TS EN 1925 standard (Turkish Standards Institute 1999). Since no established standards exist for hempcrete or similar materials using plant aggregates, the test was performed according to the previously mentioned standard, which was adjusted to adapt to hempcrete. The test was conducted on three 100 mm cube hempcrete specimens for each mixture. A waterproof tape is applied to all cube surfaces except one, which is then immersed in water, as shown in Figure 24. Only one surface is exposed to water, while the other sides are sealed. The specimen is placed in flat plastic containers, securely supported by wood bars, to ensure water absorption on the underside of the specimen. Then, the container is filled with water until the water level is 10 mm above the bottom of the hempcrete specimens. The water level is maintained at 10 mm throughout the test. The weight of the specimens is regularly recorded at time intervals (1, 15, 30, 60, 120, 240, 360, 1440, 2880, 4320, etc. in minutes). The duration of the test was 7 days. The mass gain of the specimens is plotted against the time. The initial linear portion of this plot represents the capillary water absorption phase. The water absorption coefficient measures water sorption as a function of the specimen's surface area and time. The water absorption coefficient is the slope of the linear portion of the plot, commonly expressed in $kg/m^2hr^{0.5}$.

Figure 24. Capillary water absorption of hempcrete specimens.

3.6.5. Impact Test

Impact tests indicate a material's toughness. Toughness is the ability of a material to absorb energy and plastically deform without fracturing or the amount of energy per unit volume that a material can absorb before rupturing.

ACI 544.2R-89 (ACI 1989), titled "Measurement of Properties of Fiber-Reinforced Concrete," includes impact resistance tests for fiber-reinforced concrete through various tests such as the drop weight impact test. Impact tests by this drop weight test represent one of the standard methods for evaluating the performance characteristics of concrete materials and their structural responses to impact loading.

The method recommended by ACI 544.2Rs is considered one of the simplest impact tests. However, specific standards for testing hempcrete under impact loads may not yet exist, as hempcrete is a relatively newer material in structural applications. Impact test, though, could be adapted for hempcrete. Therefore, the impact resistance test was adjusted to fit the properties of hempcrete and evaluate how the material performs when subjected to impact loads.

The experimental frame system was set up in the Structural Laboratory at Izmir Institute of Technology. The impact test setup is shown in Figure 25. The test involved dropping a 15 kg free cylindrical weight from 30 cm and 100 cm heights onto the top center of a hempcrete specimen. The hempcrete specimen was placed on a 60 cm long reinforced concrete beam with a cross-section measuring 15 cm in width and 8 cm in thickness. Based on the dimensions of the reinforced concrete beams and the drop weight, the dimensions of the hempcrete blocks were chosen as 150 mm length, 150 mm width, and 100 mm thickness.

Figure 25. Impact test.

Reinforced concrete beams were cast using C25/30 grade concrete. The concrete mix design is shown in Table 7. To resist flexure, the beams were reinforced with two 8 mm diameter bars at the bottom. The concrete was mixed for 10 minutes in a pan-type mixer and vibrated into oiled steel molds.

Table 7. Mix proportions for reinforced concrete beam.

Mix ratio by weight	W/C	Fine aggregate	Coarse aggregate	Cement	Water
1 : 2 : 2	0.5	851.9 kg/m^3	851.9 kg/m^3	424 kg/m^3	212 kg/m^3

The molds were then covered with polyethylene sheets for one day to prevent moisture loss. Afterward, the specimens were removed from the molds and stored in a curing room until they were tested. Two different hempcrete mixtures were prepared to investigate the behavior of hempcrete under impact loading. A Linear Variable Differential Transformer (LVDT) was placed at the bottom of the concrete beam to measure displacement, and two accelerometers were attached to the falling mass to measure the acceleration data. The impact test illustration is shown in Figure 26.

In this study, hempcrete mixtures were prepared by combining hemp shives, binders (such as hydrated lime, natural hydraulic lime, and pozzolan), and water in specific ratios. The mixing procedure was followed by casting the mixtures into molds and allowing them to cure for 28 and 180 days, depending on the specific test. After curing, the specimens underwent various tests, including density, compressive strength, thermal conductivity, and water absorption.

Additionally, certain hempcrete mixtures were selected to test their ability to absorb energy and protect the underlying reinforced concrete beam when a load was applied to the hempcrete blocks placed on top of the beams. The entire experimental process is outlined in the flow chart shown in Figure 27**,** which provides a visual summary of the materials, preparation steps, and testing procedures.

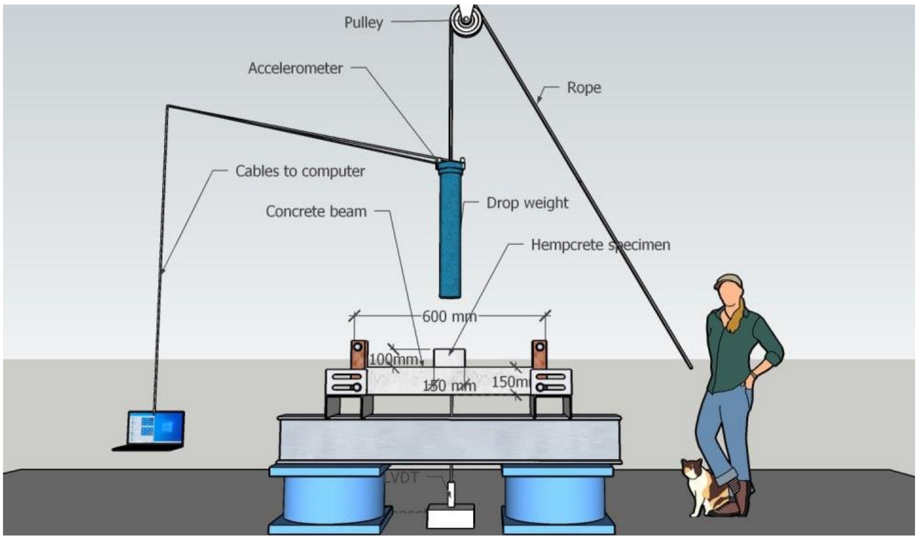


Figure 26. Illustration of the impact test.

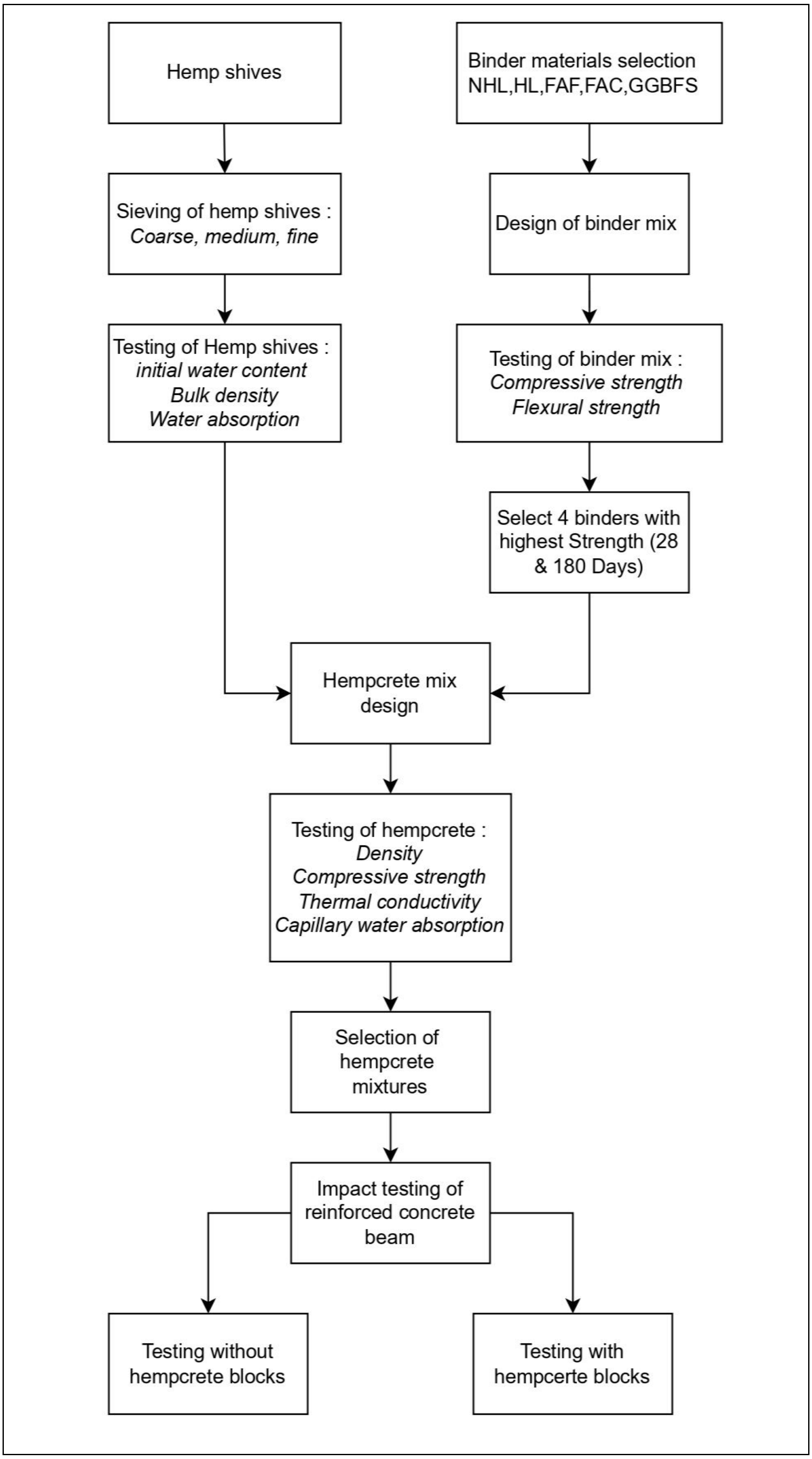


Figure 27. Flow chart of the experimental procedure for preparing and testing hempcrete specimens.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1. Binder

The compressive and flexural strength test results, presented in Table 8, show distinct trends across twenty mix compositions at different curing times (3, 7, 28, and 90 days). These trends highlight the progression of both strength types over time for each composition.

Table 8. Compressive and flexural strength results of binder paste at 28 and 90 days.

	Mixture	W/B	Compressive Strength (MPa)				Flexural strength (MPa)			
			3 days	7 days	28 days	90 days	3 days	7 days	28 days	90 days
1	1 HL	0.7	0.49	0.86	0.81	1.66	0.16	0.23	0.27	0.4
2	1 NHL	0.3	8.61	12.5	15.5	20.0	1.4	1.25	3.55	2.28
3	0.25NHL 0.75HL	0.516	1.64	3.7	4.65	5.31	0.52	0.68	1.02	0.99
4	0.5NHL 0.5HL	0.43	3.75	8.65	13.2	12.28	0.89	1.95	3.2	1.41
5	0.75NHL 0.25HL	0.35	6.93	14.1	14.4	21.86	1.74	3.05	3.32	3.65
6	0.5NHL 0.5FAF	0.33	3.15	6.5	7.05	13.9	0.82	1.01	1.5	2.0
7	0.75NHL 0.25FAF	0.3	5.84	10.04	13.6	16.93	0.95	1.57	2.98	2.15
8	0.5HL 0.5 FAF	0.463	0.81	1.25	6.5	14.1	0.28	0.29	1.7	2.2
9	0.75 HL 0.25FAF	0.505	0.65	0.85	3.72	4.68	0.11	0.29	0.8	1.3
10	0.25 NHL 0.5 HL 0.25 FAF	0.433	1.7	3.96	10.46	12.48	0.73	0.99	1.9	2.57
11	0.5 NHL 0.25HL 0.25 FAF	0.358	3.89	8.54	14.2	16.74	1.07	1.82	3.53	4.1
12	0.75NHL 0.15HL 0.1 FAF	0.342	5.75	13.1	15.7	19.4	1.57	2.3	2.31	3.5
13	0.25 HL 0.75 GGBFS	0.365	4.58	11.38	22.15	26.5	1.357	1.4	2.87	3.67
14	0.5HL 0.5 GGBFS	0.41	2.9	9.5	17.9	18.2	0.94	1.63	3.34	3.54
15	0.75 HL 0.25 GGBFS	0.575	0.64	2.9	9.2	9.4	0.23	0.78	1.88	2.11
16	0.75NHL 0.25 GGBFS	0.276	6.2	19.1	20.0	22.9	1.953	2.24	2.32	3.38
17	0.5HL 0.5 FAC	0.415	0.45	1.2	5.2	7.58	0.25	0.37	1.18	1.6
18	0.75 HL 0.25 FAC	0.515	0.39	0.55	3.5	4.5	0.19	0.4	0.64	1.06
19	0.75NHL 0.25 FAC	0.272	5.09	15.75	21.4	26.3	1.61	2.41	3.09	6.35
20	0.25 NHL 0.5 HL 0.25 GGBFS	0.409	2.21	6.5	13.2	17.0	0.75	1.7	2.4	3.1

4.1.1. Effects of Cementitious Materials on Compressive Strength

The mixtures with higher amounts of natural hydraulic lime (NHL) and ground granulated blast furnace slag (GGBFS) tend to perform significantly better in strength than those with hydrated lime (HL) or Fly Ash type F (FAF) and fly ash type C (FAC). The water binder ratio (W/B) also affects the strength development of the mixtures. The compressive strength of binder pastes at 28 and 90 days is shown in Figure 28.

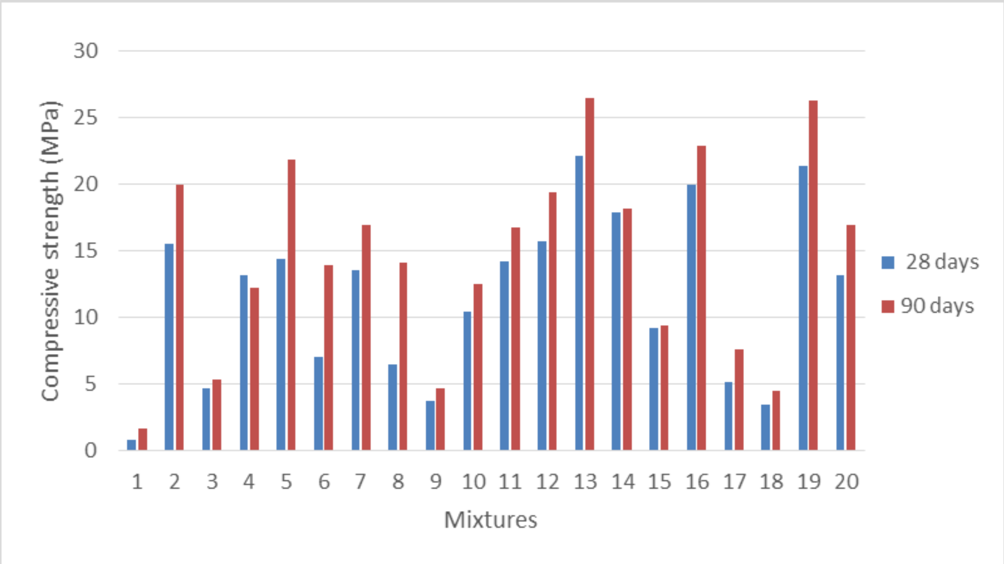


Figure 28. Compressive strength of binder pastes at 28 and 90 days.

Mix 1 with only HL has lower mechanical strength. The compressive strength was 0.49 MPa, 0.86 MPa, 0.81 MPa, and 1.66 MPa at 3 days, 7 days, 28 days, and 90 days, respectively. This is due to the slow strength development of hydrated lime and its weak bonding properties. Although hydrated lime provides excellent workability and known environmental advantages, it requires more time to react with water and gain strength, making it unsuitable for applications requiring early or high compressive strength levels. While Mix 2, which contains only NHL has much higher compressive strength than Mix 1. The compressive strength was 8.61 MPa, 12.5 MPa, 15.5 MPa and 20.0 MPa at 3, 7, 28 and 90 days respectively. This shows the stronger performance of NHL, which reacts more effectively with water and creates a denser matrix as it cures. NHL's ability to develop strength quickly and steadily over time makes it a better choice for structural applications that require both early and long-term compressive strength.

NHL sets much quicker and has higher compressive and flexural strength than hydrated lime. However, hydrated lime is more flexible and breathable, which can benefit applications requiring moisture regulation and some flexibility. Hydrated lime is partially replaced with hydraulic binders such as cement and natural hydraulic lime to decrease the setting time and improve the compressive strength of hempcrete.

NHL was replaced with 75%, 50%, and 25% hydrated lime in mixtures 3, 4, and 5 to enhance flexibility and breathability. However, this replacement decreased compressive strength, and the compressive strength decreased with the increased proportion of hydrated lime. Except for mixture 5, where the compressive strength at 90 days did not follow the trend observed in the other mixtures, it increased by approximately 9% compared with mixture 2.

In Mix 6 and 7, NHL was replaced with 50% and 25% FAF, respectively, to produce a more environmentally friendly binder by reducing the carbon footprint of natural hydraulic lime. However, this replacement decreased compressive strength at 90 days, with reductions of approximately 31% and 15% compared to mixture 2.

To increase HL's hydraulicity, 50% and 25% FAF were replaced with HL in mixtures 8 and 9, respectively. The replacement did not decrease the setting time or increase the compressive strength significantly at the early ages of 3 and 7 days. On the other hand, 50% and 25% FAF replacement increased the compressive strength by 702% and 359% at 28 days and 749% and 182% at 90 days, respectively.

Another combination was investigated using different NHL, HL, and FAF ratios in mixtures 10, 11, and 12. Mixture 12 has a compressive strength similar to mixture 2 but with 25% less natural hydraulic lime. , making it more environmentally friendly than mixture 2.

In Mix 13, 14, and 15, HL is replaced with 75%, 50%, and 25% GGBFS. The compressive strength improved significantly with the increase in the amount of GGBFS. This replacement decreased the setting time by allowing for the earlier removal of specimens from the molds. Mix 13 has the highest compressive strength among all the 20 mixtures at both 28 and 90 days.

The hydrated lime acts as an activator for the GGBFS (Majhi and Nayak 2020). GGBFS is considered more of a latent hydraulic material than a pozzolan because it can hydrate in the presence of water. While it has a self-hydration ability, adding HL to GGBFS can further activate the reaction. In addition to the hydration process, pozzolanic reactions occur when alumina and silica from the GGBFS react with the lime (Regourd and Hewlett 2001).

In mixture 16, replacing NHL with 25% GGBFS improved the compressive strength after 7 days. This replacement increased the compressive strength by 29% at 28 days and 14.5% at 90 days.

To increase HL's hydraulicity, FAC was replaced with HL by 50% and 25% in mixtures 17 and 18, respectively. The replacement did not decrease the setting time or increase the compressive strength significantly at the early ages of 3 and 7 days. When FAC reacts with HL, the reaction is slower and less efficient because HL is non-hydraulic. As a result, the material takes longer to reach full strength due to the slower carbonation process and the lack of strong hydraulic binding. On the other hand, 50% and 25% FAF replacement increased the compressive strength by 542% and 332% at 28 days and 357% and 171% at 90 days, respectively.

The 25% replacement of NHL with FAC in Mix 19 did not increase the strength at 3 days but increased the compressive strength by 26%,38%, and 32% at 7, 28, and 90 days, respectively.

The replacement with FAC increased NHL's compressive strength due to its self-cementing properties and higher calcium content. When FAC is mixed with NHL, the calcium from the NHL interacts with the silica in the FAC to form more C-S-H, which improves the composite material's strength. In comparison, FAF did not increase NHL's compressive strength due to its lower calcium content and reliance on pozzolanic activity.

In Mix 20, a combination of NHL, HL, and FAF ratios was investigated. The compressive strength was higher than in Mix 1 but lower than in Mix 2.

These results align with those achieved by Zúniga, Eires, and Malheiro (2023), who point out that pozzolanic materials perform best when activated with calcium hydroxide. Indeed, this evidences lime's relevance to pozzolanic reactions since it creates favorable conditions for forming extra-binding compounds, such as calcium silicate hydrate, which enhances the material's mechanical properties.

4.1.2. Effects of Cementitious Materials on Water Content in Lime Pastes

Fly ash can increase workability due to its physical properties, such as its small spherical shape and particle size distribution. Replacing NHL with 25% of the FAC reduced the water content by about 9% for the same consistency of 50%. GGBFS also reduced the water content by about 8% due to micro-filling spaces that minimize internal friction among lime paste components. Replacing 15% or 25% of NHL with HL increased the water demand of the mixture. NHL is generally coarser than HL. HL has finer particles with a larger surface area, requiring more water to reach the same workability. HL absorbs water and increases the mixture's water demand. Figure 29 shows the effect of adding cementitious materials to NHL.

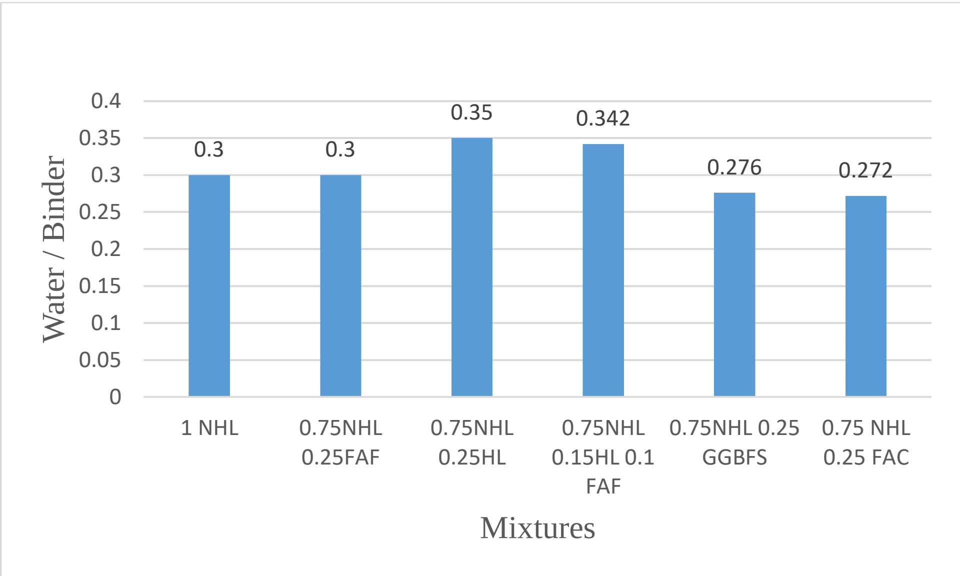


Figure 29.Effect of adding cementitious materials to NHL.

For the same reasons mentioned above, replacing 25% of HL with NHL, FAC, and FAF reduced the water content by about 26%, while GGBFS reduced it by 18% for the same consistency of 50%, as shown in Figure 30. It was found that increasing the percentage of cementitious material replacement reduces the water demand. Reducing water demand as the cementitious material content increased probably contributed significantly to the strength increase.

These results are consistent with those obtained by Walker and Pavia (2010), who replaced lime with different pozzolans, including GGBFS and Pulverised Fuel Ash. The pozzolans lowered the water demand for all lime-pozzolan pastes. Lime-pozzolan pastes' setting times are strongly dependent on their water content; even a slight increase in water content greatly slows down the setting time. They also found that the water demand of hydrated lime paste depends significantly on the pozzolan surface area rather than its particle size and hydrated lime pozzolan ratio.

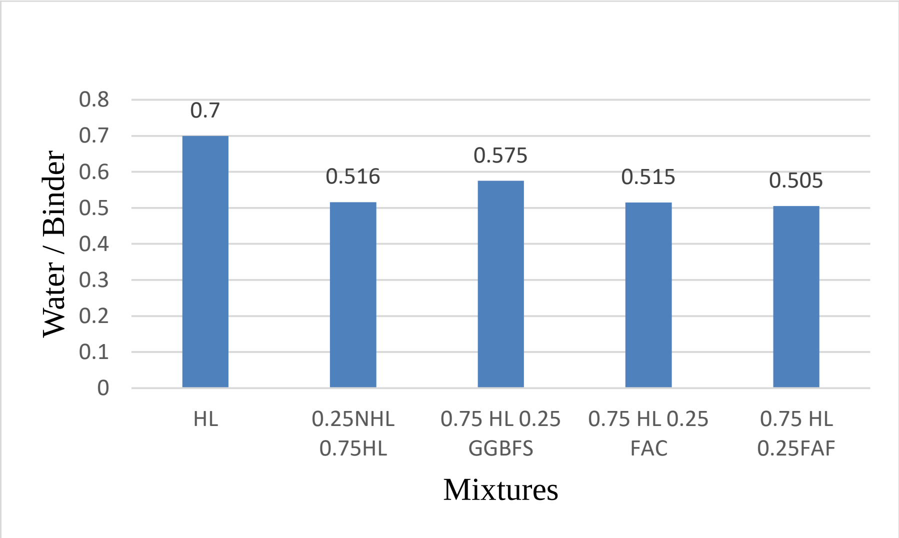


Figure 30. Effect of adding cementitious materials to HL.

4.1.3. Effects of Cementitious Materials on Hardening in Lime Pastes

According to the test results, the mix containing a large amount of hydrated lime exhibits a slow hardening, taking several days. This delay is due to the high concentration of calcium hydroxide ($Ca(OH)_2$) in the hydrated lime, which reacts with water and undergoes carbonation in the presence of carbon dioxide, forming calcium carbonate ($CaCO_3$). In contrast, mixtures with a higher hydraulic binder content, such as NHL, harden much more quickly, typically within a few hours. This rapid hardening is driven by the main components, such as tricalcium aluminate and dicalcium silicate, which react with water to form calcium silicate hydrates (C-S-H), calcium aluminate hydrates (C-A-H), and calcium hydroxide ($Ca(OH)_2$). The addition of natural hydraulic lime and GGBFS speed up the hardening of lime paste.

4.2. Tests on Hemp Shives

Tests were conducted on hemp shives, including measurements of the initial water content, water absorption, and bulk density, all of which significantly affect the overall performance of hempcrete mixtures.

4.2.1. The Initial Water Content Test

The initial water content test measures the natural moisture present in hemp shives. The results are presented in Table 9. The initial water content for fine, medium, and coarse hemp shives was 3.5%, 5.6%, and 4.1%, respectively. Because medium and coarse shives have bigger pore sizes than fine shives, they retain moisture better initially, which could explain their higher initial water contents.

4.2.2. Water Absorption Test

The ability of different dry hemp shives to absorb water is very fast. The initial absorption rates at 1 minute for coarse, medium, and fine hemp shives were 59.6%, 75.2%, and 111.2%, respectively. Water absorption measured after 48 hours of immersion was 233.2%, 242.4%, and 245.6% for coarse, medium, and fine hemp shives, respectively. After four days of immersion, the absorption of medium and fine shives was around 250%, while coarse shives absorbed 236.8%. The results of water absorption of coarse, medium, and fine hemp shives are shown in Table 9. These results demonstrate hemp shiv's high water absorption and retention capacity, attributed to its high porosity and capillary structure, as confirmedin previous studies, such as those by Arnaud and Gourlay (2012).

The variations in absorption between hemp shive particles can be accounted for mainly by particle size and porosity. Large hemp particles like coarse hemp shives have less surface area and absorb less water than small particles like fine hemp shives. A comparison of water absorption of coarse, medium, and fine hemp shives is shown in Figure 31.

4.2.3. The Dry Bulk Density Test

The average dry bulk density values for coarse, medium, and fine hemp shives were 112.3 kg/m³, 96.8 kg/m³, and 105.95kg/m³, respectively. These results indicate that coarse shives have the highest bulk density, while medium shives have a lower density than fine and coarse shives. This unexpected result can be attributed to several factors. Medium shives might have a higher porosity, which means they contain more air spaces and are less compactly packed, thus resulting in lower dry bulk density. Moreover, various sizes of particles in medium shives might also contribute to the packing being ineffective and therefore to the reduced dry bulk density. Consistency in measurement methods is crucial; any discrepancies in sample preparation could affect bulk density results. The results of dry bulk density of coarse, medium, and fine hemp shives are shown in Table 9.

Table 9. Results of the hemp shive tests for coarse, medium, and fine sizes.

	Fine hemp	**Medium hemp**	**Coarse hemp**
Initial water content	3.5%	5.6%	4.1%
Water absorption @ 1 min.	111.2 %	75.2%	59.6%
Water absorption @ 15 min.	159.6%	122%	110%
Water absorption @ 4 hr.	197.2%	173.6%	162%
Water absorption @ 24 hr.	233.2%	227.2%	214%
Water absorption @48 hr.	245.6%	242.4%	233%
Water absorption @ 4 days	250.4%	250%	236.8%
Average Dry bulk density	105.95 kg/m^3	96.8 kg/m^3	112.3 kg/m^3

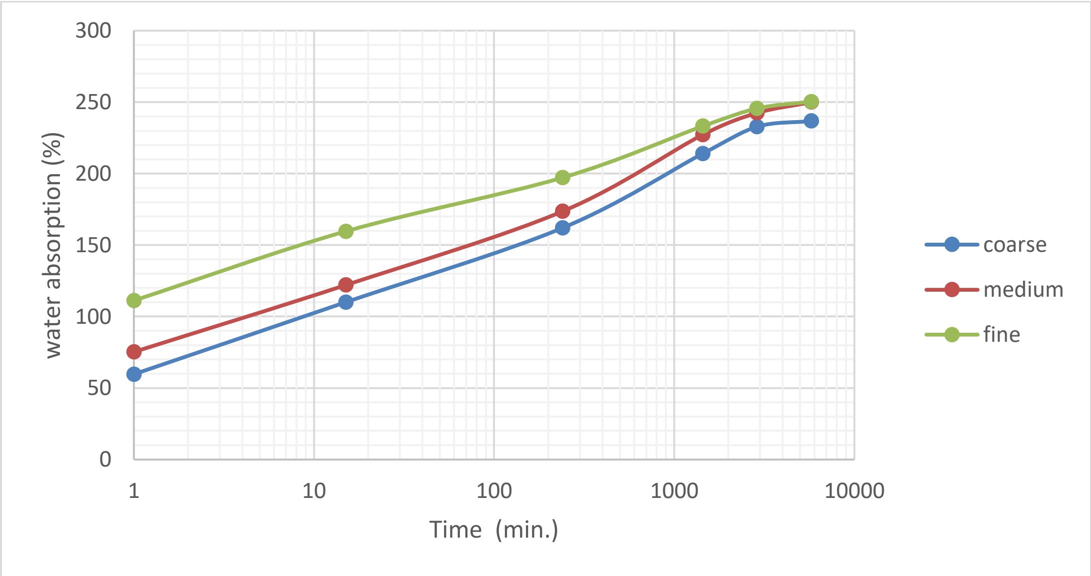


Figure 31. Water absorption of the three hemp shive sizes coarse, medium, and fine.

4.3. Tests on Hempcrete

Tests on hempcrete, including compressive strength, flexural strength, thermal conductivity, impact resistance, and capillary water absorption, assess the material's mechanical, thermal, and moisture properties, helping to evaluate its suitability for construction applications.

4.3.1. Dry Bulk Density

The results of dry density are shown in Table 10. The main factors affecting density are air content, aggregate density, binder, and water content (Page, Amziane, and Sonebi 2015).

Table 10. Results of bulk density, compressive strength, thermal conductivity, and water absorption of hempcrete.

Mix	**Binder composition**	**Hemp shive size**	**Hemp : Binder**	**Hemp: water**	**Dry bulk density (kg/m^3)**	**Thermal conductivity (W/m·K)**	**Compressive strength (MPa.) Parallel to fiber direction**	**Compressive strength (MPa.) perpendicular to fiber direction**	**Water absorption ($kg/m^2 h^{0.5}$)**
1	0.75NHL 0.15HL 0.1 FAF	coarse	1 : 3	1: 2	595	0.188	0.392	0.547	2.673
2	0.75NHL0.25GBFS				585	0.185	0.316	0.447	2.812
3	0.75NHL0.25FAC				576	0.186	0.287	0.433	2.863
4	0.75GGBFS 0.25HL				605	0.194	0.405	0.519	3.174
5	0.75NHL 0.15HL 0.1 FAF	Coarse	1 : 3	1: 2.5	615	0.192	0.340	0.469	2.870
6		Medium			628	0.194	0.352	0.884	3.050
7		Fine			685	0.214	0.273	0.568	3.285
8	0.75NHL 0.15HL 0.1 FAF	Medium	1 : 2	1 : 2.5	420	0.142	0.202	0.364	3.094
6			1 : 3		628	0.194	0.352	0.884	3.05
9			1: 4		700	0.212	0.422	1.119	2.598
1	0.75NHL 0.15HL 0.1 FAF	Coarse	1 : 3	1: 2	595	0.181	0.392	0.547	2.673
5				1: 2.5	615	0.192	0.340	0.469	2.870
10				1 : 3	574	0.189	0.225	0.371	3.27

For the various mixes, dry bulk density varied from 441 to 700 kg/m^3. The results of dry density are shown in Figure 32. The obtained hempcrete dry density falls within the range reported in the literature. In a review article by Ahmed et al. (2022), hempcrete dry density can range from 200 to 800 kg/m^3, making it suitable for walls, flooring, and roof insulation.

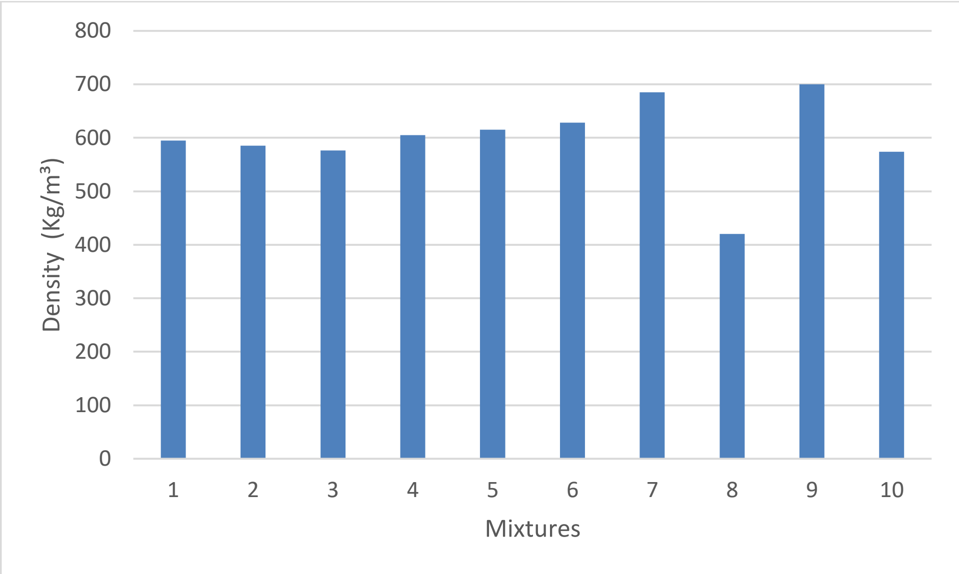


Figure 32.The density of the mixtures in the research.

4.3.1.1 The Effect of Binder Composition

The different binder compositions used in the mixes had varying densities, significantly impacting the hempcrete's overall density. Mix 3, which combined NHL and FAC, resulted in the lowest density among the mixes. This is likely due to the lower bulk density of the binders used. In contrast, Mix 4, made with ground granulated blast furnace slag and hydrated lime, exhibited the highest density. The higher density of these binders contributed to the increased density of the mix.

The choice of binder is essential in determining the final density and performance of the hempcrete, as it directly influences how densely the materials can pack together. However, its impact is minor compared to other parameters, such as particle size and binder content, significantly affecting the material's overall density.

4.3.1.2 The Effect of Particle Size

The binder compositions, the proportions of hemp shives to binder, and the bulk density of mixes were constant to investigate the effect of particle size on the density of hempcrete. Hempcrete specimens with three particle sizes are shown in Figure 33. Mix 5 with coarse hemp shives results in the lowest density, while Mix 7 with fine hemp shives results in the highest density. The density of hempcrete made with fine hemp shives is 9.4% and 7.7% higher than that made with coarse and medium hemp shives, respectively. The mix with small shives is slightly denser because the finer shives were more susceptible to compaction, reducing voids and increasing bulk density. The density of hempcrete increases with the decrease in the size of hemp shives.

The results align with a previous study by Williams et al. (2018) and Stevulova et al. (2012), which also found that large hemp shives produce a naturally less dense material, while small hemp shives result in a naturally denser material.

Figure 33. Hempcrete specimens with three distinct particle sizes: A) Coarse, B) Medium, C) Fine.

4.3.1.3 The Effect of Hemp : Binder Ratio

Mix 8 with a 1:2 hemp : binder ratio results in the lowest density, while Mix 9 with a 1:4 hemp : binder ratio results in the highest density. The density of hempcrete made with the 1:4 hemp : binder ratio is 59% higher than that of the 1:2 ratio and 11.5% higher than that of the 1:3 ratio. The increase in bulk density of hempcrete is due to the higher binder content, which is denser than the hemp shives. The density of hempcrete increases with the increase in binder content. This was due to the porous structure of hemp shive, where increasing hemp shive contents led to increased porosity and, thus, decreased density.

4.3.1.4 The Effect of Hemp : Water Ratio

The variation in density with different hemp : water ratios shows how the water affects the specimen's compaction and binder hydration. Mix 1 with a lower hemp : water ratio (1:2), which has enough water to hydrate the binder and make the mix workable. However, this amount of water is inadequate to fill the voids and reach maximum compaction, leading to a moderate density of 595 kg/m^3.

On the other hand, Mix 5 with a moderate hemp : water ratio (1:2.5) results in a density of 615 kg/m^3, providing the optimum amount of water for better compaction and more efficient binder hydration, resulting in a denser specimen.

Mix 10 with the higher hemp : water ratio (1:3) results in a 574 kg/m^3 density, the lowest density among the three hemp-water ratios. It was found that increasing the hemp : water ratio beyond the optimal level leads to excess water and enhances workability. However, when excess water evaporates, it creates more voids, increases the specimen's porosity, and reduces density.

4.3.2. Compressive Strength

The compressive strength results for the mixtures are shown in Figure 34. The obtained stress-strain curves provide valuable insights into the behavior of hempcrete under compression, considering different factors such as binder composition, particle size, hemp-to-binder ratio, water-to-binder ratio, and orientations of hemp shive.

Hempcrete specimens were tested both perpendicular and parallel to the casting surface. Significant variations were observed when the compressive strength tests were conducted in both directions. The compressive experiments revealed that this material is anisotropic, having different physical properties when measured in different directions.

When the specimen is tested perpendicular to the casting surface, the alignment of the hemp shive particles within the matrix is also perpendicular to the direction of the applied stress. This alignment likely occurs because the casting process causes the hemp particles to be more oriented in that direction. As the strain increases, the stress increases, making determining the maximum strength from the stress-strain curve challenging. Higher compressive strength values indicate that the hempcrete is stiffer and more rigid when the load is applied in this direction. This is because the orientation of the hemp particles in this loading direction helps resist deformation more effectively, leading to greater strength and rigidity.

In contrast, when the specimen is tested parallel to the casting surface, the alignment of the hemp shive particles within the matrix is parallel to the direction of the applied stress, the stress increase making it easier to characterize the maximum strength from the stress-strain curve.

Because hempcrete is a non-load-bearing material with low density and high porosity, and its behavior is different from that of traditional concrete, specimens made of hempcrete cannot have a point that can be spotted on the graph as representing the maximum admissible load.

Under increasing force, the material deforms plastically without significant resistance or an apparent breaking point. Therefore, to compare the compressive strength of the samples, the maximum stress recorded for each sample at a strain of 15% was used to determine the compressive strength values, as shown in Table 10. This strain value of 15% was chosen to align with previous studies on hempcrete, which used it as a benchmark for evaluating compressive stress.

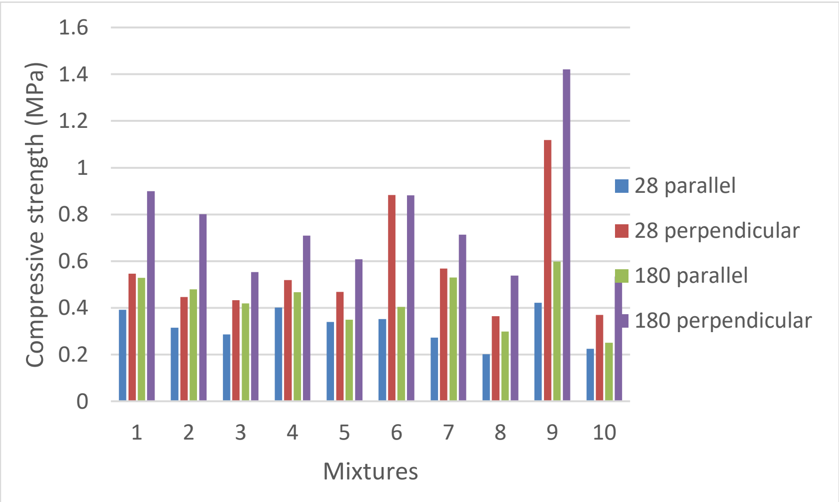


Figure 34. Compressive strength of hempcrete mixtures at 28 and 180 days in parallel and perpendicular directions to the hemp shiv orientation.

As mentioned in the literature, some researchers prefer testing the hempcrete specimens parallel to hemp shives orientation because, in this direction, the relation between strain and stress gives indications about the performance of specimens by giving a plateau and the highest strength.

In this study, the perpendicular direction also gave indications about the performance if the specimens were compared at a specific strain ratio. The performance of the specimen in the parallel direction matched the performance in the perpendicular direction. If the specimen of a mixture had higher compressive strength than the specimens of other mixtures in parallel, it would also have high compressive in the perpendicular direction.

Figure 35 illustrates the relationship between density and compressive strength for hempcrete under compressive loading in two directions: parallel and perpendicular to the hemp shive orientation. While the compressive strength generally increases with density in both parallel and perpendicular directions at both curing times, density alone does not fully determine the compressive strength.

The relationship between density and compressive strength is approximately linear, as indicated by the trendlines and corresponding R^2 values. The R^2 values (ranging from 0.3783 to 0.459) suggest a moderate correlation between these two properties. Other factors, such as binder composition, the direction of the applied load relative to the shive orientation, and the age of the specimens, also significantly influence the compressive strength of hempcrete.

This observation agrees with the study by Nozahic et al. (2012), which found that compaction enhances the material's compressive strength. Interestingly, this increased strength does not directly correspond to a proportional increase in density due to the orthotropic properties developed during the compaction process.

The compaction during the casting process allows plant particles to reorganize into distinct layers, resulting in orthotropic mechanical behavior. This behavior causes the material's mechanical properties to vary depending on the direction of the applied force (e.g., exhibiting higher strength in one direction compared to others).

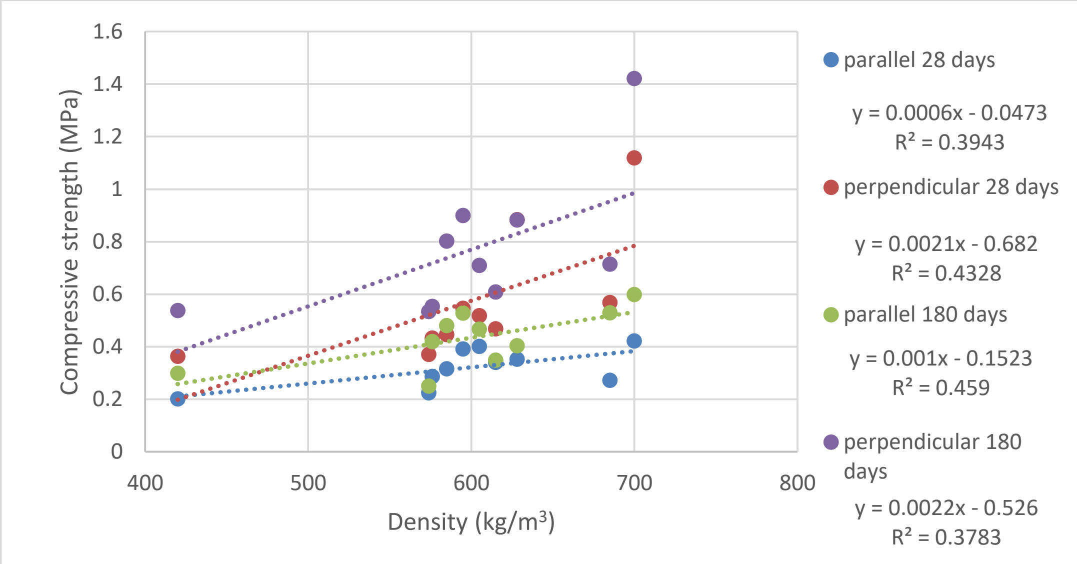


Figure 35. Compressive strength of hempcrete versus density.

4.3.2.1 Compressive Strength at 28 Days

Compressive strength test results at 28 days show variations based on several factors, including binder composition, particle size, hemp: binder ratio, and hemp : water ratio. Additionally, the loading direction of the specimens significantly affects the compressive strength. The compressive strength range is between 0.202 MPa and 0.422 MPa in the parallel direction at 28 days. However, most researchers report that hempcrete shows a compressive strength of less than 1 MPa (Abdellatef et al. 2020).

4.3.2.1.1 The Effect of Binder Composition

Different binder compositions lead to differences in hempcrete compressive strength depending on the properties and ratios of materials used in each mixture. The compressive strength range is between 0.2867 MPa and 0.4015 MPa in the parallel direction and between 0.4328 and 0.5468 MPa in the perpendicular direction. The effect of binder composition on the compressive stress-strain relationship of hempcrete specimens loaded parallel to the hemp shives' direction at 28 days is shown in Figure 36, while the corresponding stress-strain relationship for the perpendicular direction is shown in Figure 37.

The compressive strength values in Mix 1 are comparable to those in Mix 4 in the parallel direction. While Mix 1 shows marginally better performance in the perpendicular direction. Mix 2 has a compressive strength lower than Mix 1 and Mix 4 and higher than Mix 3 in both directions. Mix 3 shows slightly lower compressive strength than Mix 1, Mix 2, and Mix 4 in both parallel and perpendicular directions.

FAC may be less effective than GGBFS in enhancing the compressive strength of hempcrete since GGBFS has higher reactivity and calcium content than FAC. Its more intense hydration and pozzolanic reactions form a denser microstructure and stronger C-S-H bonds (Topçu 2013).

In Mix 4, GGBFS and HL give a highly reactive binder system in which calcium hydroxide from HL reacts with silica and alumina in GGBFS to produce higher quantities of C-S-H gel that significantly increases the compressive strength of hempcrete. In parallel direction, Mix 1 and mix 4 have higher strain capacity up to failure, which may indicate that mixtures with FAF or GGBFS and HL are more ductile and can absorb higher deformation before significant loss of compressive strength. Mix 2 and Mix 3 are more brittle and exhibit lower strain capacity. This means that they fail more quickly once their maximum stress level is reached. In the perpendicular direction, Mix 1 and Mix 4 exhibit a steady increase in strength with strain, indicating a more ductile behavior and better energy absorption capacity than Mix 2 and Mix 3.

Adding pozzolanas to lime-based hempcrete can improve the compressive strength of materials like hempcrete. Pozzolanas react with the calcium hydroxide produced during lime hydration. This reaction produces more C-S-H, which densifies the matrix and enhances strength. Pozzolans like fly ash may also act as partial water retainers by slowing water movement through the mix. Water retention is crucial for effectively carbonating lime-based binders and avoiding premature drying, which can weaken the bond between the hemp shiv and the binder matrix. Nguyen et al. (2010) found that increasing the pozzolana content increases mechanical strength.

The results are in agreement with the findings of Nguyen, et al.(2010), who concluded that the choice of lime-based binder is a key parameter, as it significantly influences mechanical strength.

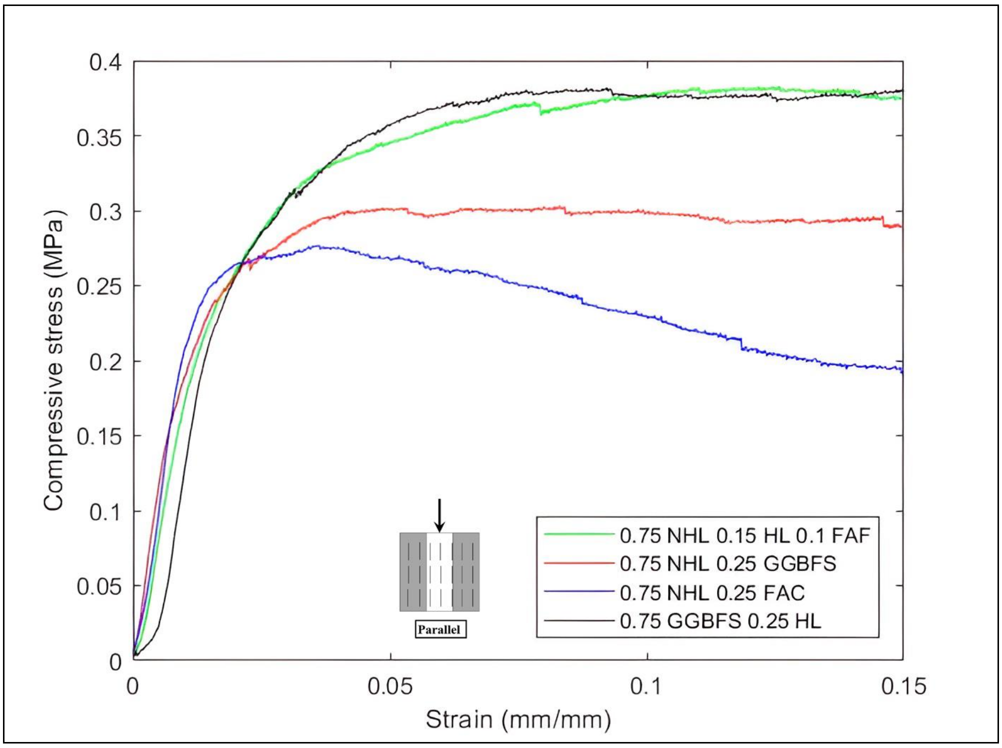


Figure 36. Effect of binder composition on the compressive stress-strain relationship of hempcrete specimens loaded parallel to the hemp shives' direction at 28 days.

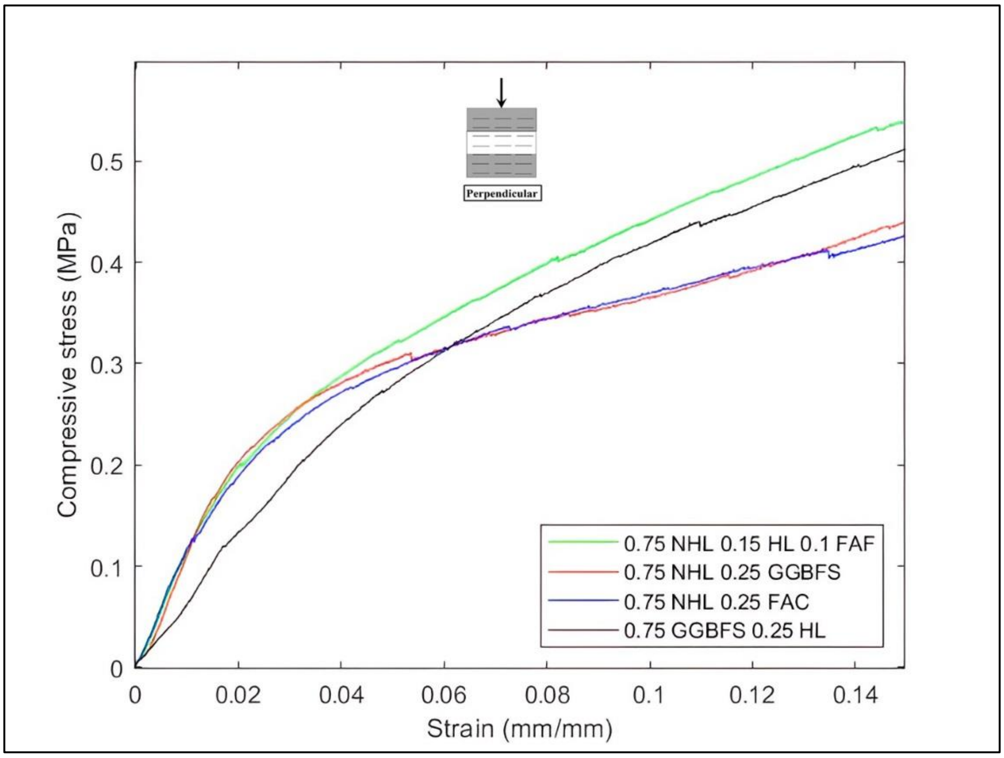


Figure 37. Effect of binder composition on the compressive stress-strain relationship of hempcrete specimens loaded perpendicular to the hemp shives' orientation at 28 days.

4.3.2.1.2 The Effect of Particle Size

The impact of hemp shive size on the compressive strength of hempcrete can be significant due to its effect on the mixture's overall microstructure, porosity, and bond strength. The effect of particle size on the compressive stress-strain relationship of hempcrete specimens loaded parallel to the hemp shives' direction at 28 days is shown in Figure 38, while the corresponding stress-strain relationship for the perpendicular direction is shown in Figure 39.

In both parallel and perpendicular directions, the samples where larger shives were used show poorer compressive strength. The reason could be the granulometric composition, as too many large shives create voids. Medium-sized hemp particles are better coated by binder, which may explain the superior mechanical properties of the hempcrete with coarse particles (Laurent Arnaud and Gourlay 2012). In fine particles, the binder was observed not to be spread very well to cover the particles.

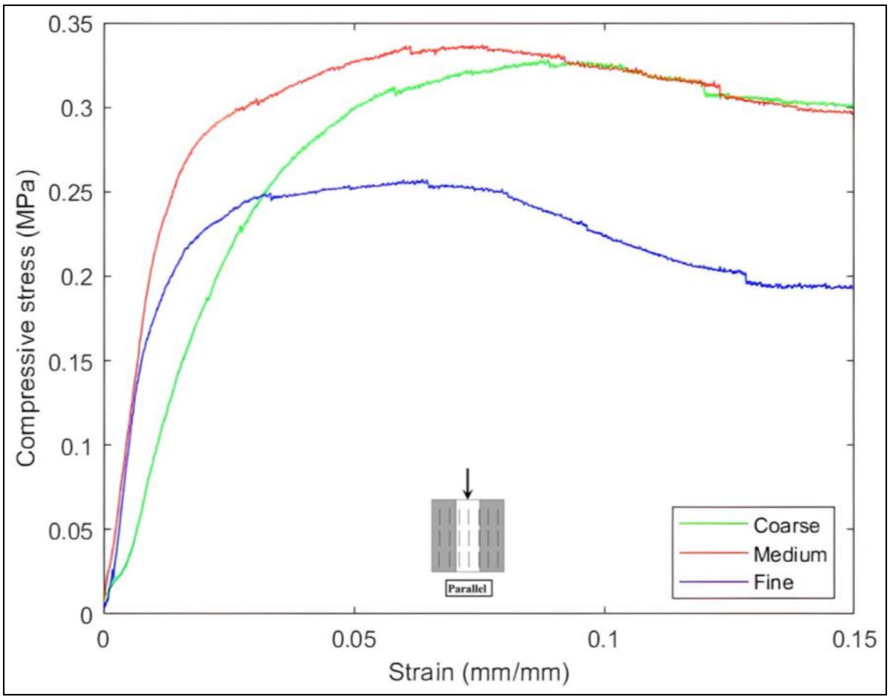


Figure 38. Effect of particle size on the compressive stress-strain relationship of hempcrete specimens loaded parallel to the hemp shives' orientation at 28 days.

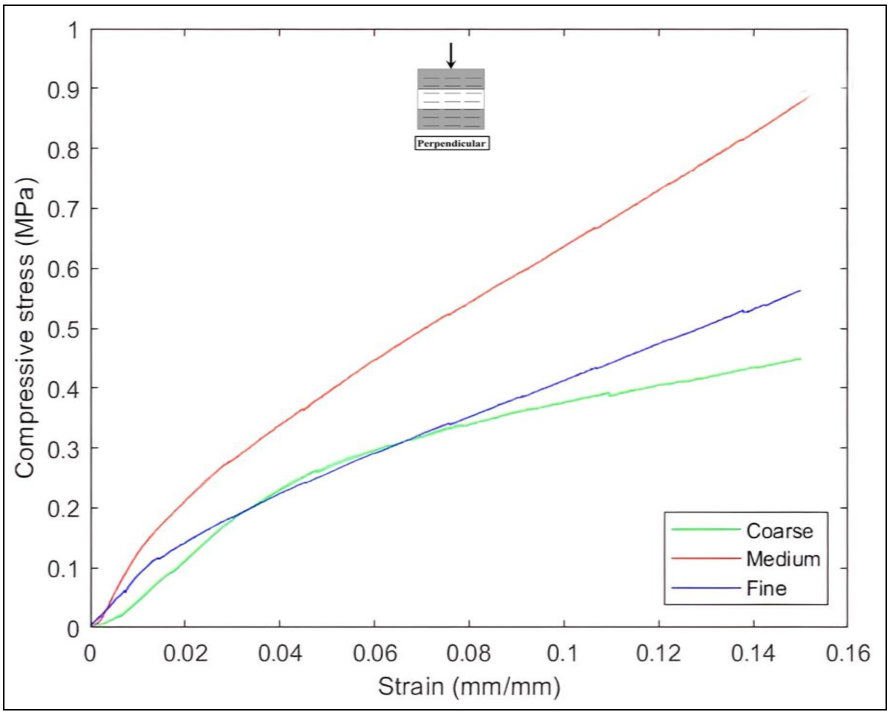


Figure 39. Effect of particle size on the compressive stress-strain relationship of hempcrete specimens loaded perpendicular to the hemp shives' orientation at 28 days.

The results agree with Laurent Arnaud and Gourlay (2012), Stevulova et al. (2012), and Niyigena et al. (2016), who also found that smaller hemp shive particles exhibit higher compressive strength than larger particles. In contrast, Williams et al. (2018) found that particle size does not affect compressive strength in both parallel and perpendicular directions.

4.3.2.1.3 The Effect of Hemp : Binder Ratio

The binder, functioning as the adhesive, binds the hemp shives together, creating a composite material with enhanced cohesion and resistance to internal forces. Using more binder results in more bonding points between the hemp shive, producing a more robust material. Furthermore, the increased binder content effectively fills more voids within the hempcrete, significantly reducing the presence of weak points and ensuring a more uniform and solid material with superior load-bearing capacity. The effect of hemp : binder ratio on the compressive stress-strain relationship of hempcrete specimens loaded parallel to the hemp shives' direction at 28 days is shown in Figure 40, while the corresponding stress-strain relationship for the perpendicular direction is shown in Figure 41.

Three types of behaviors of hempcrete were observed depending on the ratio of hemp : binder. For low hemp : binder ratio (1:2), the material exhibited poor mechanical strength and high deformation. The behavior was more like a loose assembly of particles with binder bridges. When the binder content is low relative to the hemp, the binder is insufficient to thoroughly coat the hemp shives, leading to a loose structure with minimal cohesion. This ratio can be used where thermal or acoustic insulation and low density are more important than mechanical strength.

For moderate hemp: binder ratio (1:3), the material's performance improved as more binder was added. As the binder content increased, more hemp shives were coated and bound together, creating a stronger, more cohesive structure. This ratio balances insulation and structural properties, providing moderate strength while retaining some of the insulation properties.

For a high hemp : binder ratio (1:4), the material resembled a continuous binder matrix with shive particles embedded in it, and the mechanical performance approached that of a pure binder. With an even higher binder content, the binder dominates the material's structure, with hemp shives acting more as inclusions. The mechanical strength improved as the matrix became more rigid and cohesive, making the material perform more like a solid binder-based composite rather than a particle-based structure. This was due to the porous structure of hemp shive, where increasing hemp shive contents led to an increase in porosity and, thus, the reduction of compressive strength. It can be observed that samples with a lower binder content (higher hemp : binder ratio) have lower compressive strength than those with a higher binder content. This aligns with the observations of Hirst et al. (2010), who noted that the material's ultimate strength depends on the percentage of binder used during mixing. Sonebi et al. (2015) reported that the compressive strength of hempcrete depends on the hemp shiv content, with a higher percentage of hemp resulting in lower compressive strength. Mazhoud, Collet, and Lanos (2017) found that the mechanical properties of hempcrete depend strongly on the Hemp to binder ratio and density.

In the study by Williams et al. (2018), a strong positive correlation was observed between binder content and compressive strength in the perpendicular direction of loading. In the parallel direction, compressive strength showed a positive correlation with binder ratios between 1:1.8 and 1:2.2. However, no significant difference was found at the higher 1:2.6 binder ratio, which showed a slight decrease in strength.

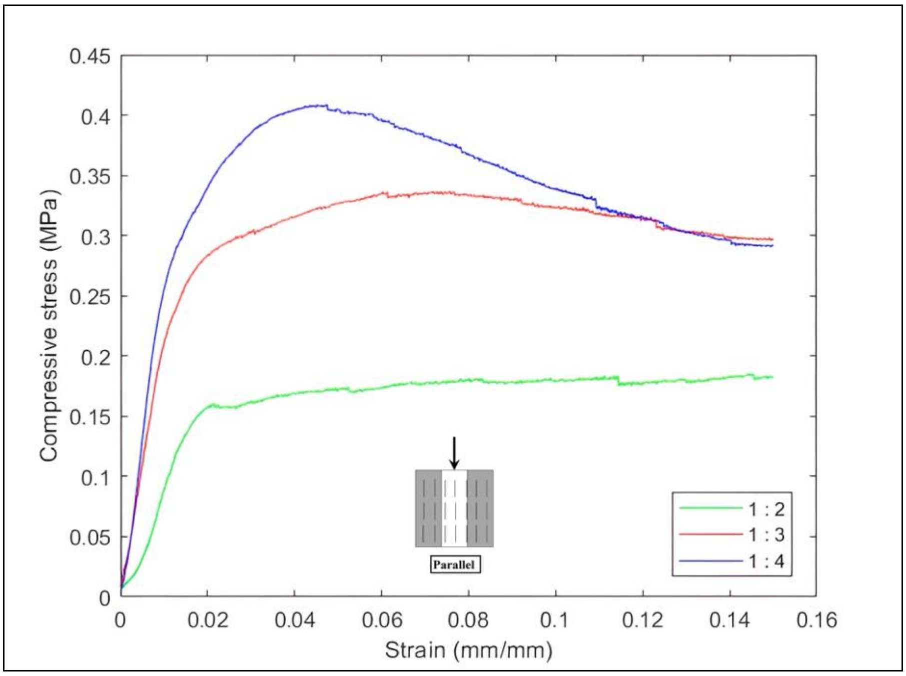


Figure 40. Effect of hemp : binder on the compressive stress-strain relationship of hempcrete specimens loaded parallel to the hemp shives' orientation at 28 days.

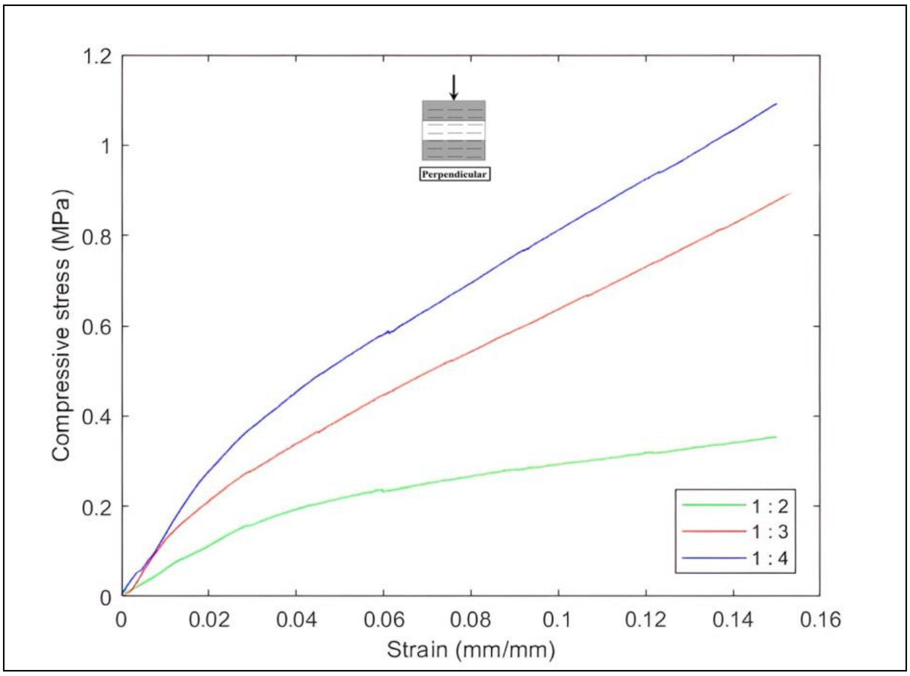


Figure 41. Effect of hemp : binder ratio on the compressive stress-strain relationship of hempcrete specimens loaded perpendicular to the hemp shives' orientation at 28 days.

4.3.2.1.4 The Effect of Hemp : Water Ratio

The hemp : water ratio plays a critical role in the compressive strength development of hempcrete. Water is necessary for the binder's hydration, but excess water can increase porosity, reduce density, and negatively impact the strength of the hempcrete. Moreover, excess water can slow down the hardening process and reduce the strength development of hempcrete. The effect of hemp : water ratio on the compressive stress-strain relationship of hempcrete specimens loaded parallel to the hemp shives' direction at 28 days is shown in Figure 42, while the corresponding stress-strain relationship for the perpendicular direction is shown in Figure 43.

The water demand for hemp shives increases with the decrease in particle size and the increase in binder content.

Mix 1, with the lower hemp : water ratio (1:2), has the highest compressive strength compared to Mix 5 with a hemp : water ratio of (1:2.5) and Mix 10 with a hemp : water ratio of (1:3) in parallel and perpendicular directions.

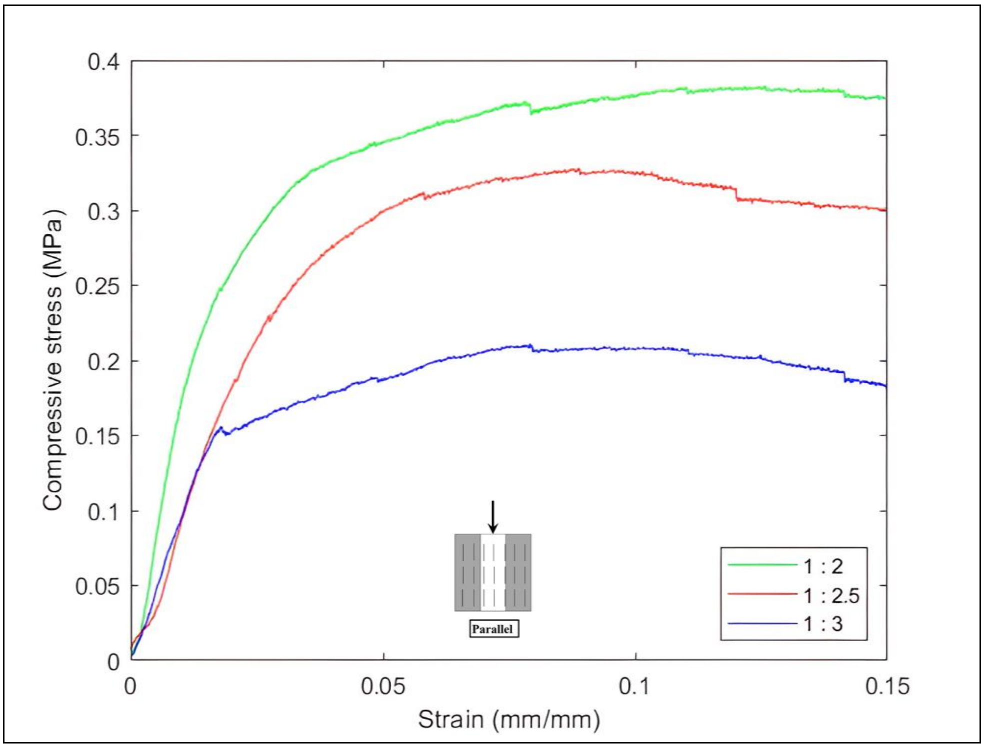


Figure 42. Effect of hemp : water on the compressive stress-strain relationship of hempcrete specimens loaded parallel to the hemp shives' orientation at 28 days.

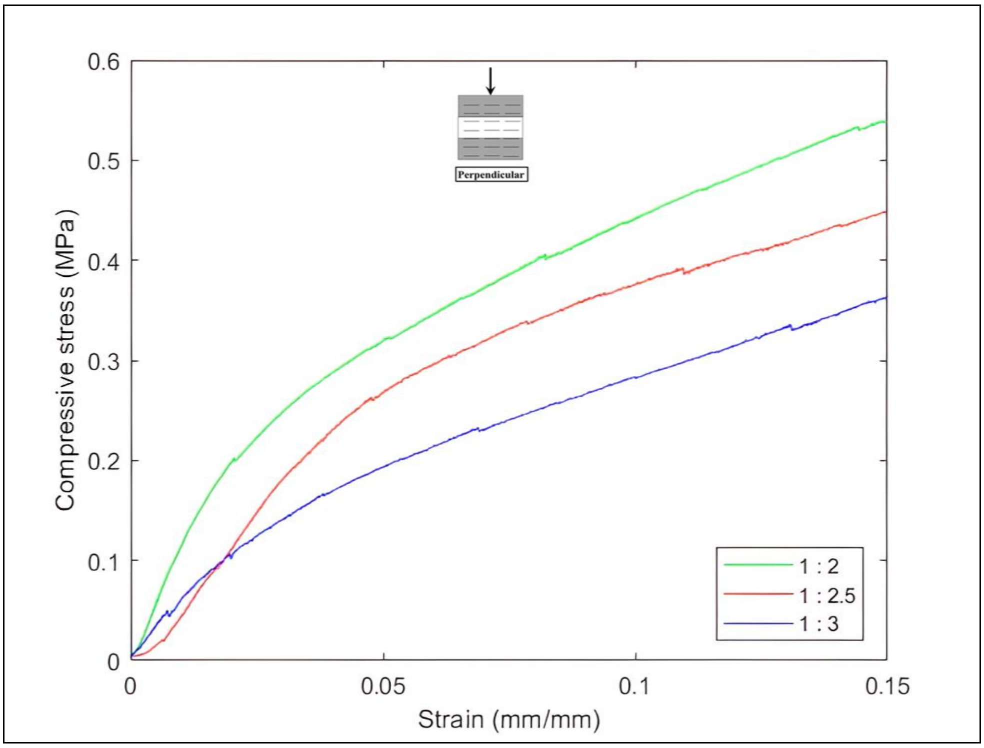


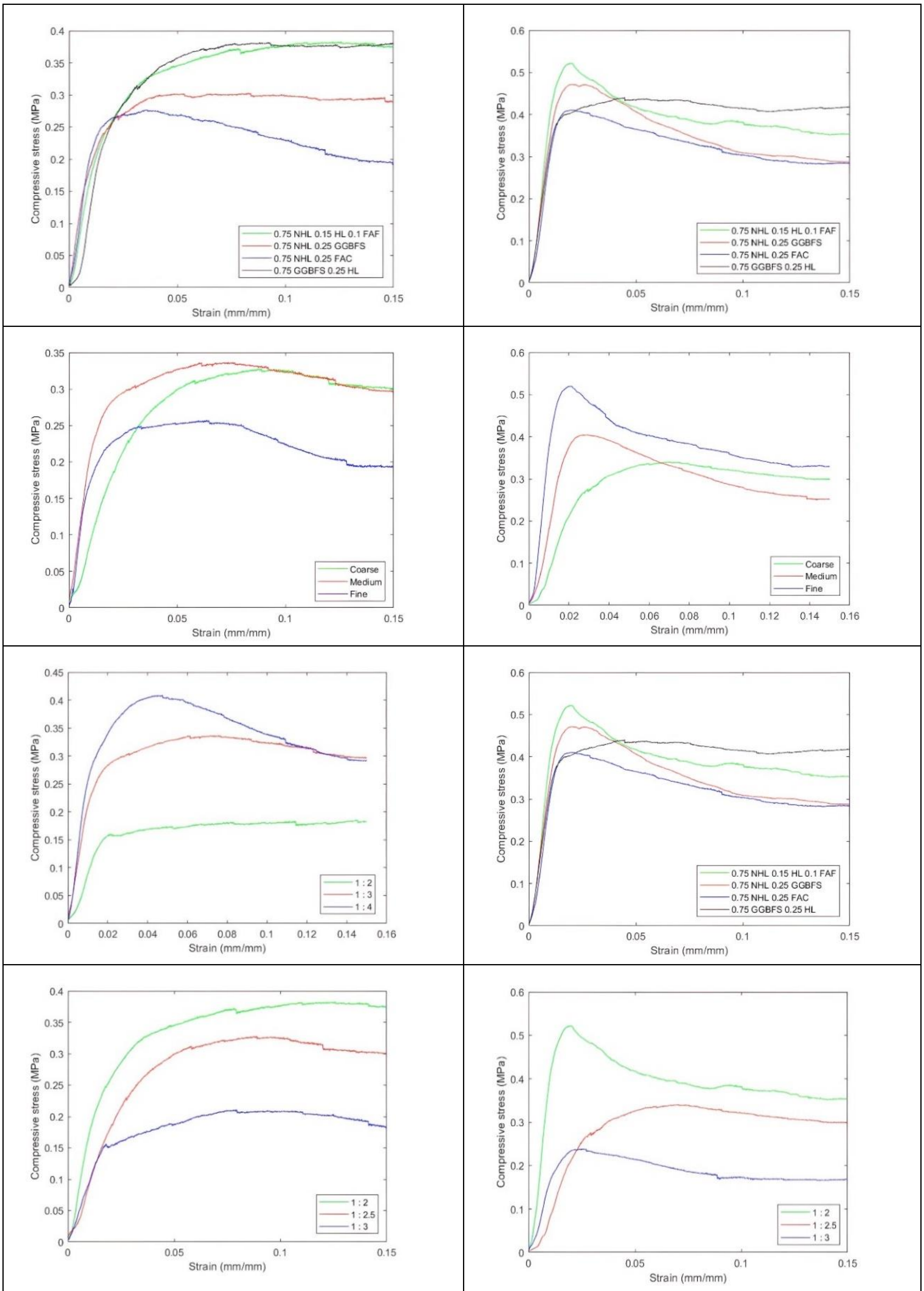
Figure 43. Effect of hemp : water on the compressive stress-strain relationship of hempcrete specimens loaded perpendicular to the hemp shives' orientation at 28 days.

Increasing the water content reduces the compressive strength, leading to higher porosity and weaker bonds within the matrix. Therefore, to achieve better compressive strength, it is essential to use only the amount of water required to hydrate the cement (Adam, Isopescu, and Lepadatu 2023). Excess water creates voids as it evaporates and dilutes the binder, reducing its binding efficiency.

4.3.2.2 The Compressive Strength at 180 Days

Compressive strength tests were conducted on specimens after 28 days and 180 days of curing to evaluate the hardening process of hempcrete. The hardening of hempcrete is relatively slow, meaning its age significantly influences its mechanical behavior. The compressive strength comparison of hemp concrete is shown in Figure 44.

The behavior of hempcrete over time, observed at 28 and 180 days, is consistent with the findings of Arnaud and Gourlay (2012), who reported similar behavior in their study. At early stages, hemp concretes exhibit a highly ductile behavior, evident in the stress-strain curve with a long, flat post-peak plastic phase.



A- 28-day specimens	B- 180-day specimens

Figure 44. Compressive strength comparison of hemp concrete: A- 28-day specimens and B- 180-day specimens, with the load applied parallel to the hemp shives orientation.

This is because the binder's hydrates have not yet formed a fully connected network, so the material's behavior is primarily governed by the hemp particles, which can endure significant deformation. Over time, as the binder hydrates gradually connect and form a continuous network, stress transfer within the material improves. The binder's properties dominate the mixture, increasing strength and reducing ductility as the material becomes stiffer and more deformation-resistant.

4.3.2.2.1 The Effect of Binder Composition

The compressive strength of Mix1 improved from 0.392 MPa to 0.528 MPa for parallel and from 0.547 MPa to 0.899 MPa for perpendicular loading; this means the mixture matures and develops strength over time in both directions. Moreover, Mix1 offers the best long-term performance among the other mixtures (Mix 2, Mix 3, and Mix4) in both parallel and perpendicular directions. The compressive strength increases significantly due to the binder's ongoing carbonation and hydration reactions, especially with lime-based binders. The effect of binder composition on the compressive stress-strain relationship of hempcrete specimens, loaded parallel and perpendicular to the direction of the hemp shives at 180 days, is shown in Figures 45 and 46, respectively.

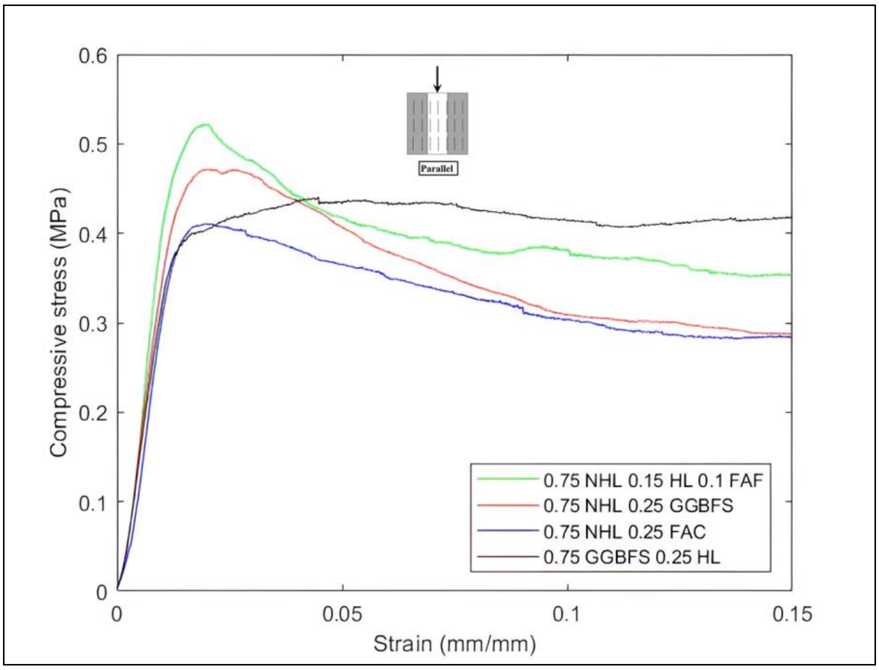


Figure 45. Effect of binder composition on the compressive stress-strain relationship of hempcrete specimens loaded parallel to the hemp shives' orientation at 180 days.

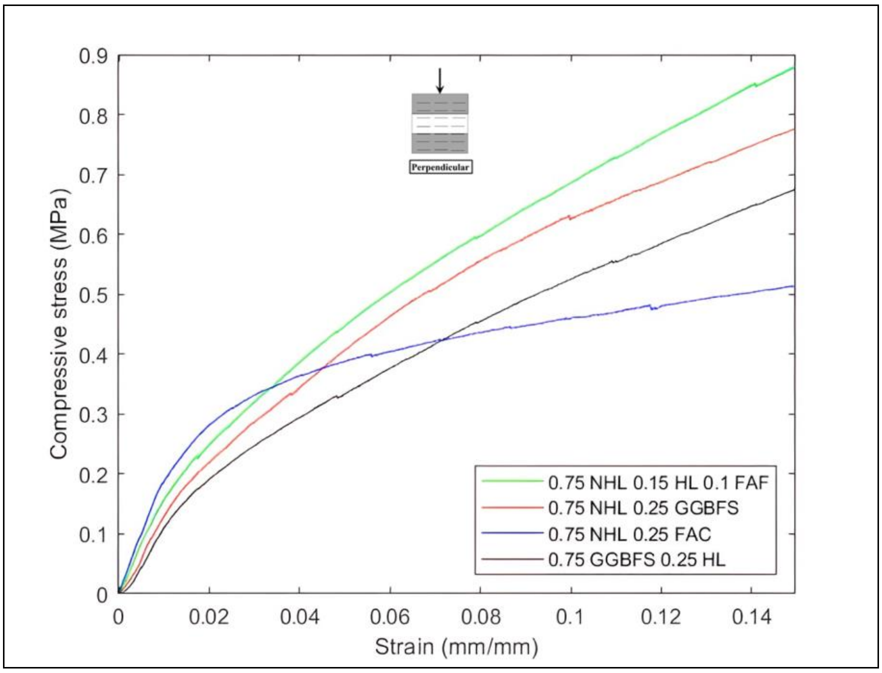


Figure 46. Effect of binder composition on the compressive stress-strain relationship of hempcrete specimens loaded perpendicular to the hemp shives' orientation at 180 days.

4.3.2.2.2 The Effect of Particle Size

The compressive strength of Mix5 improved from 0.34 MPa to 0.3492 MPa for parallel, and from 0.4687 MPa to 0.6085 MPa for perpendicular loading; this means the mixture matures and develops strength over time in both directions due to the binder's ongoing carbonation and hydration reactions.

The larger coarse hemp shive particles used in Mix 5 may have resulted in a more porous structure, reducing density and potentially lowering compressive strength compared to Mix 6 with medium particles or Mix 7 with fine particles.

Mix 7 with fine hemp shives resulted in a denser hempcrete, which required more binder to fill the same volume as coarser mixes. Increasing the binder content improved the compressive strength because more bonding points between the hemp shives led to a more robust material. Furthermore, the increased binder content effectively filled more voids within the hempcrete.

In Mix 7, the hemp shives varied in shape; some particles were flaky, with a longer length than their width, while others were more uniform. In the specimens tested at 28 days, there was a higher proportion of very fine particles, which have a larger surface area and require more water. This caused the binder to spread unevenly, leading to particle agglomeration and reducing the compressive strength of hempcrete in the parallel direction. While the specimens tested at 180 days, the mixture contained more flaky particles, allowing the binder to distribute more evenly, resulting in improved compressive strength in the parallel direction. The effect of particle size on the compressive stress-strain relationship of hempcrete specimens loaded parallel to the hemp shives' direction at 180 days is shown in Figure 47, while the corresponding stress-strain relationship for the perpendicular direction is shown in Figure 48.

Thus, particle size's influence on hempcrete's performance is important. In general, a reduction in particle size will produce a denser composite with possibly higher compressive strength. The ideal particle size is based on a favorable balance between mechanical stability and thermal efficiency and the specific application to which the hempcrete is to be put. In addition, the difference in particle size can influence the binder's distribution and adhesion, thus modifying its extensive properties further.

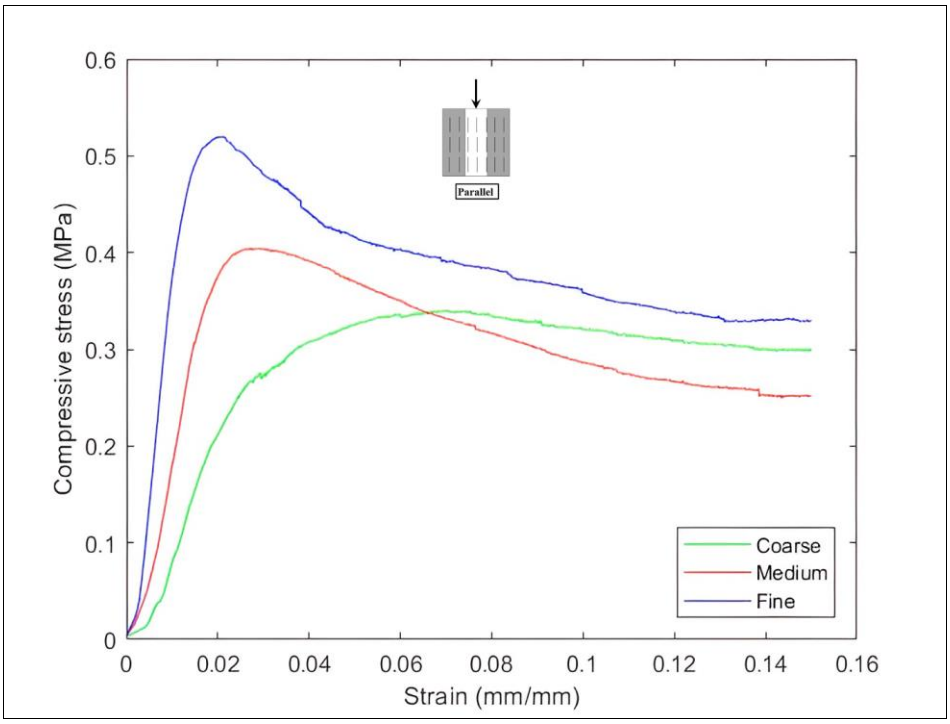


Figure 47. Effect of particle size on the compressive stress-strain relationship of hempcrete specimens loaded parallel to the hemp shives' orientation at 180 days

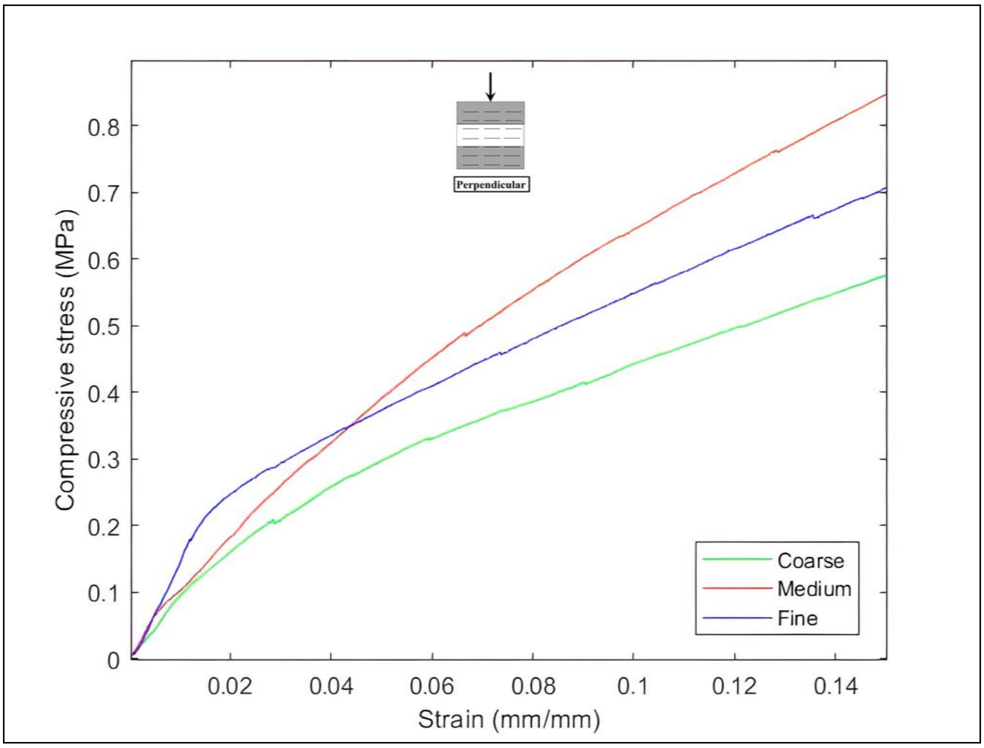


Figure 48. Effect of particle size on the compressive stress-strain relationship of hempcrete specimens loaded perpendicular to the hemp shives' orientation at 180 days.

4.3.2.2.3 The Effect of Hemp : Binder Ratio

Similar to the 28-day specimens, Mix 9 had higher compressive strength than Mix 6 and Mix 8 due to the increased binder content. This enhanced bonding between the hemp shive particles and reduced voids, resulting in a more compact and cohesive structure.

The compressive strength of Mix 9 improved from 0.4218 MPa to 0.5984 MPa for parallel and from 1.1187 MPa to 1.4203 MPa for perpendicular loading; this means the mixture matures and develops strength over time in both directions. The effect of hemp : binder ratio on the compressive stress-strain relationship of hempcrete specimens loaded parallel to the hemp shives' direction at 28 days is shown in Figure 49, while the corresponding stress-strain relationship for the perpendicular direction is shown in Figure 50.

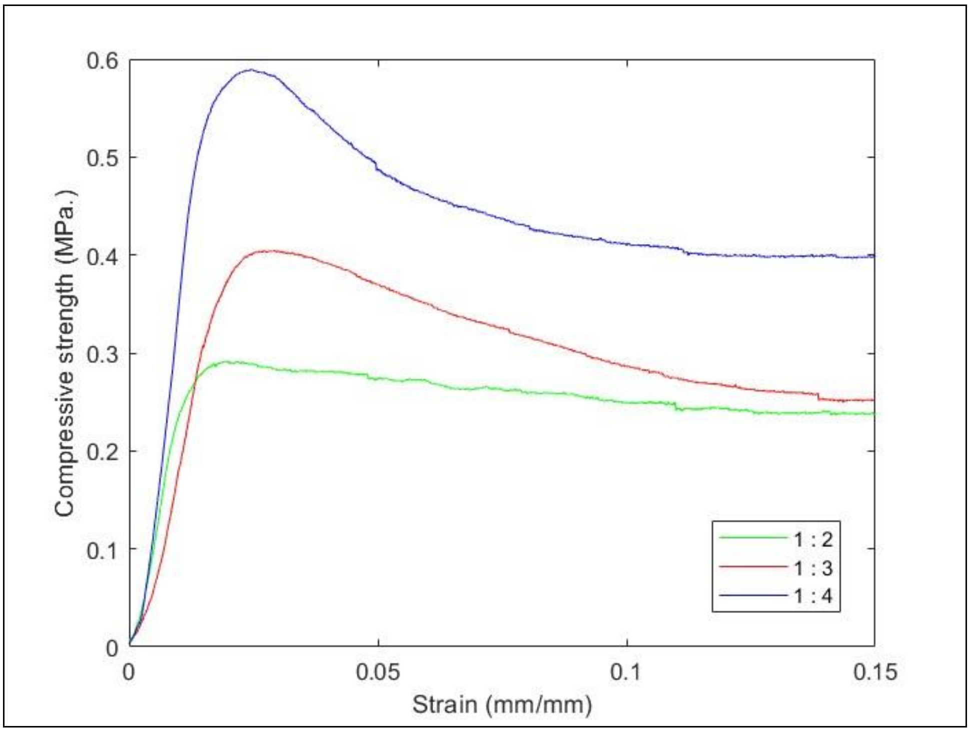


Figure 49. Effect of hemp : binder ratio on the compressive stress-strain relationship of hempcrete specimens loaded parallel to the hemp shives' orientation at 180 days.

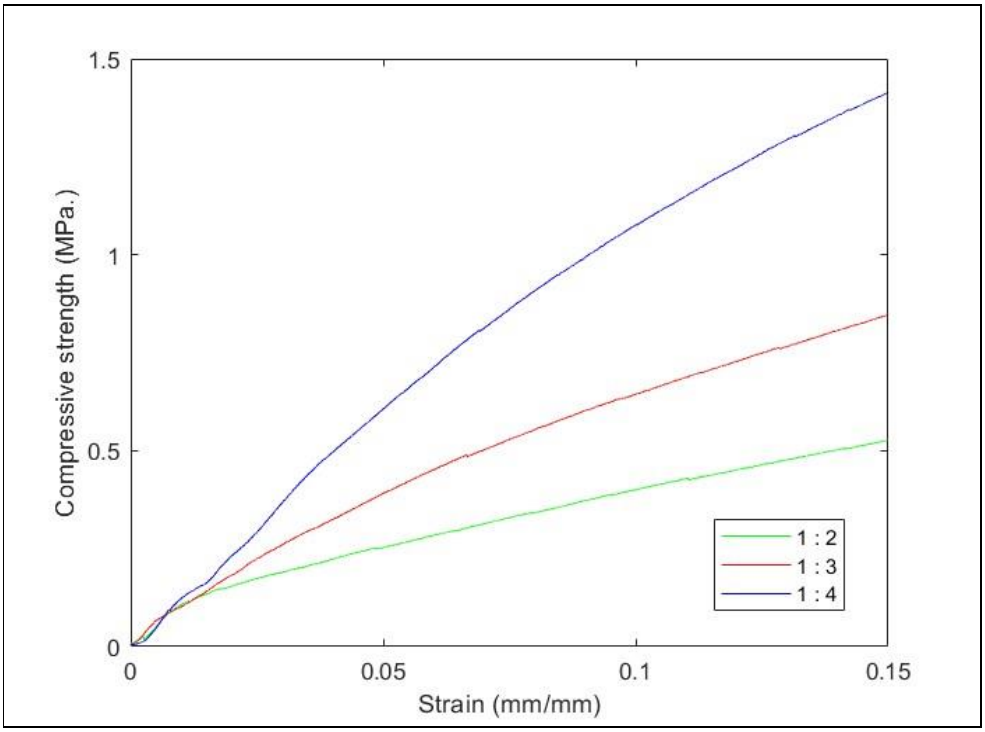


Figure 50. Effect of hemp : binder ratio on the compressive stress-strain relationship of hempcrete specimens loaded perpendicular to the hemp shives' orientation at 180 days.

4.3.2.2.4 The Effect of Hemp : Water Ratio

Similar to the 28-day specimens, Mix 1, with a lower hemp-water ratio (1:2), has the highest compressive strength compared to Mix 5, with a hemp-water ratio of (1:2.5), and Mix 10, with a hemp-water ratio of (1:3) in both parallel and perpendicular directions. Therefore, it can be concluded that the strength increases as the hemp : water ratio decreases. This trend highlights the importance of optimizing the hemp: water ratio to achieve maximum strength and durability in hempcrete.

The effect of hemp : water ratio on the compressive stress-strain relationship of hempcrete specimens loaded parallel to the hemp shives' direction at 180 days is shown in Figure 51, while the corresponding stress-strain relationship for the perpendicular direction is shown in Figure 52.

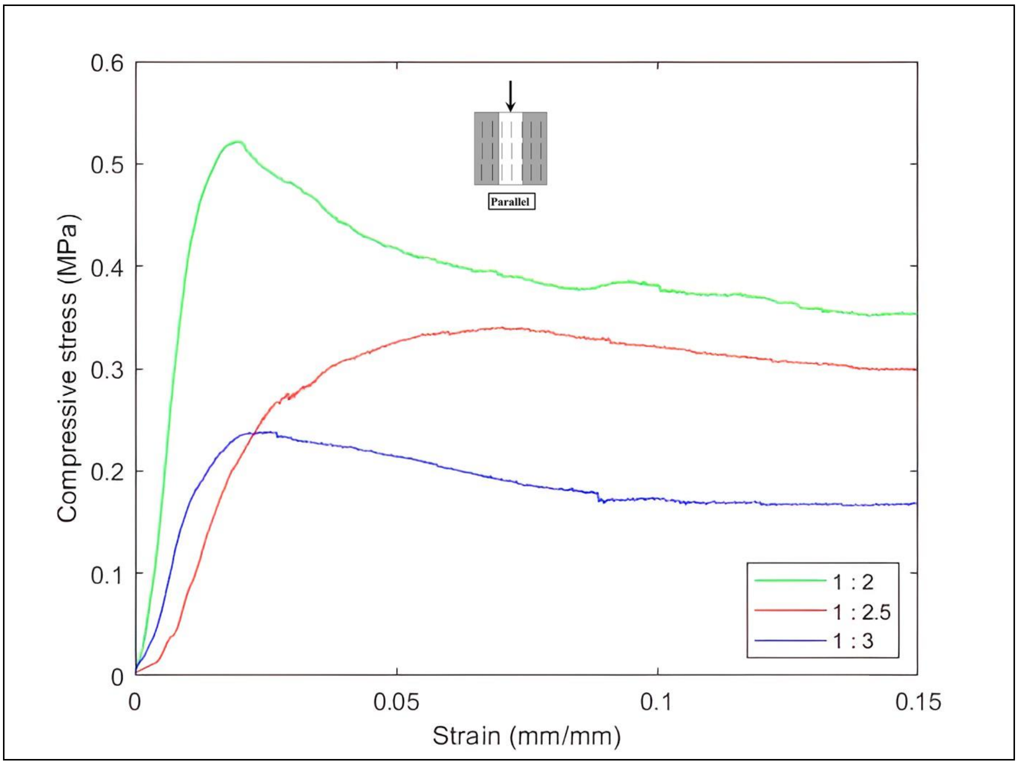


Figure 51. Effect of hemp : water ratio on the compressive stress-strain relationship of hempcrete specimens loaded parallel to the hemp shives' orientation at 180 days

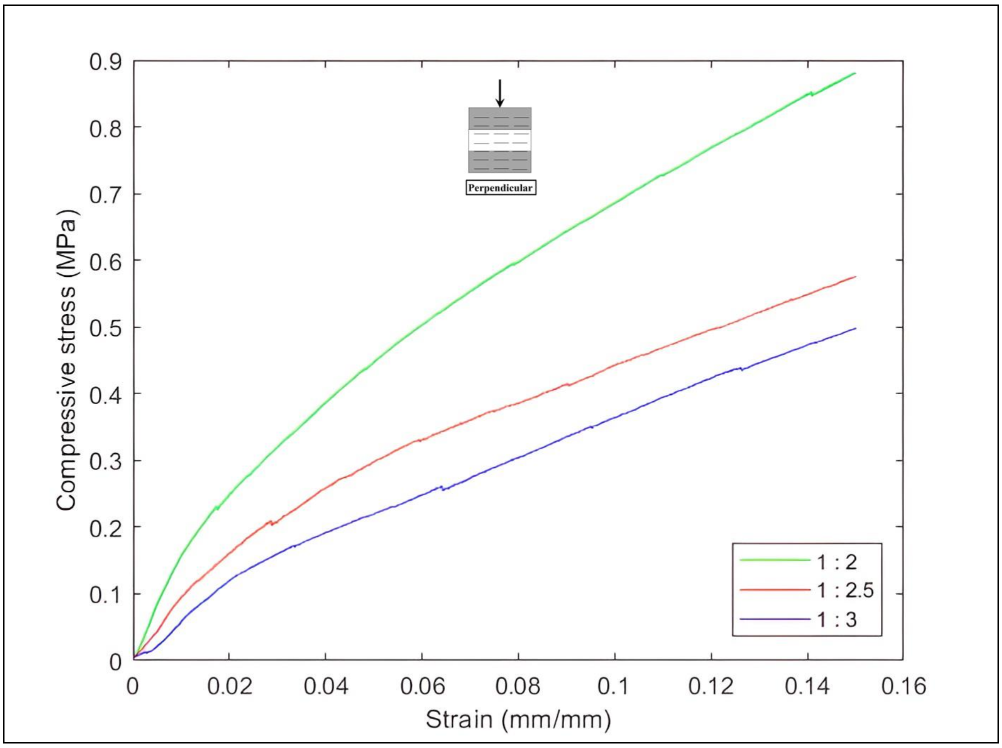


Figure 52. Effect of hemp : water on the compressive stress-strain relationship of hempcrete specimens loaded perpendicular to the hemp shives' orientation at 180 days.

4.3.2.3 Application of Load Parallel and Perpendicular to the Hemp Shives' Orientation

For illustrative purposes, Mix 1 was selected to compare the stress-strain behavior when the load is applied parallel and perpendicular to the hemp shiv orientation at a strain of 15%, as shown in Figure 53. Although all mixtures exhibit similar characteristics, Mix 1 is a representative example highlighting the differences in loading direction.

In the parallel direction to the shive orientation, the stress shows a rapid initial rise, indicating elastic behavior. Then, it reaches a maximum stress at a relatively small strain, and a slow drop occurs. It can be concluded that loading parallel to the shive alignment results in lower compressive strength and premature failure.

In the perpendicular direction, the stress increases in a straight line with strain, showing more ductile behavior than in the parallel direction. The curve does not peak but keeps rising to a considerably larger compressive stress value than in the parallel loading direction. It can be concluded that loading perpendicular to the direction of shives gives greater resistance.

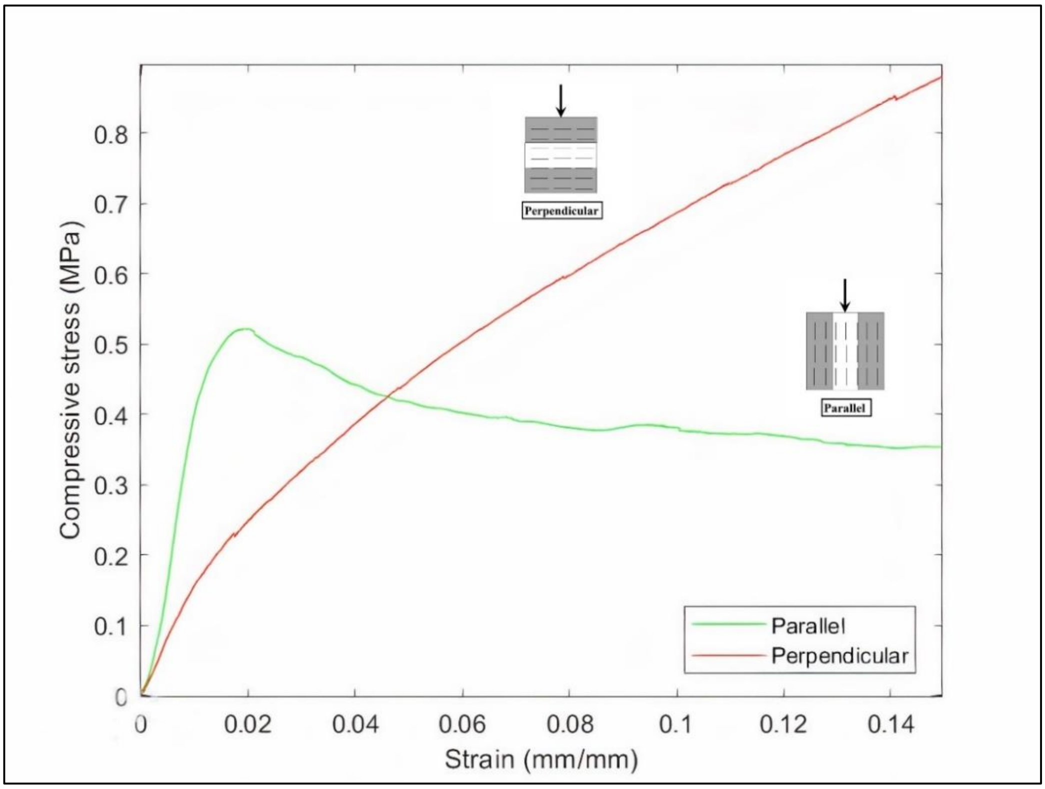


Figure 53. Comparison of the stress-strain curve behavior of Mix 1 when the load is applied parallel and perpendicular to the hemp shiv orientation at a strain of 0.15

The mechanical behavior of plant-based concretes under compression highlights their orthotropic nature, where properties vary significantly depending on the compaction direction. This behavior is attributed to the layered or laminated structure formed during compaction. The material exhibits higher ductility when the load is perpendicular to the plant particle orientation, allowing for more deformation before failure. The material deforms plastically after the peak stress (rupture) rather than breaking apart immediately.

According to the study by Nozahic et al. (2012), this ductility can be attributed to two hypotheses: the crushing of plant particles, where plant aggregates are compressed and deform significantly, absorbing energy, and the matrix-particle interface, where defects such as voids or suboptimal bonds around the particles allow further deformation to occur without sudden failure.

Conversely, when the load is parallel to the plant particle orientation, the material demonstrates greater rigidity but undergoes brittle failure after reaching the peak load. In this direction, the layered structure resists interfacial shearing, making the material less ductile and more prone to sudden breakage.

Like wood, which has longitudinal, radial, and tangential directions, plant-based concretes exhibit higher rigidity and compressive strength in the longitudinal direction (parallel to the layers) than in other directions (Al-musawi et al. 2024).

Figure 54 shows the Mix 1 specimens tested under compression with the load applied parallel and perpendicular to the hemp shive orientation until a strain of 0.15. When the load was applied parallel to the hemp shive orientation, the failure was catastrophic, characterized by large fragments separating from the specimen (Figure 54 B). In contrast, when the load was applied perpendicular to the hemp shive orientation, the failure was less severe, with fewer fragments and the specimen remaining more cohesive (Figure 54 D).

Figure 54. Comparison of the failure of Mix 1 at a strain of 15% : A) Before testing B) After testing parallel to the hemp shiv orientation C) Before testing D) After testing perpendicular to the hemp shiv orientation.

As mentioned before, some researchers prefer testing the hempcrete specimens parallel to hemp shive orientation because, in this direction, the relation between stress and strain indicates the performance of specimens by giving a plateau and the highest strength. In this study, it was observed that the perpendicular direction also reflected the performance of the specimens if they were compared at a specific strain ratio.

4.3.3. Thermal Conductivity

The thermal conductivity of hempcrete is the key factor defining whether this material is suitable as a building insulator. The values of thermal conductivity for test mixes range between 0.1416 W/m·K and 0.2139 W/m·K, proving that the binder composition, the size of the hemp shive particles, and mix proportions influence the development of the thermal properties of this material. The thermal conductivity of investigated hempcrete specimens is presented in Figure 55.

The thermal conductivity test is carried out only on a surface perpendicular to the compaction or casting surface, as this orientation represents the real-life positioning of hempcrete blocks in a wall. Moreover, the casting surface is not smooth, and the testing machine cannot test rough surfaces. Capping the specimen surface with gypsum is not applicable since it will negatively impact the results.

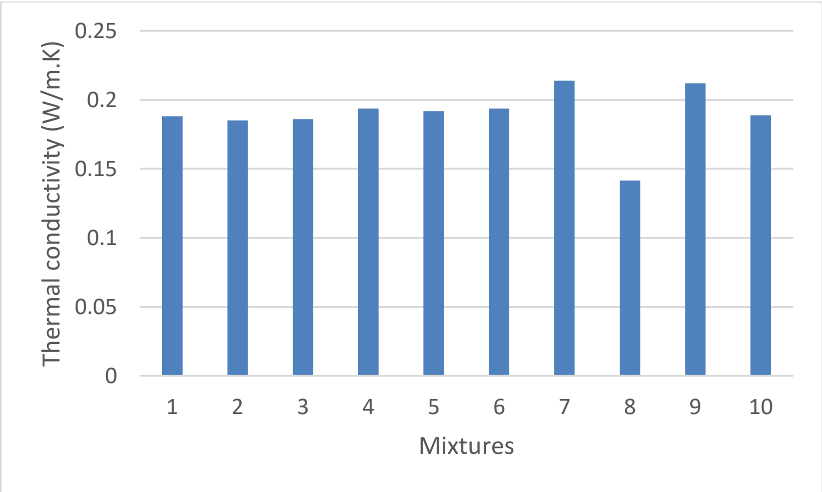


Figure 55. The thermal conductivity of hempcrete specimens.

The density of hempcrete plays a significant role in determining its thermal conductivity. Therefore, Mix 8 specimens with the lowest dry density of 420 kg/m3 have the lowest thermal conductivity of 0.1416 W/m K. In contrast, Mix 9 specimens with the highest dry density of 700 kg/m3 have a thermal conductivity of 0.212 W/m K. Figure 56 illustrates the relation between thermal conductivity and density in the dry states for all design mixes. Collet and Pretot (2014) found that, even when the same formulation is used, the thermal conductivity of the high-density mixture is more than twice that of the low-density mixture.

The specimens show a positive linear relationship between the specimens' thermal conductivities and densities with R^2 values of 0.9685. Several authors have already emphasized this relationship (Page, Sonebi, and Amziane 2017).

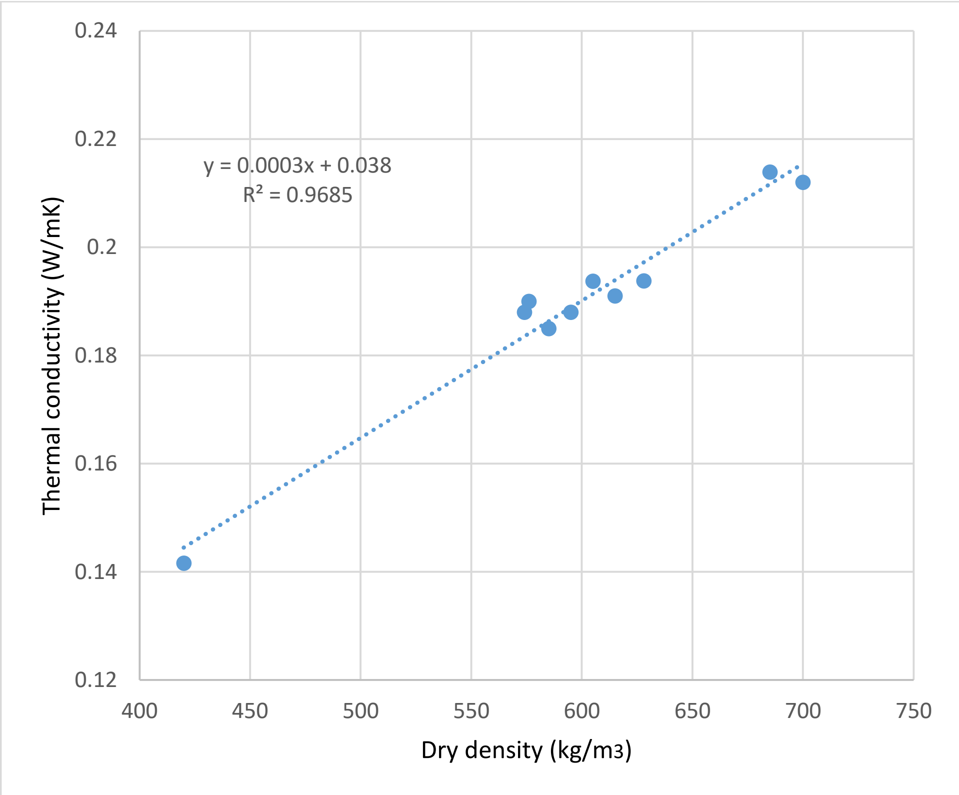


Figure 56. Thermal conductivity of hempcrete versus density.

The thermal conductivity results of fine hempcrete vary because the water was insufficient for the binder paste to spread and cover the hemp particles, resulting in pores in some parts, which affected the results. When water is added to the hemp and binder mixture, the mix forms into small clumps or balls.

According to Amziane, Nozahic, and Sonebi (2015), the thermal conductivity in the parallel to hemp shives orientation was found to be 15–20% lower than in the perpendicular direction. In contrast, Williams et al. (2018) found that the thermal conductivity in the parallel to hemp shives orientation was 20% higher than that in the perpendicular to hemp shives direction.

The values for thermal conductivity are, hence, closer to the following materials: aerated concrete 0.16; calcium silicate board 0.17; prefabricated timber wall panels, 0.12, and timber blocks, 0.14 (650 kg/m^3) (Chabannes et al. 2015). The smaller this value, the better its behavior, and it could be considered that the developed composite presented a good thermal performance. Comparison of hempcrete's thermal conductivity (W/mK) with other types of concrete is shown in Figure 57 (Ansari, Tabish, and Zaheer 2025).

The measured values were in agreement with those found in the literature. For example, in the study by Kosiński et al. (2022), the thermal conductivity of hempcrete bricks made of clay and hemp shives was in the range of about 0.09–0.18 W/(m·K), depending on the density.

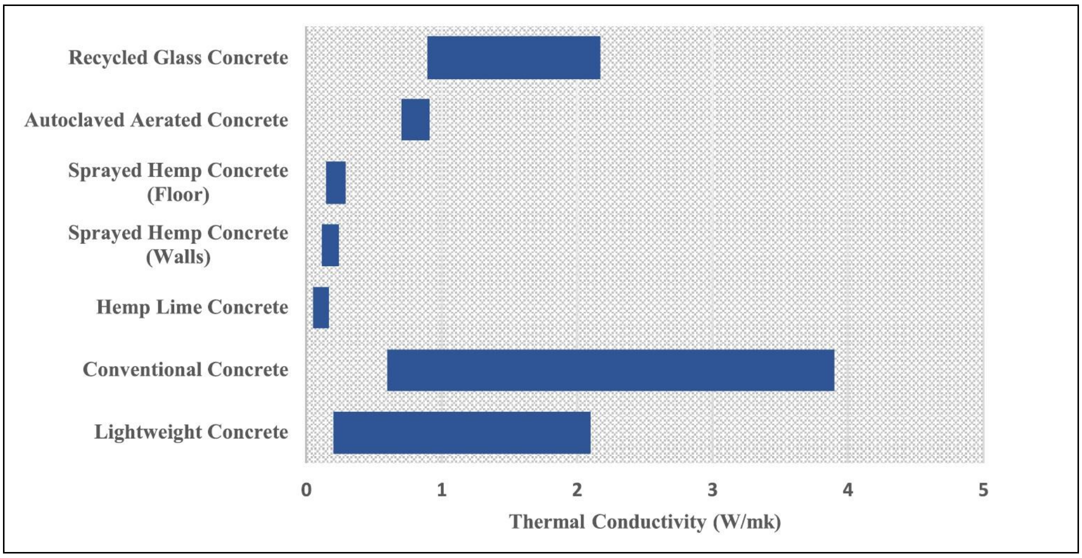


Figure 57. Comparison of hempcrete thermal conductivity with other types of concrete. (Source : Ansari, Tabish, and Zaheer 2025)

4.3.3.1 The Effect of Binder Composition

The Effect of binder composition on the thermal conductivity of hempcrete is shown in Figure 58. The differences in the thermal conductivity of the binder compositions were small.

The results agree with those obtained by Walker and Pavia (2014), Nguyen et al. (2010), and Ahmed et al. (2022), who found that the binder type does not significantly affect thermal conductivity. However, these results differ from those of Gourlay and Arnaud (2010), who found that thermal conductivity significantly varies with the type of binder.

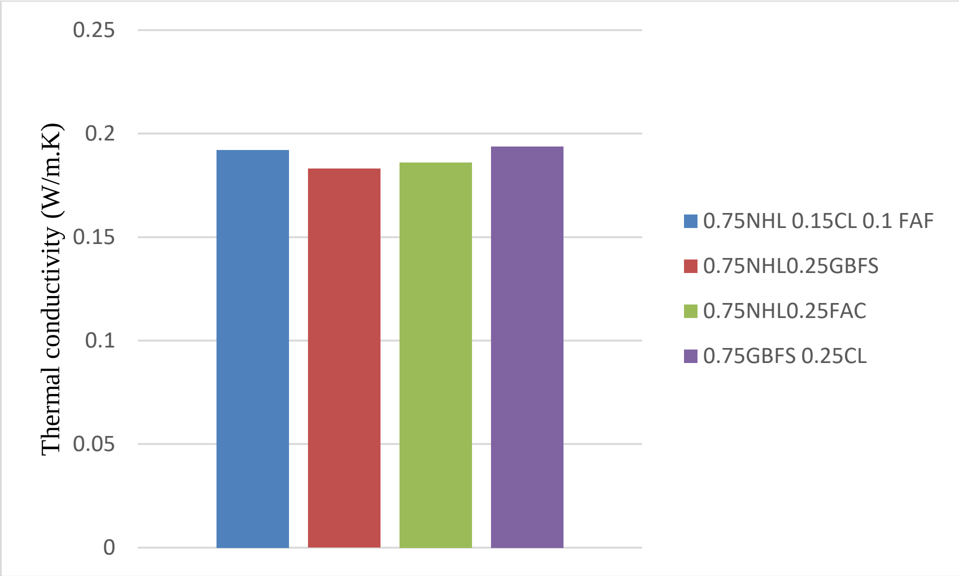


Figure 58. Effect of binder composition on the thermal conductivity of hempcrete.

4.3.3.2 The Effect of Particle Size

The particle size of hemp shives is a crucial factor that predefines the overall density and internal structure of hempcrete and, hence, its thermal conductivity. Mixtures containing finer hemp shives tend to have higher thermal conductivity values due to denser packing with fewer air pockets inside the material. The effect of hemp shives particle size on the thermal conductivity of hempcrete is shown in Figure 59.

Mix 7 had the finest particle size with fine hemp shives and gave the highest thermal conductivity value of 0.2139 W/m·K. The finer the size, the more the bulk density of the mix increases, thereby increasing the efficiency of heat conduction through the material.

Conversely, Mix 5 with coarse and Mix 6 with medium hemp shives have thermal conductivity values of 0.1918 W/m·K and 0.1938 W/m·K, respectively. Larger hemp shives create more air voids within the matrix, enriching the material's insulation capacity by reducing heat transfer.

The mix with fine shives was more sensitive to compaction, as the shives were arranged better, making the structure more compact and homogeneous. In contrast, the coarse and medium hemp shives were more variable and included long shives, making laying the mixture accurately difficult; therefore, the structure was less homogeneous.

The results were consistent with those reported by Brzyski et al. (2020), who also found that hempcrete with fine shives exhibits higher thermal conductivity than hempcrete with coarse shives. However, the results were inconsistent with those of Stevulova et al. (2012) and Williams et al. (2018), who found that the impact of particle size distribution on thermal conductivity could be negligible.

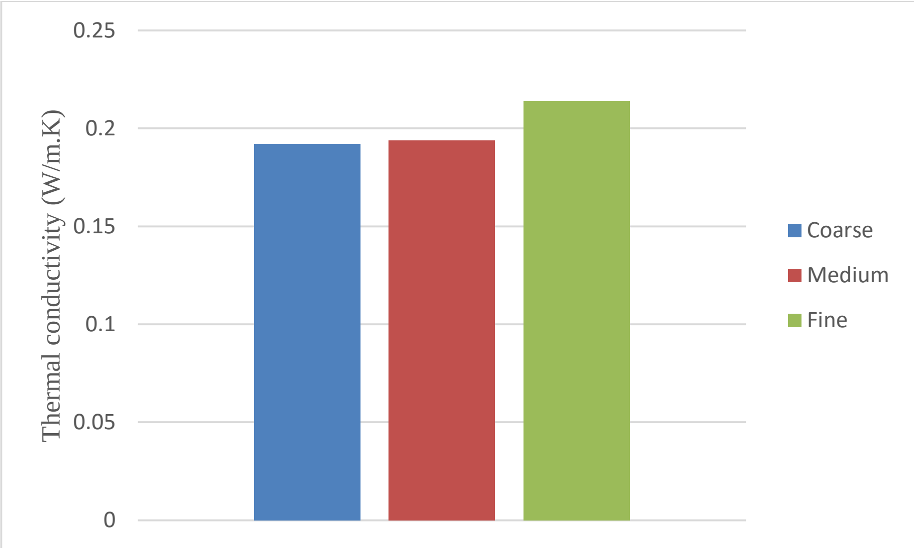


Figure 59. Effect of hemp shive particle size on the thermal conductivity of hempcrete.

4.3.3.3 The Effect of Hemp : Binder Ratio

The hemp-to-binder ratio also determines the degree of thermal conductivity within the composites. The results show that the composite with a greater amount of binder tends to have a slightly higher thermal conductivity only because of the increased density. The effect of hemp : binder ratio on the thermal conductivity of hempcrete is shown in Figure 60.

Mix 9, with a hemp-to-binder mix ratio of 1:4, develops one of the highest thermal conductivities of 0.212 W/m·K among the mixtures tested. The increased binder content in mixing results in a denser structure upon drying, facilitating more significant heat transfer.

The hemp : binder ratio of Mix 8, at a ratio of 1:2, has a lower thermal conductivity at 0.1416 W/m·K. Its reduced density, along with the lower binder content within this mix, contributes to the reduced rate of heat conduction.

The measured thermal conductivity in the hempcrete specimens tested in this study is within the findings of Williams et al. (2018), who observed a similar trend: an increase in the binder ratio leads to increased thermal conductivity. This rise is attributed to the more significant percentage of the stiffer, denser, and thermally conductive constituent.

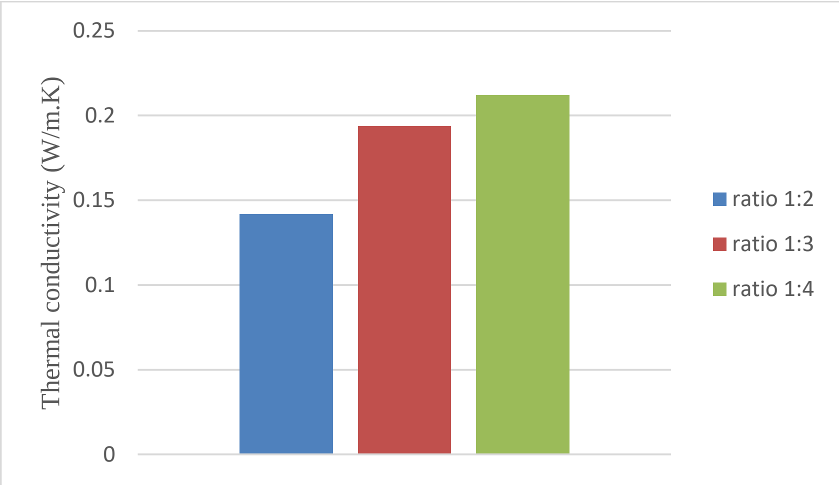


Figure 60. Effect of hemp : binder ratio on the thermal conductivity of hempcrete.

4.3.3.4 The Effect of Hemp : Water Ratio

The water content in the mixture has a slight impact on thermal conductivity. The effect of hemp : water ratio on the thermal conductivity of hempcrete is shown in Figure 61. When the water ratio increased from 1:2 as in Mix 1 to 1:2.5 as in Mix 5, thermal conductivity rose from 0.1881 to 0.1918 W/m·K. This increase was due to the enhanced density and, subsequently, the compaction of the specimen which facilitated heat transfer.

However, when the water ratio increased to 1:3, as in Mix 10, the thermal conductivity decreased to 0.1888 W/m·K. This decrease can be explained by the fact that too much water diluted the binder dispersion surrounding the hemp particles, increasing porosity. After drying, the excess water created voids of air that reduced heat transfer into the material and decreased its thermal conductivity.

The study by Gourlay et al. (2017) demonstrated that the thermal conductivity of various hemp concrete mixtures increases almost linearly with water content. This suggests that higher moisture levels within the matrix enhance thermal transfer, likely due to water's higher thermal conductivity than air. However, as demonstrated by Collet and Pretot (2014), water content has a lower effect on thermal conductivity than density.

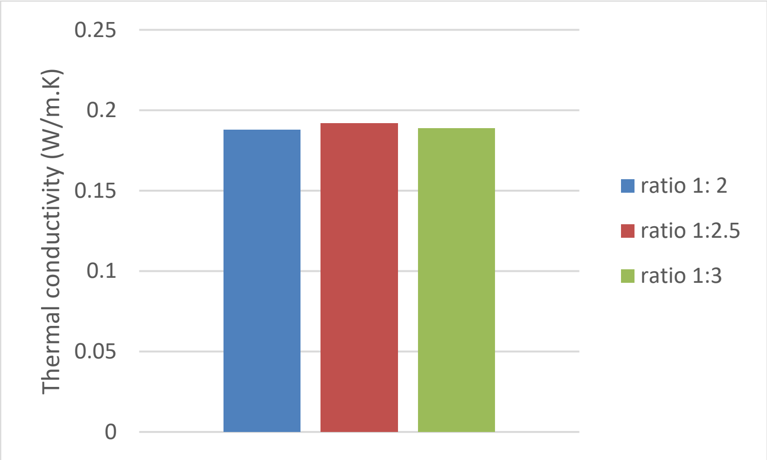


Figure 61. Effect of hemp : water ratio on the thermal conductivity of hempcrete.

4.3.4. Capillary Water Absorption

The hempcrete specimens initially absorb water quickly, but the rate gradually slows with time. All curves follow a similar trend, as illustrated in Figure 62.

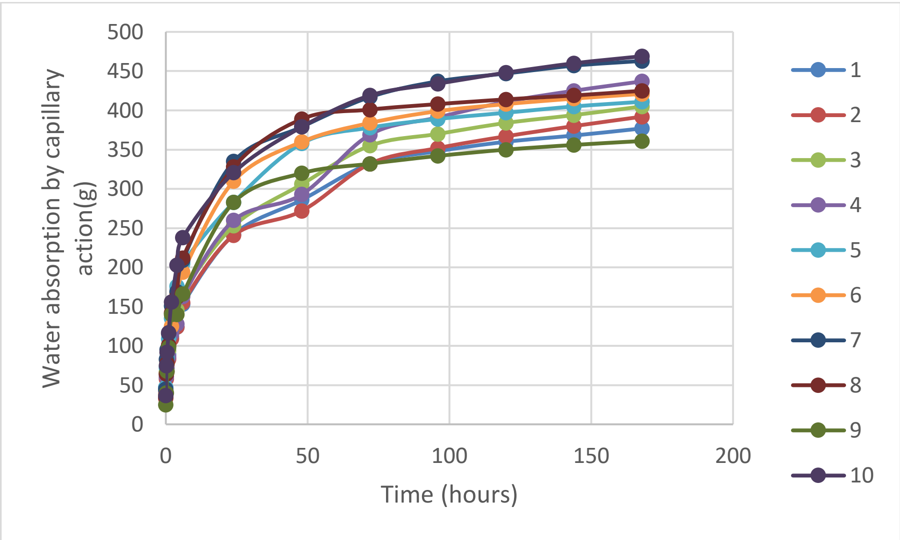


Figure 62.The capillary water absorption of hempcrete specimens for 7 days.

There is fast water absorption during the early stage and a gradual plateau as they approach saturation. Lower values indicate a less absorbent mix, while higher values suggest a more porous and absorbent mix.

The capillary water absorption behavior of hemp shives particles in hempcrete occurs in two stages, as Page et al. (2017) described. In the first stage, the particles undergo an almost quick increase in mass. The surface of the hemp aggregates quickly absorbs water upon contact, highlighting the materials' rapid absorbing properties. This phase occurs quickly and is often complete in minutes to hours, depending on the particle size and surface area. The second stage occurs more gradually as water penetrates deeper into the internal structure of the shive particle. This slower process involves water diffusion through the plant material's cellular structure. This phase can last up to 48 hours or more.

The porous nature of composites determines their absorbability. The rate of capillary water absorption varies significantly among the hempcrete mixtures. In mix 10, the specimens with the highest hemp-water ratio of 1:3 have the highest capillary water absorptions, suggesting a correlation between increased water content in hemp and increased water absorption through capillary suction. The specimens of mix 9 with the highest hemp : binder ratio of 1:4 have the lowest capillary water absorptions, thus reducing the potential for water absorption. This result confirms the observations made in previous studies.

The water absorption coefficients obtained in this study were between 2.598 and 3.285 $kg/m^2h^{0.5}$, which fall within the range reported by Walker and Pavía (2014) who observed values between 2.65 and 3.37 $kg/m^2h^{0.5}$. These results are slightly higher than the absorption coefficients Brzyski and Suchorab (2020) reported for HLP1 (with a binder ratio of 2), ranging from 2.62 to 2.76 $kg/m^2h^{0.5}$. In contrast, the HLP2 (with a binder ratio of 1.5) composite in Brzyski and Suchorab's (2020) study showed a significantly higher coefficient, exceeding 4 $kg/m^2h^{0.5}$.

Furthermore, the absorption coefficients Page, Sonebi, and Amziane (2017) observed were lower, ranging from 0.81 to 2.52 $kg/m^2h^{0.5}$ indicates a lower water absorption capacity compared to this study and those by Walker and Pavía (2014) and Brzyski and Suchorab (2020).

4.3.4.1 The Effect of Binder Composition

The effect of binder composition on the capillary water absorption of hempcrete is shown in Figure 63. Mix 1 has the lowest water absorption among the mixes. The combination of NHL, HL, and FAF results in a binder that seems to produce a relatively less porous structure, possibly due to the pozzolanic reaction of fly ash contributing to denser matrix formation.

It is observed that replacing HL and FAF with GGBFS in Mix 2 results in a slightly higher water absorption. Mix 2 has a slightly more porous structure compared to Mix 1. The amount of pozzolanic material in the mix affects the reaction efficiency. More than 25% GGBFS might be needed to densify the matrix and reduce porosity. Curing conditions and moisture also affect the pozzolanic reaction. In some cases, incompletely developed pozzolanic reactions may reduce porosity.

Using FAC instead of GGBFS further increases the water absorption in Mix 3. FAC is more reactive than FAF because of its higher CaO content; however, this may lead to faster setting and incomplete pozzolanic reaction in a binder system with lime, leaving behind some open pore structure. This may explain why Mix 3 shows higher water absorption than Mix 1 despite containing pozzolans.

The binder composition in Mix 4 has the highest water absorption. Combining GGBFS and HL may lead to a more porous structure, allowing more water to be absorbed. GGBFS is a highly reactive pozzolan mixed with lime and water. However, Mix 4 could yield a structure expected to develop micro-pores due to unreacted GGBFS and hydrated lime particles. The ratio of GGBFS and HL, in this case, could yield an incomplete reaction during curing, hence increasing water absorption.

Another reason for this higher porosity may be the presence of HL content in Mix 4, as HL alone tends to yield more porous structures than hydraulic limes or fully pozzolanic reactions.

Replacing hydrated lime with pozzolanas makes the binder matrix denser due to the formation of hydration products from pozzolanic activity. This reduces porosity and also exhibits a filler effect on the voids (Zúniga, Eires, and Malheiro 2023). Water absorption differences are closely related to the type of binder used. Lime-based binders combined with pozzolanic materials (like fly ash and GGBFS) contribute to varying degrees of matrix density and porosity, directly impacting water absorption. This finding aligns with Walker and Pavia's conclusion that the type of binder, along with pozzolans such as metakaolin and GGBFS, influences the capillary absorption of hempcrete. These materials enhance the hydraulicity of the binder and reduce capillary absorption, likely due to the formation of hydrates (products of cement clinker and hydraulic lime hydration, as well as pozzolanic reactions) that fill micropores within the binder (Walker and Pavía 2014).

Even though pozzolanic materials generally reduce porosity, other factors such as binder proportions, type of pozzolan (FAC, FAF, GGBFS), efficiency of reaction, curing conditions, or presence of hydrated lime may also impact the resultant porosity and, hence, water absorption. Sometimes, the pozzolanic reaction is not fully developed, or the combination of materials may give residual porosity; that is why, in general, the decrease in water absorption is not as expected.

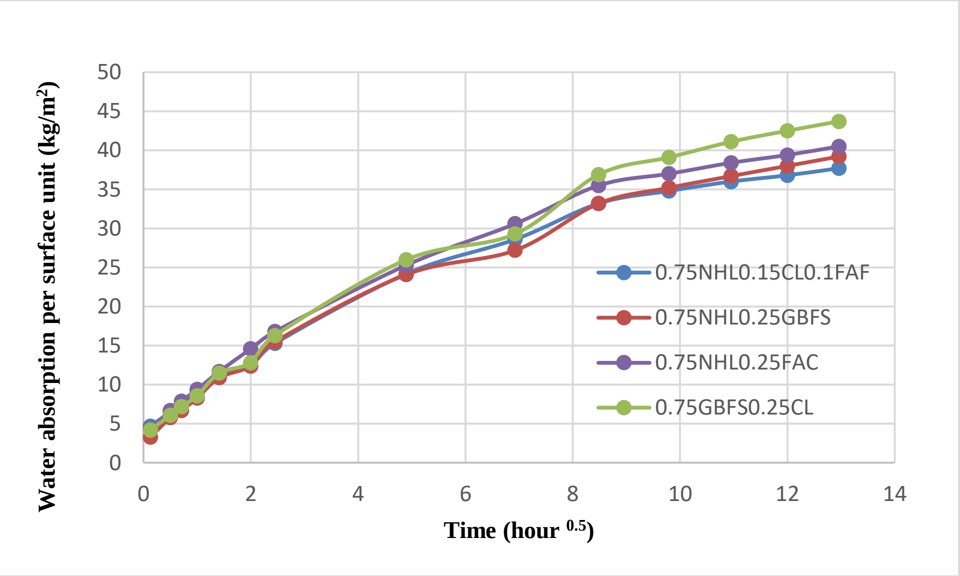


Figure 63. Effect of binder composition on the capillary water absorption of hempcrete.

4.3.4.2 The Effect of Particle Size

Hempcrete made with fine hemp shives had higher water absorption than that produced with medium and coarse shives. The effect of particle size on the capillary water absorption of hempcrete is shown in Figure 64.

Coarse hemp shives in Mix 5 have the lowest water absorption among the three sizes. This is likely because larger hemp shive particles have less surface area relative to their volume. With less surface area, there is less space for water to be absorbed into the structure. Additionally, coarser particles may create fewer overall voids in the matrix, leading to lower porosity.

Medium hemp shives in mix 6 show a moderate rise in water absorption. Since the shive is smaller than coarse particles, it has a higher surface area and could, therefore, create more voids in the matrix. This results in slightly higher porosity and water absorption.

Fine hemp shives in Mix 7 have the highest water absorption. Due to the much smaller particle size, the matrix may contain more micropores and have a much higher surface area. The fine particles lead to a more porous structure that can absorb more water due to the increased number of voids in the mixture.

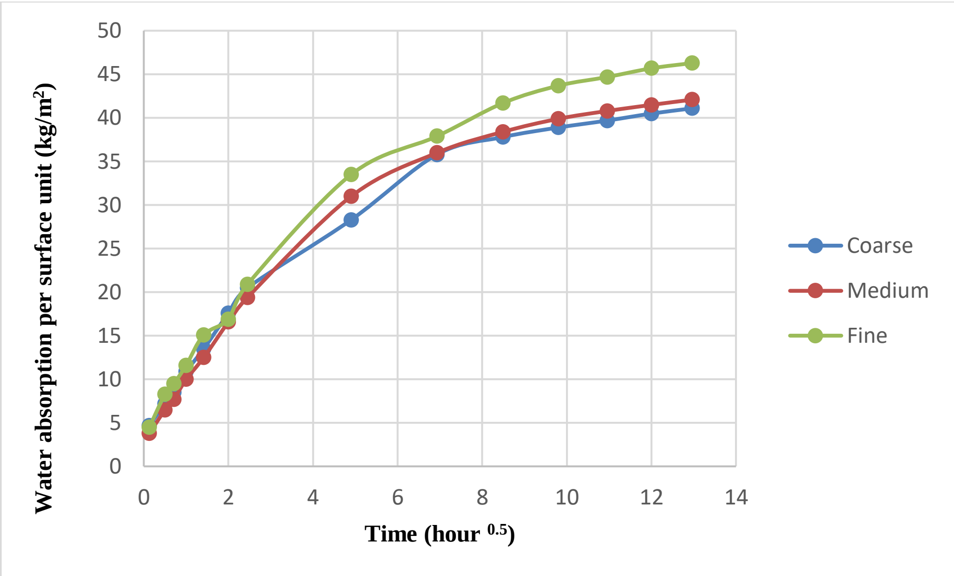


Figure 64. Effect of particle size on the capillary water absorption of hempcrete.

When the particle size decreases, water absorption increases due to the increased surface area. Consequently, there is a potential for more voids, which contribute to greater porosity in the hempcrete mixture. Moreover, fine hemp shives have a larger surface area relative to their volume, allowing them to adsorb more water than coarser hemp shives.

For instance, Mix 7, with a density of 685 kg/m³, exhibited higher water absorption (3.28 kg/m²·hr) compared to Mix 5, which had a lower density of 615 kg/m³ and a water absorption rate of 2.87 kg/m²·hr. The results of this study are consistent with those reported by Stevulova et al. (2012) and Brzyski et al. (2020), who also found that composites with fine shives exhibit faster and higher water absorption, which may be due to their larger specific surface area and the structure of the shives, particularly the opening of closed pores in the wooden core during crushing.

This study does not agree with the findings of Hussain et al. (2019), which stated that hempcrete specimens with lower density have higher water absorption due to more voids in the composite where water may become trapped during testing. Additionally, this study does not support the findings of Przemysław Brzyski et al. (2020), who reported that hempcrete made with longer hemp shives exhibits higher capillary water absorption than hempcrete made with fine hemp shives. The higher water absorption in the longer shives hempcrete in this study is likely due to the larger pores between the longer shives, which allow for more significant water movement. In contrast, smaller shives pack more closely together, resulting in fewer large pores.

4.3.4.3 The Effect of Hemp : Binder Ratio

The effect of hemp : binder ratio on the capillary water absorption of hempcrete is shown in Figure 65. Mix 8 has the lowest binder content of the other mixes. Water absorption is higher than the other binder ratios because less binder is available to fill the voids between the hemp particles. A more porous matrix is developed, which leads to increased absorption.

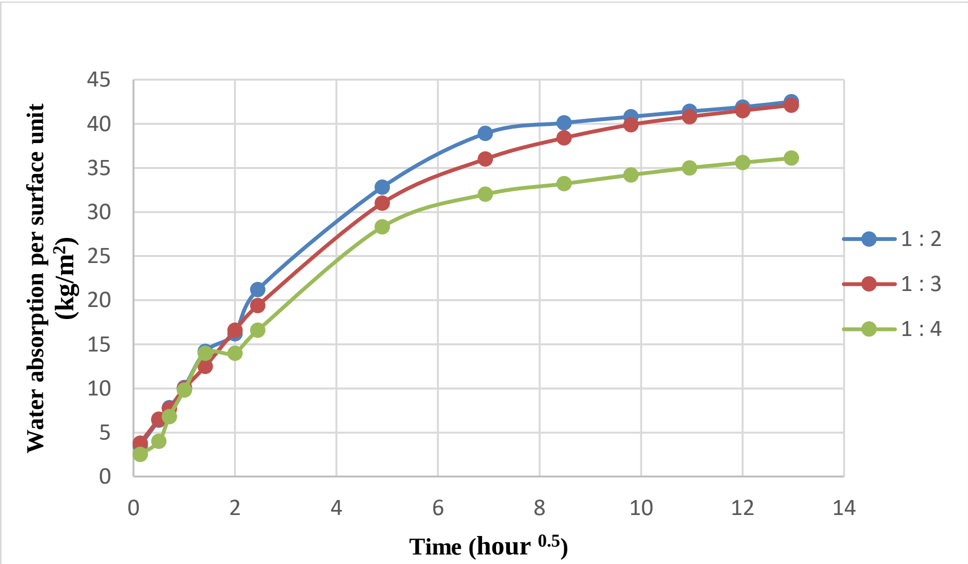


Figure 65. Effect of hemp : binder ratio on the capillary water absorption of hempcrete.

Mix 6 has lower water absorption than Mix 8 but higher than Mix 9. The increased binder content in the mixes makes the matrix less porous since more binder fills the gaps between hemp particles, thus reducing the matrix's ability to absorb more water.

Mix 9 has a higher binder content. Water absorption is less than that of mixes 8 and 6. As the binder content increases, the water absorption decreases more significantly. The additional binder effectively fills more of the voids in the matrix, resulting in a denser structure with fewer pores, which limits the water absorption capacity.

Some studies, such as the one by Page et al. (2017), show that the capillary water absorption of hempcrete depends significantly on the amount of shives used. A higher proportion of hemp shives or lower binder content increases capillary water absorption because more hemp shives increase capillary voids, which are directly linked to water absorption.

4.3.4.4 The Effect of Hemp : Water Ratio

The effect of hemp : water ratio on the capillary water absorption of hempcrete is shown in Figure 66. Mix 1, having a lower water content of a 1:2 ratio, yields a lower water absorption. The matrix is much denser since there is less excess water to evaporate and leave voids, thereby reducing the overall porosity of the material.

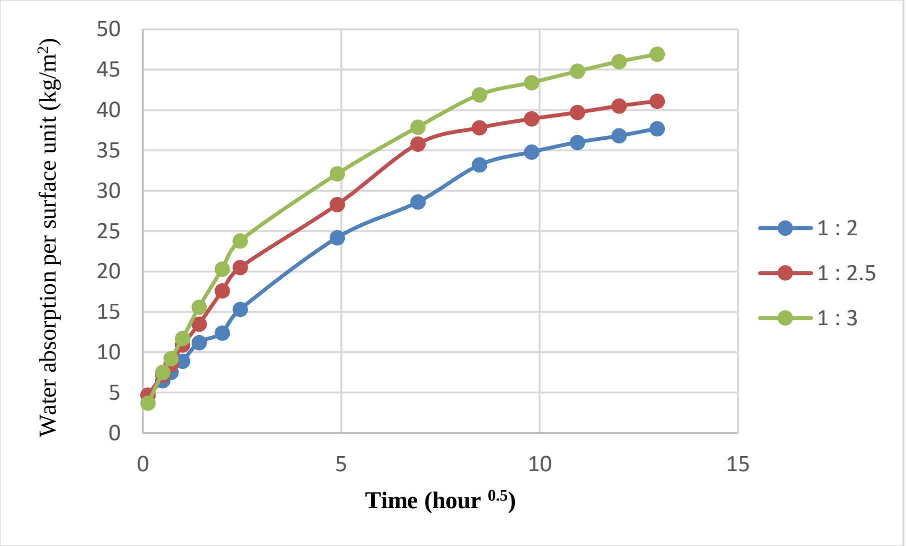


Figure 66. Effect of hemp : water ratio on the capillary water absorption of hempcrete.

Increasing the water content to 2.5 in Mix 5 slightly increases water absorption. Additional water in the mix likely forms more voids as it evaporates during curing, making the matrix more porous.

Mix 10 has the highest water absorption. The higher the water content, the more the porosity increases since more water evaporates, creating a more porous structure that absorbs more water.

4.3.5. Energy Absorption

The area under the stress-strain curve represents the energy absorbed by the material up to a certain point (usually until failure). It is also known as the toughness of the material. Hempcrete's energy absorption capability makes it a good material for impact-resistant structures. Its porous structure allows it to deform and absorb impact energy without breaking. As a result, hempcrete can be used to create structures that can withstand earthquakes, explosions, and other types of impact. The range of absorbed energy is between 24497 and 120400 N·mm, depending on the mixture, the direction of the hemp shives, and the testing age as presented in Table 11.

Table 11. Results of hempcrete absorbed energy at 28 and 180 days in parallel and perpendicular directions.

Mix	Binder composition	Hemp shive size	Hemp : Binder	Hemp : water	Absorbed Energy of Hempcrete Specimens at 28 days		Absorbed Energy of Hempcrete Specimens at 180 Days	
					Parallel to fiber direction N·mm.	Perpendicular to fiber direction N·mm.	Parallel to fiber direction N·mm.	Perpendicular to fiber direction N·mm.
1	0.75NHL 0.15HL 0.1 FAF	coarse	1 : 3	1: 2	49692	54000	60200	81500
2	0.75NHL0.25GBFS				41630	46800	51900	73400
3	0.75NHL0.25FAC				34459	46400	47900	59400
4	0.75GGBFS 0.25HL				49516	48700	58200	61800
5	0.75NHL 0.15HL 0.1 FAF	Coarse	1 : 3	1: 2.5	40825	44000	42,400	52800
6		Medium			44889	81900	44,900	74400
7		Fine			32841	48900	56500	66700
8	0.75NHL 0.15HL 0.1 FAF	Medium	1 : 2	1 : 2.5	24497	35400	37500	47600
6			1 : 3		44889	81900	44,900	74400
9			1: 4		51449	95900	65,000	120400
1	0.75NHL 0.15HL 0.1 FAF	Coarse	1 : 3	1: 2	49692	54000	60200	81500
5				1: 2.5	40825	44000	42,400	52800
10				1 : 3	27085	33900	27400	42600

The results indicate that the absorbed energy was higher in the perpendicular direction than the parallel direction, primarily due to the orientation of the hemp shives. The best mechanical properties can generally be obtained for composites when hemp shives are oriented perpendicular to the applied load, as this orientation creates better mechanical interlocking between the hemp particles and the binder. In contrast, when hemp shives are oriented parallel to the applied load, it results in weaker bonding at the interfaces between the hemp shives and the binder (Pickering, Efendy, and Le 2016). A comparison of the absorbed energy of hempcrete specimens at 28 and 180 days in parallel and perpendicular directions is shown in Figure 67.

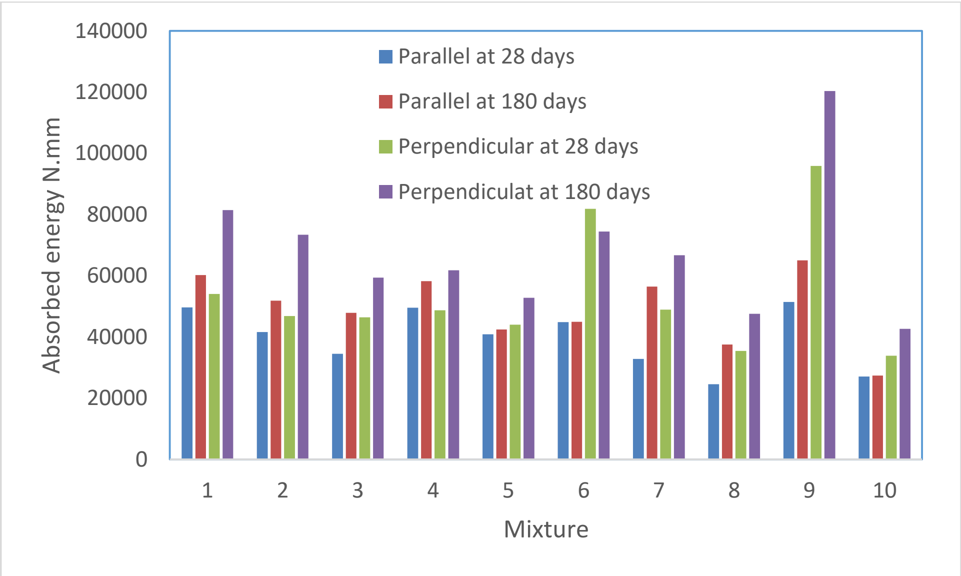


Figure 67. The absorbed energy of hempcrete specimens under compression at 28 and 180 days was evaluated in both parallel and perpendicular loading directions.

4.3.5.1 The Effect of Binder Composition

Mix 1 had the highest absorbed energy values in both parallel and perpendicular directions at 28 days and 6 months. At 6 months, it shows significant improvement, with 60,200 N·mm in the parallel direction and 81,500 N·mm in the perpendicular direction.

Mix 4, which consisted of GGBFS and HL, provided strong long-term energy absorption, while mixture 3, which consisted of NHL and FAC, resulted in lower absorbed energy. That demonstrates that FAC is less effective in enhancing toughness than GGBFS or FAF.

The results suggest that optimizing binder composition, particularly by using GGBFS or FAF, can significantly enhance the energy absorption capacity of hempcrete over time, especially in the perpendicular direction.

4.3.5.2 The Effect of Particle Size

Mix 6 with medium hemp shives showed the highest absorbed energy at 28 days, with 44889 N.mm in the parallel direction and 81900 N.mm in the perpendicular direction. At 180 days, it recorded 74400 N.mm in the perpendicular direction. In contrast, Mix 7 with fine hemp shives exhibited the lowest energy absorption at 28 days, especially in the parallel direction. However, at 180 days, it showed the highest absorbed energy in the parallel direction, reaching 56500 N.mm.

It can be concluded that medium hemp shives provide the best particle size for energy absorption, mainly when performance in the perpendicular direction is crucial.

4.3.5.3 The Effect of Hemp : Binder Ratio

The hemp : binder ratio impacts the mechanical properties and energy absorption of hempcrete. As the binder content increases, the absorbed energy also increases. Mix 9, with the highest binder content (1:4 ratio), showed the best performance in the parallel direction, with 51,449 N.mm at 28 days and 65,000 N.mm at 180 days, and in the perpendicular direction, with 95,900 N.mm at 28 days and 120,400 N.mm at 180 days. The much higher binder content improves the hemp-binder interaction and reduces voids, creating a more cohesive and compact structure.

Mix 8, with the lower binder content (1:2 ratio), had the lowest absorbed energy in the parallel direction, with 24497 N.mm at 28 days and 37500 N.mm at 180 days, and in the perpendicular direction, with 35400 N.mm at 28 days and 47600 N.mm at 180 days. It can be concluded that when there is not enough binder, the bond between the hemp and the binder becomes less effective, resulting in lower energy absorption and weaker overall mechanical performance.

4.3.5.4 The Effect of Hemp : Water Ratio

The hemp-water ratio significantly impacts the energy absorption and mechanical properties of hempcrete. Lower water content improves the mechanical performance. Mix 1 with lower water content (1:2 ratio) results in the best performance, with higher absorbed energy in the parallel direction, with 49692 N.mm at 28 days and 60200 N.mm at 180 days, and in the perpendicular direction, with 54000 N.mm at 28 days and 81500 N.mm at 180 days.

Mix 10 with higher water content (1:3 ratio), results in the lowest absorbed energy in the parallel direction, with 27085 N.mm at 28 days and 27400 N.mm at 180 days, and in the perpendicular direction, with 33900 N.mm at 28 days and 42600 N.mm at 180 days. Increasing the water content beyond what is necessary for the mixture prolongs the setting time, slows down strength development, and diminishes mechanical performance. The optimal energy absorption is achieved with lower water content (1:2), while higher water content (1:3) reduces energy absorption regardless of particle size.

4.3.6. Impact Test

The impact behavior of hempcrete was investigated by dropping a 15 kg drop weight on hempcrete specimens placed on top of a reinforced concrete beam, as shown in Figure 68.

Figure 68. An experimental setup was used to investigate the impact behavior of hempcrete.

The binder used for all hempcrete specimens was 0.75 NHL 0.15 CL 0.1 FAF. Two different hemp : binder : water ratios were used for specimens as 1:3:2.5 and 1:2:2.5, and three specimens were tested from each ratio.

Impact tests were performed from two different heights of 30 cm and 100 cm to observe the impact absorbing capacities of hempcrete specimens under different impact energies. In addition, impact tests directly on the reinforced concrete beam without hempcrete were also performed for each height after all tests with hempcrete were completed. Accelerations on the drop weight and midspan displacement of the reinforced concrete beam were recorded in each test. High-speed camera recordings were also taken during the tests. Figure 69 A) shows the impact test with hempcrete, while Figure 69 B) shows the impact test without hempcrete.

Figure 69. Impact test: A) with hempcrete and B) without hempcrete.

A comparison of the maximum accelerations is presented in Table 12. Acceleration-time response of the drop weight for 30 cm and 100 cm drop heights are presented in Figures 70 and 71, respectively. Note that acceleration experienced by the drop weight multiplied by its mass gives the impact force transmitted to the specimens. Therefore, higher accelerations measured on the drop weight indicate higher impact force imparted on the bottom reinforced concrete beam.

As seen in the figures, hempcrete greatly affected the impact force experienced by the reinforced concrete beam. Compared with the accelerations measured on tests with no hemp, it can be observed that the presence of hempcrete significantly reduced the impact force.

It can be seen in Table 12 that hempcrete reduced the impact accelerations from 62 to 84%. The effect of hempcrete is more significant for the higher drop height, as reductions in the impact accelerations are more significant than those without hemp.

Table 12. Maximum accelerations recorded on the drop weight.

Drop height	Specimen Type – Test	Max. acceleration (g)	Difference with respect to "No Hemp" (%)
30 cm	No Hemp	154	-
	1:3:2.5 (1)	58	62
	1:3:2.5 (2)	62	60
	1:3:2.5 (3)	64	58
	1:2:2.5 (1)	50	68
	1:2:2.5 (2)	50	68
	1:2:2.5 (3)	50	68
100 cm	No Hemp	534	-
	1:3:2.5 (1)	104	81
	1:3:2.5 (2)	110	79
	1:3:2.5 (3)	112	79
	1:2:2.5 (1)	92	83
	1:2:2.5 (2)	86	84
	1:2:2.5 (3)	90	83

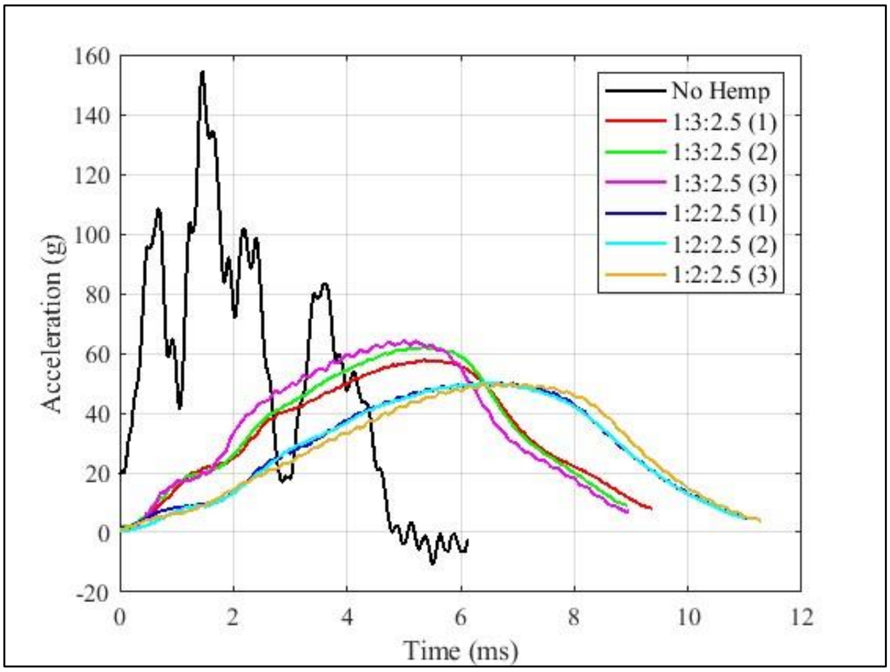


Figure 70. Effect of hemp : binder : water ratio on the drop weight acceleration-time response for 30 cm drop-height.

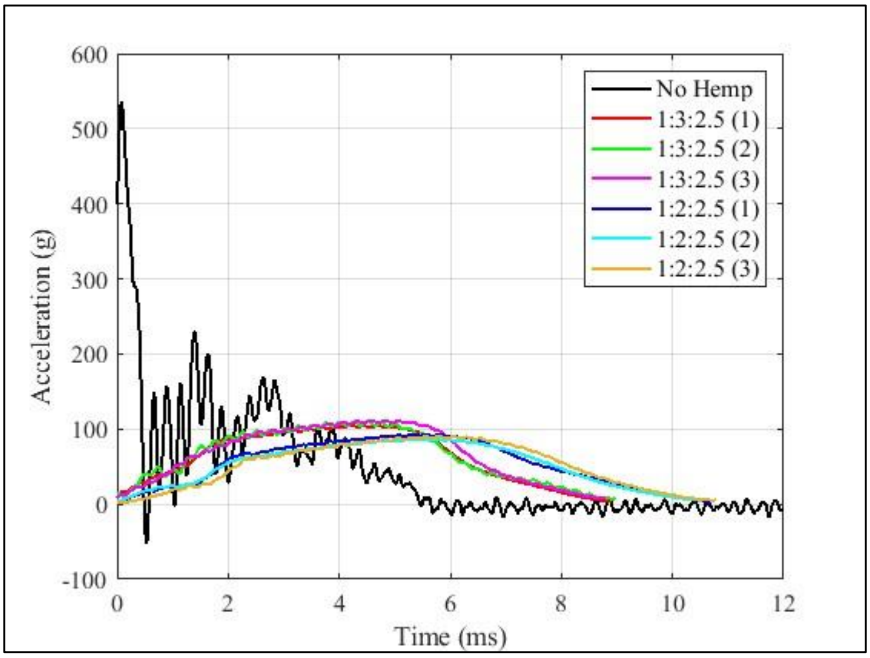


Figure 71. Effect of hemp : binder : water ratio on the drop weight acceleration-time response for 100 cm drop-height.

It has to be noted that the reinforced concrete beam did not suffer any visible damage or cracking in any of these tests except for the case of impact from 100 cm with no hemp. The beam developed some shear and bending cracks in this last test, as shown in Figure 72. Therefore, hempcrete effectively protected the reinforced concrete beam, which would otherwise suffer damage.

Figure 72. Damage suffered by the reinforced concrete beam after 100 cm drop test with no hempcrete.

The effect of hemp : binder: water ratio on the drop weight acceleration-time response was also clear. As seen for both drop heights, specimens with higher binder content resulted in higher drop weight accelerations. In addition, lower binder content resulted in a higher contact duration. As the binder content was reduced, the cushion effect of hempcrete became more pronounced. Similar observations can also be made when mid span displacement responses of the reinforced concrete beam were compared for tests.

Figures 73 and 74 present the midspan displacements of the beam for 30 cm and 100 cm drop heights, respectively. Note that in the figures, time zero corresponds to the time when the drop weight acceleration started to increase, or the drop weight made its first contact with the specimen. Therefore, the time elapsed until the first non-zero displacement was recorded on the beam partly corresponds to the compaction time of the hempcrete until the force is transferred to the beam. This delay highlights the energy absorption characteristics of hempcrete, where its compressibility helps dissipate impact forces before transmitting them to the reinforced concrete beam.

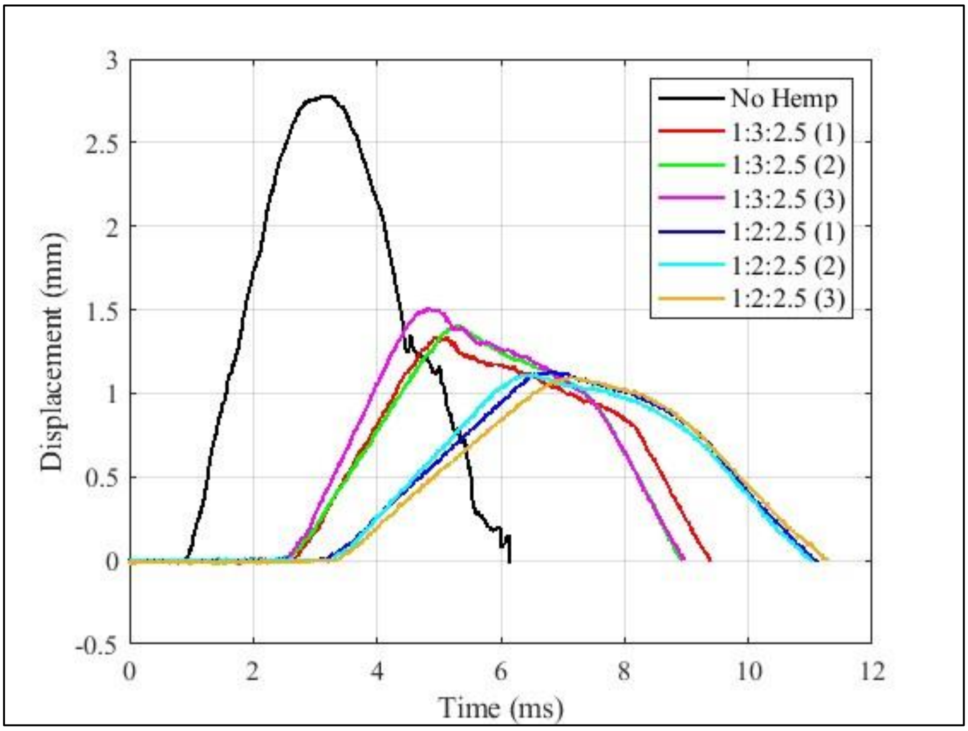


Figure 73. Effect of hemp : binder : water ratio on the mid-span displacement response of reinforced concrete beam for 30 cm drop-height.

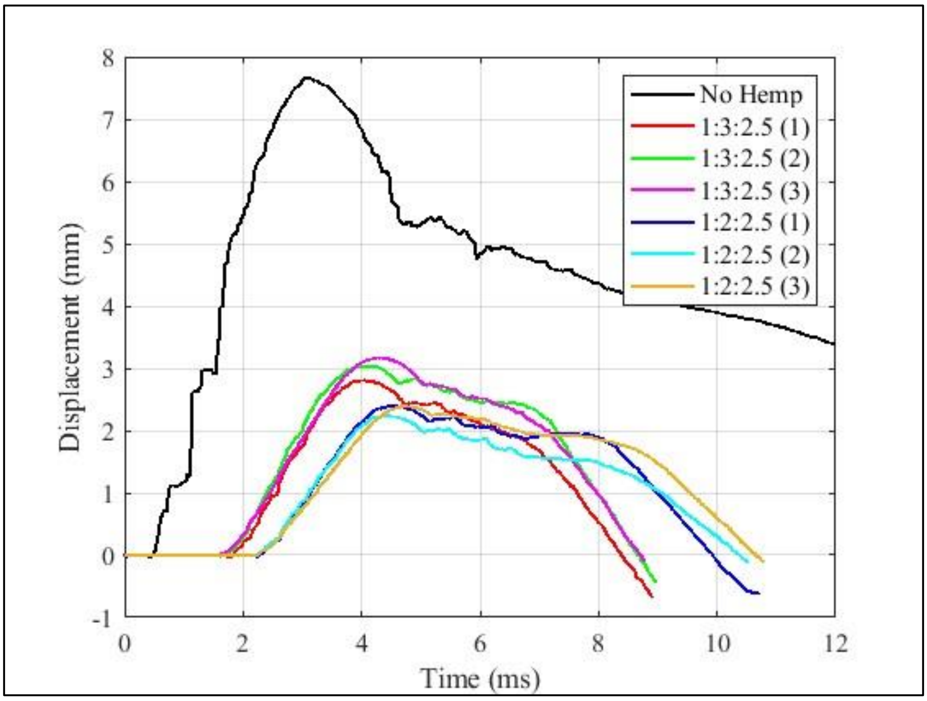


Figure 74. Effect of hemp : binder : water ratio on the mid span displacement response of reinforced concrete beam for 100 cm drop-height.

As seen in the figures, hempcrete was very effective in reducing the displacements of the reinforced concrete beam. A comparison of maximum displacements are presented in Table 13. It can be seen that hempcrete reduced the maximum displacements of the beam from 46 to 71% compared to the case without hempcrete. Percentage reduction in displacements was higher in the case of higher drop height. When the effects of hemp : binder : water ratio were investigated, in agreement with the acceleration results, higher binder content resulted in higher beam displacements. In addition, compaction time was higher in specimens with lower binder content. In general, hempcrete with lower binder content had a better cushioning effect, reducing the impact force and resulting displacements more effectively, possibly through enabling more compaction and dissipation of the impact energy. On the other hand, when the hempcrete blocks were investigated after the tests, it was observed that the blocks with lower binder content were in poorer condition, almost at the edge of crumbling when handled (Figures 75 and 76). Hempcrete blocks with higher binder content were more intact and in better condition, although they were also loose.

Table 13. Maximum mid-span displacements recorded on the reinforced concrete beam.

Drop height	Specimen Type – Test	Max. displacement (mm)	Difference with respect to "No Hemp" (%)
30 cm	No Hemp	2.8	-
	1:3:2.5 (1)	1.3	54
	1:3:2.5 (2)	1.4	50
	1:3:2.5 (3)	1.5	46
	1:2:2.5 (1)	1.1	61
	1:2:2.5 (2)	1.1	61
	1:2:2.5 (3)	1.1	61
100 cm	No Hemp	7.6	-
	1:3:2.5 (1)	2.8	63
	1:3:2.5 (2)	3.1	59
	1:3:2.5 (3)	3.2	58
	1:2:2.5 (1)	2.4	68
	1:2:2.5 (2)	2.2	71
	1:2:2.5 (3)	2.4	68

Figure 75. Hempcrete block 1:3:2.5 (1)

Figure 76. Hempcrete block 1:2:2.5 (3)

After performing impact tests on hempcrete, its ability to absorb impact forces has been demonstrated, confirming its suitability for protective applications. Hempcrete can be used in car parks to protect structural elements from accidental vehicle crashes. Similarly, it can be used in industrial locations, such as factories, to protect structural elements from potential damage from crane operations when moving products around. Besides its protection function, hempcrete's natural impact-absorbing and deformable properties, without smashing it, make it a viable, sustainable alternative to conventional materials in impact protection. Being lightweight further reduces the overall load on the structure, adding to the thermal and acoustic insulation; this improves the environment within both industrial and commercial buildings.

CHAPTER 5

CONCLUSIONS

5.1. Objective and Contribution to Knowledge

The study aimed to investigate the effect of different types of pozzolans in hempcrete and to improve their performance while reducing their environmental impact. Knowledge Development Contribution: Extensive investigation on density, compressive strength, thermal conductivity, capillary water absorption, and energy absorption of hempcrete was carried out, considering several parameters such as binder compositions, hemp shives particle size, hemp/binder ratio, and hemp/water ratio.

The increased strength of hempcrete enhances the load-bearing capacity and stiffness of the structure, but it also results in adverse effects, such as increased density and reduced thermal insulation.

Considering the better thermal properties, lower water absorptivity, and greater stability under compressive load, medium hemp shives are more effective as a filler in a hemp-lime composite for use as a timber frame wall-filling material or insulation prefabricate.

5.2. Conclusions

The highest compressive strength of the binder does not necessarily result in higher overall strength for the hempcrete. The results show that the choice of binder compositions depends on the properties required for hempcrete.

An increased water content extends the setting time, while hydrated lime improves the workability of the hempcrete mixture. The water demand for hemp shives varies depending on the aggregate size. Coarse hemp shives require less water, with hemp : water ratio of 2 being ideal, while medium and fine hemp shives prefer a ratio of 2.5.

Medium hemp shives were easier to work with than coarse hemp shives, as they were simpler to compact into molds. While fine hemp shives were also easy to work with, they tended to form balls, making it difficult to spread the binder evenly.

According to the results, the density of hempcrete depends more on the hemp shive particle size and hemp : binder ratio than on the hemp : water ratio and binder composition. Hempcrete specimens with lower hemp : binder ratio had the lowest density among the mixtures, while those with higher hemp : binder ratio had the highest density. The hemp : binder ratio plays a significant role in the density of hempcrete. Increasing the binder content, or, in other words, decreasing the hemp content, increased the density as the binder filled more voids. On the other hand, higher hemp content reduced the density due to the porous and lightweight properties of hemp shives.

The difference in strength between parallel and perpendicular directions demonstrates the influence of fiber alignment and the anisotropic characteristics of hempcrete on its mechanical properties. Some researchers prefer testing the hempcrete specimens parallel to hemp shives orientation because, in this direction, the relation between stress and strain indicates the performance of specimens by giving a plateau and the highest strength. In this study, it was observed that the perpendicular direction also reflected the performance of the specimens if they were compared at a specific strain ratio.

The hemp shive particle size significantly influences the compressive strength of hempcrete, the hemp : binder ratio, and the hemp water ratio. Specimens with a binder composition of (0.75NHL0.15CL0.1FAF) exhibited the highest compressive strength at 180 days compared to other binder compositions. Similarly, specimens containing medium-sized hemp shives showed greater compressive strength than those with other particle sizes. Specimens with a hemp : binder ratio 1:4 also outperformed those with other ratios. Additionally, specimens with a lower hemp-to-water ratio demonstrated superior compressive strength relative to higher ratios.

Compressive strength tests show that hempcrete hardens slowly over time. Initially, due to the hemp particles, it behaves ductile, but as the binder hydrates, strength increases, and ductility decreases. The compressive strength results at 28 and 180 days in both parallel and perpendicular directions indicate that hempcrete's strength increases over time due to ongoing binder hydration and carbonation. However, the rate of increase varies depending on the binder composition, hemp shive particle size, and the hemp : binder and hemp : water ratios.

According to the results, the most significant factors affecting the thermal conductivity of hempcrete were the hemp shive particle size and the hemp : binder ratio. In contrast, the binder composition and hemp : water ratio were less significant.

The density of hempcrete plays a significant role in determining its thermal conductivity, as evidenced by the results and the observed relationship between thermal conductivity and density in the dry state across all design mixes. Specimens with lower hemp : binder ratio (1:2) had the lowest thermal conductivity, with values of 0.14 W/mK among the mixtures, while specimens with higher hemp : binder ratio (1:4) had the highest, with values of 0.212 W/mK.

The hemp : binder ratio plays a significant role in the density of hempcrete. Increasing the binder content (or decreasing the hemp content) increases the density as the binder fills more voids, subsequently increasing thermal conductivity. On the other hand, higher hemp content reduces the density due to the porous and lightweight properties of hemp shives, which subsequently decreases thermal conductivity.

The research demonstrated that water absorption in hempcrete is significantly influenced by a binder composition, the hemp shive particle size, the hemp-to-binder ratio, and the hemp-to-water ratio. Specimens with fine hemp shives showed the highest water absorption due to the increased surface area of the smaller particles, which require more water during mixing. Specimens with coarse hemp shives absorbed less water demonstrating that larger particles reduce the water retention capacity of the mix.

Lower water absorption was observed in mixtures with a lower hemp : water ratio. Specimens with a lower hemp : water ratio (1:2) exhibited the lowest water absorption . In contrast, specimens with higher water ratios (1:3) resulted in increased water absorption. Excess water in the mixture leaves voids after drying, and when exposed to water, it fills with moisture, increasing water absorption. Moreover, excess water content extends the setting time and enhances the water absorption capability of hempcrete.

Increasing the binder content reduced water absorption. Specimens with a higher hemp : binder (1:4) exhibited lower water absorption compared to those with lower hemp : binder (1:2). A higher binder content improves the material’s ability to resist water penetration due to better bonding between the particles.

The results indicate that the absorbed energy was higher in the perpendicular direction than the parallel direction, primarily due to the orientation of the hemp shives. In the perpendicular direction, the hemp shives compress, reducing voids. The load aligns with the compaction direction in this direction, and mechanical interlocking occurs between the shives and the binder. In contrast, in the parallel direction, compression of the hemp shives results in weaker bonding and limited mechanical interlocking, resulting in specimen fragmentation and less energy absorption.

The energy absorption of hempcrete, like its compressive strength, is significantly influenced by the hemp shive particle size, the hemp-to-binder ratio, and the hemp water ratio.

The presence of hempcrete in the experimental setup significantly reduces the impact force compared to tests without hempcrete, demonstrating its effectiveness in absorbing and dissipating impact energy. Hempcrete effectively protected the reinforced concrete beam under, which would otherwise suffer damage. The effect of hempcrete is more significant for the higher drop height.

For both drop heights, 30 cm and 100cm, specimens with higher binder content resulted in higher drop weight accelerations. In addition, lower binder content resulted in a higher contact duration. As the binder content in hempcrete decreases, the material becomes more flexible, which results in a longer contact duration during impact and a more pronounced ability to absorb and dissipate impact energy (the "cushion effect"). Conversely, higher binder content makes the hempcrete stiffer, leading to higher accelerations upon impact.

When the effects of the hemp : binder: water ratio were investigated, the acceleration results were in agreement, and higher binder content resulted in higher beam displacements. Hempcrete with lower binder content had a better cushioning effect, reducing the impact force and resulting displacements more effectively, possibly by enabling more compaction and dissipation of the impact energy. On the other hand, when the hempcrete blocks were investigated after the tests, it was observed that the blocks with lower binder content were in poorer condition, almost at the edge of crumbling when handled.

Impact tests have shown that hempcrete effectively absorbs impact forces, making it suitable for protective applications. It can be used in car parks to protect structural elements from vehicle collisions and in factories to prevent damage from crane operations.

5.3. Future Studies

A recommended future study would examine the durability of the hempcrete mixtures used in this research against severe conditions such as high humidity and freeze-thaw cycles. Since this material can potentially be used for soundproofing purposes, the acoustic insulation properties of the suggested hempcrete compositions could also be studied.

A complete LCA of hempcrete mixtures could be conducted better to quantify their environmental impact from cradle to grave. This analysis gives valuable insights into the benefits of sustainability with hempcrete compared to traditional materials throughout its life cycle.

Another future study could cast reinforced hempcrete beams with sustainable reinforcement materials, such as bamboo bars, basalt fiber rebar, or glass fiber rebar, and then be tested to examine their performance under impact load.

A study could investigate the fire resistance of hempcrete mixtures, exploring the effects of different binder compositions and additives on improving its fireproofing capabilities.

A study could create a well-graded mix of hemp shives comprising coarse, medium, and fine particles and compare the results with those investigated in this study.

Another study could investigate the effect of the length of hemp shives by using short hemp shives rather than elongated ones in hempcrete mixtures.

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Work Experience

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  School Construction Projects, Mosul, Iraq, 2012–2013.
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- Site Engineer
  Residential Housing Complex, Salahdin, Iraq, 2013–2014.
  Managed on-site engineering tasks for a housing complex project, including supervising construction phases, liaising with contractors, and monitoring project progress.
- Lecturer
  Architecture Department, Mediterranean International University, Libyan Private University, Istanbul, Türkiye, 2018.
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Publications

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