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Review

State of the Art Review of Attributes and Mechanical Properties of Hempcrete

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Abstract: The global surge in environmental pollution, largely attributed to industrialization, has fueled a pressing need for sustainable solutions. In response, the construction sector is increasingly focusing on bio-based materials such as hemp, recognized for its low environmental footprint and prominent carbon-negative quality. As designers, housebuilders, and an environmentally conscious society pivot towards ecological alternatives to standard building materials, hempcrete emerges as a promising candidate. As a composite material mainly made from hemp hurd/shiv, water, and lime, hempcrete offers the ability to sequester carbon long after its incorporation into structures. As a result, the hemp cultivation process—which can be completed within less than four months—ensures that more carbon is absorbed during production and deployment than emitted, e.g., per one study, sequestration on the order of 300 kg of CO_2 per m^3 of hempcrete. In comparison to concrete, hempcrete offers a more sustainable footprint, given its recyclability post life cycle. This state-of-the-art review paper delves deep into different aspects of hempcrete, summarizing its multifaceted attributes, particularly its compressive strength. Based on the study conducted, the paper also suggests strategies to augment this strength, thereby transitioning hempcrete from a non-load-bearing material to one capable of shouldering significant weight. As architects and designers consistently strive to align their projects with high ecological standards, focusing not just on aesthetic appeal but also environmental compatibility, hempcrete becomes an increasingly fitting solution for the future of construction.

Keywords: hemp; hempcrete; insulation; sustainable material; zero-carbon concrete

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1. Introduction

In the face of the escalating climate emergency, there is an undeniable urgency. The stark reality is that the time to act and address the climate crisis is now; any delay only accelerates the impending repercussions. The construction industry which accounts for a staggering 38% of all carbon dioxide emissions in the United States stands at the forefront of this battle against environmental degradation. Given that buildings consume approximately 40% of all energy used in the U.S., there is a pressing need to innovate and shift towards sustainable, energy-efficient, and environmentally friendly construction practices [1–5].

As a primary component of concrete and traditionally a staple in the construction industry, cement has been identified as a significant polluter. As this material becomes scarcer and its cost escalates, relying on such a polluting substance in massive quantities is no longer sustainable. The race for dwindling natural resources will intensify in tandem with the growth of global economies and populations. In this dire situation, it is paramount to adopt resources that are sustainable and healthy, ensuring that our present actions do not jeopardize the needs of future generations.

Modern challenges compel scientists, engineers, and construction manufacturers to search for natural alternatives to widely used materials. The emphasis on ecology and sustainability has never been more pronounced. Traditional insulating materials used for residential and commercial buildings have remained unchanged for decades, many of which have adverse environmental and health impacts. As global efforts tilt towards improving insulation to reduce energy consumption, there is an impending increase in the volume of insulating materials used. This scenario underlines the urgency to adopt composite materials like hempcrete, the main ingredient of which, hemp hurd, is renewable, environmentally benign, and derived from waste streams or by-products of the hemp stalk, with bast fibers being the more valuable part. In comparison to conventional insulating materials such as fiberglass batt, hempcrete has superior environmental advantages [4,6].

A promising solution lies in hemp, often lauded as a "miracle crop" for its carbon-negative cultivation. Hemp is a non-psychoactive variant of *Cannabis sativa* L. and possesses physical attributes that make it an ideal candidate for use in construction. As an eco-friendly bio-aggregate lightweight mixture, hempcrete is a composite material primarily crafted from lime and the inner woody core of the hemp crop, known as hemp hurd or shives. Although it is most commonly employed in wall construction [2,3,7], its versatility extends to floor slabs, ceiling, and roof insulation [2–4,8]. Notably, hempcrete blocks are rapidly becoming a preferred choice for wall and roof construction. Furthermore, hempcrete is not only an effective insulator but also an economical choice for both new builds and refurbishments. Estimates suggest that walls constructed using hempcrete can be cost effective at around USD 135/m^2 with a workforce of 5–6 [4,9,10]. Estimated prices are subject to change based on the project type, material source and location, and labor cost. While we may focus on its upfront costs, hempcrete stands out as an exceptional building material. Notably, it excels in regulating indoor temperatures, proving its effectiveness particularly in humid settings by resisting mold. Over time, the advantages of reduced energy consumption in buildings manifest, translating into notable savings on heating and cooling expenses throughout the building's life cycle. This not only offers financial relief but also fosters the well-being of the building's occupants. There are signs that show the home building industry is starting to recognize hempcrete for its thermal benefits and its environmentally friendly nature. Moreover, with the anticipated increase in hemp availability, we can expect the cost of hempcrete to decrease, making it an even more cost-effective and appealing choice for builders and homeowners.

Currently, the use of hempcrete is more as an insulation material or non-load bearing nonstructural component [11–14], but it also does have the potential to be used as an alternative to more conventional building materials such as concrete masonry units or lightweight autoclaved aerated concrete [15–17].

The scope of this paper is to offer a thorough examination of hempcrete, highlighting its diverse properties and significance for construction. The intended perspective, its basic definition, reasons for its adoption, and consideration of its key characteristics are meant to primarily be of interest to the home building construction sector. Both its advantages and limitations are explored, and an examination of how various binders, like nano-particles, cement, natural hydraulic lime (NHL), and magnesium oxide (MgO), influence its mechanical attributes is undertaken. Special focus is placed on hempcrete's vital features, such as its density, strength, fire resistance, durability, thermal and acoustic properties, and, notably, its environmental sustainability. Based on past research results, suggestions are made on ways to enhance hempcrete's compressive strength, with the objective of transitioning it from a supplementary material to a primary load-bearing option.

2. Methodology

A broad array of sources was reviewed to compile the literature for this paper, focusing on scientific and industrial insights. The relevant literature was retrieved from databases such as Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. The search was guided by terms including "hemplime", "hempcrete", "properties of hempcrete", "applications of hempcrete", "Carbon Sequestration of hempcrete", "lime binders", "hempcrete binders", "mechanical properties of hempcrete", and "compressive strength of hempcrete". A wide variety of sources, such as books, chapters, journal papers, web publications, reports, standards, and theses, were used for this literature review.

The primary goal of this paper is to introduce hempcrete as an emerging construction composite material, with the main objective of exploring its mechanical properties and the compressive strength it offers. In particular, we delve into the practical application of hempcrete as a new construction material, outlining its advantages, shortcomings, and potential uses. By providing a comprehensive overview of hempcrete's properties and potential applications, this paper illustrates its viability as a sustainable and environmentally friendly building material. The measures considered in screening the literature for relevance to this study include the following: stated objectives, research methods, materials employed, properties of the materials, potential applications, and future research directions.

3. Definition of Hempcrete

3.1. Understanding Hempcrete

A bio-fiber composite made up of hemp hurd or shiv (Figure 1) and mineral binder, hempcrete is a form of lime-based construction material. The binder that is made by combining water with these ingredients is expected to completely coat all of the hemp shiv particles after sufficient mixing. A chemical reaction between the lime binder and water hardens the binder, cementing the hurd pieces together. The term "bonded cellulose insulation" could be broadly used to describe this mixture. Hempcrete is what is left after the binder has dried and been allowed to build up strength with time. In contrast to the binder used in many other construction composites (including concrete, mortar, and plaster), the purpose of the binder in hempcrete is only to coat the hemp particles and make them attach to one another. The final output of a hempcrete mixture often has a great deal of void space, which gives hempcrete its excellent thermal and moisture-handling properties, making it a desirable insulation material for buildings. Depending on the combined factors, hempcrete can be used for a variety of purposes and formed into building components, including roof, wall, and floor insulation [18–21].

Figure 1. Hemp fiber (**left**), hemp hurd (**center**), and hempcrete (**right**).

The physiological properties of bio-composites such as hempcrete are primarily influenced by the composition of the agro-waste materials they contain. This encompasses several sources, such as hemp or other forms of biomass. The composite's ultimate qualities are shaped by a combination of inherent properties found in natural materials, including their chemical composition, cellular structure, and fiber concentration. When examining the details, it becomes evident that polysaccharides assume a crucial function. One example of a polysaccharide is cellulose, which is widely present in the cell walls of plants. It is characterized by its straight-chain structure and is formed of units of β-D-glucose. The inclusion of cellulose fibers in materials such as hemp contributes to their significant tensile strength and rigidity. Hence, the quantity of cellulose in a material can have a direct influence on its mechanical characteristics. Conversely, hemicellulose, a complex polysaccharide composed of several sugar monomers and characterized by its branching structure, has the potential to impact the moisture equilibrium of hempcrete. Increased levels of hemicellulose have the potential to improve water retention; nevertheless, they may also pose some difficulties, such as the risk of warping or bulging [22–24].

In addition to polysaccharides, the presence of metal concentrations in agricultural wastes can have significant repercussions. The presence of metal traces in hemp and related agricultural waste materials can be attributed to several factors such as soil composition, the plant's natural absorption mechanisms, or post-harvest processes. However, the inclusion of these metal traces in hempcrete typically does not give rise to significant difficulties. Nevertheless, in cases where these concentrations are substantial, they have the potential to influence the chemical reactions involving the lime binder in hempcrete. Mediation has the potential to impact many characteristics, encompassing the curing duration of hempcrete as well as its durability over an extended period. Certain metals have the ability to function as catalysts, hence, potentially expediting the carbonation process of lime. Conversely, these metals could also act as inhibitors [25–27].

As a composite material made from hemp shiv and a lime-based binder, hempcrete is deeply influenced by its constituent components. Accounting for 44–55% of hemp shiv, cellulose bestows tensile strength and contributes to hempcrete's insulation properties due to its porosity [28,29]. Present at 16–18%, hemicellulose binds the fibers and aids in moisture regulation. Varying between 4–28%, lignin imparts compressive strength and protects against decay, while extractives influence color, odor, and durability. Furthermore, the robustness of hempcrete is directly linked to the concentration of cellulose and lignin in the hemp shiv; a greater quantity of these fibers results in enhanced strength and longevity [28–30]. With cellulose and hemicellulose's inherent porosity, their abundance in hemp shiv correlates with superior thermal insulation, effectively blocking the transfer of heat and cold. These fibers also play a role in sound dampening, with increased levels improving hempcrete's sound absorption abilities. Hemicellulose's ability to manage moisture through absorption and release aids in maintaining optimal indoor humidity. Furthermore, the fire-resistant quality of hempcrete is amplified by the presence of lignin, a natural fire retardant [28,31].

Lignin, a prevalent component found in the cell walls of plants, contributes to the reinforcement of the material's stiffness and provides defense against microbiological hazards, hence, potentially augmenting the durability of the composite. Agricultural residues, including hemp, frequently possess extractable compounds such as lipids, waxes, and phenolic compounds. The aforementioned ingredients possess the capability to impact not just the hydrophobic properties of hempcrete, but also its ability to resist microbial deterioration. Moreover, they contribute to the characterization of the bond quality between the hemp hurd and the lime binder [23,32–35].

In summary, the selection and arrangement of agricultural waste materials in hempcrete construction play a crucial role in determining its physiological characteristics. Polysaccharides exert a discernible and immediate influence, but metals, when present in substantial amounts, can gently yet considerably modulate the interactions and overall performance of the composite material.

3.2. Hempcrete; an Alternative to Conventional Insulating Materials

Although the compressive strength of conventional hempcrete is notably lower compared to concrete, around 10–15% of concrete's strength, it effectively fulfills its purpose in non-load-bearing scenarios. Further improvements in binder technology and the precise adjustment of the hemp–lime ratio have the potential to enhance its compressive strength to a greater extent. One of the desirable characteristics of hempcrete is its high-temperature resistance. Due to the cellular composition of hemp hurd, which results in substantial air gaps inside the cured mixture, it exhibits notable heat resistance, hence, promoting energy efficiency [36–38].

Insulation for buildings has mostly been made from fiberglass batt and rigid board insulation for decades, despite the fact that many of these compounds can be harmful to human health and the environment once disposed of in landfills. Given that insulating buildings is crucial to lowering energy consumption, our use of insulating material is expected to rise dramatically. Ecologically and economically, it makes sense to fill this capacity with easily renewable, low-impact materials that are ideally generated from waste streams or leftovers of other processes. Crafted from hemp hurd, hempcrete stands out to become recognized in the insulation market for its affordability and sustainability. Some of the desirable attributes of hempcrete include moisture control, fire resistance, and thermal regulation. The structural integrity of hempcrete is robust, and its agricultural origins offer a by-product that contributes positively to carbon sequestration. Moreover, it is a non-toxic alternative that promises better indoor air quality. Recent advancements suggest that as the supply chain for hempcrete stabilizes, the costs may align more closely with traditional materials, bolstered by its long-term energy-saving benefits [13,21].

4. Hemp's Rise in Bio-Composite Materials and Sustainable Construction

Hemp stands out as an excellent material for bio-composite production, especially when contrasted with woody biomass or agricultural wastes. One of its primary advantages is its high cellulose content. As a principal component of the stalk, cellulose bestows strength and durability, making hemp fibers robust and stiff. The fibers themselves are long, a trait that bolsters the strength and stiffness of bio-composites. Furthermore, hemp's low lignin content, in contrast to many natural fibers, is favorable for composite manufacturing. While lignin acts as a natural binder in plant fibers, its presence can sometimes complicate processing and potentially reduce the strength of the resultant composite [39,40].

Hemp fiber also brings ease of workability, catering to diverse manufacturing techniques like injection molding, compression molding, and extrusion. The lightweight nature of hemp is a boon for sectors like automotive and aerospace, where weight efficiency is paramount. Additionally, hemp fibers offer good thermal insulation—a characteristic valuable in the building materials sector. The antiseptic nature of hemp combined with breathability makes hemp versatile, especially in scenarios demanding moisture management and hygiene [40].

The chemical makeup of hemp includes not only cellulose but also hemicellulose, lignin, pectin, and waxes. While cellulose and hemicellulose confer strength and stiffness, lignin and pectin play pivotal roles in binding fibers. Waxes naturally coat these fibers, acting as a moisture barrier. In essence, the unique chemical composition, combined with its inherent properties, earmarks hemp as a preferred choice for bio-composite development [41,42].

As homebuilders look to the future, the construction industry is increasingly embracing crop-based materials like hempcrete that align with sustainable and healthy living standards. The qualities of hempcrete, such as its minimal carbon footprint and non-toxic nature, directly connect to the growing demand for green building practices [19]. These attributes not only improve indoor air quality but also promise long-term durability and energy efficiency, which are key selling points for new homes. The industry's trajectory indicates that materials offering such environmental and health benefits, alongside practical durability and cost-effectiveness, will likely become the cornerstone of future construction standards, shaping the way homebuilders plan, design, and construct new homes [20,21].

These desirable attributes come at a slight increase in the builder's initial material prices as well as some more effort in sourcing the necessary materials through less conventional means. To capitalize on the growing demand for hempcrete, builders may expect to see increased profits as more and more home builders start using such a product. Carbon reduction, fewer toxic materials, moisture resistance, and durability are among some of the desirable parameters of interest. Furthermore, because the use of hempcrete as a natural insulating option is compatible with conventional frame techniques, experienced framers can easily adjust to accommodate the unique requirements of hempcrete installation. Furthermore, hempcrete has the potential to become a lightweight alternative to traditional concrete, using similar formwork as traditional concrete construction. As such, hempcrete allows perfectly straight frame-walled construction. Because of its high thermal insulation property and moisture absorptance attribute, hempcrete can be a suitable choice for different climates. Specifically, the lime in hempcrete possesses antibacterial and anti-fungal properties, making it an ideal option for humid environements [18–21,39].

Hempcrete has attracted considerable interest due to its environmentally sustainable characteristics and energy-efficient attributes. The International Code Council (ICC) granted certification to hempcrete for use in the United States building regulations in September 2022 [43]. The granting of this approval signifies the potential for hempcrete to be incorporated as a conventional material in the realm of residential construction, commencing in the year 2024. Such acceptance of hempcrete for residential building construction in the United States is a notable milestone in facilitating its extensive integration within the construction sector. The forthcoming code, scheduled for formal publication in 2023, will incorporate hemp–lime (commonly known as hempcrete) inside the framework of "Appendix BA" [43]. Hempcrete has already received approval as a non-structural wall filler method. Such an acceptance and clearing of the path pertains to residential structures consisting of one- and two-family dwellings, as well as townhouses. This recent development is expected to enhance the accessibility of building materials derived from hemp and promote environmentally sustainable construction initiatives throughout the United States [43,44].

5. Binders

Similar to how cement serves as the essential binder in concrete, lime acts as the key binding agent in hempcrete. For this reason (as mentioned earlier), sometimes hempcrete is referred to as limecrete or hemp–lime. This preference is due to its abundant availability and lower emissions during production. Furthermore, compared to cement, lime is more compatible with hemp shiv [45,46].

Lime has a high water absorption rate, which slows down hydraulic flow. This will prevent the concrete's interior from setting. Binder and dosage influence the mechanical, thermal, hygrothermal, and acoustic properties of hempcrete [47–51]. Hydrated lime ($Ca(OH)_2$) is widely used as a binding agent in hempcrete due to the material's importance as a hydraulic medium. Researchers have used pozzolanic materials such as fly ash, Ground Granulated Blast-furnace Slag (GGBS), and silica fume to boost the strength and setting properties of hydrated lime [52]. Desirable properties of mixing lime and pozzolana have been known in history, as ancient buildings that have stood the test of time have benefitted from lime for strength and durability. As reported by Walker [53], when compared to fly ash, hydrated lime's performance with GGBS and metakaolin has been shown to be superior. To compensate for lime's and fly ash's low reactivity, activators such as sodium sulfate and calcium chloride can be added to the mix.

To boost early and 28-day strengths, activators aid in the synthesis of Calcium Silicate Hydrates (C-S-H), ettringite, and mono-sulpho-aluminate during the pozzolanic reaction of lime and fly ash. Based on the use of a patented binder, Sassoni et al. [54] have demonstrated that hempcrete has superior mechanical qualities. In this case, the binder was made from MgO, $MgSO_4$, or $MgCl_2$ solution and a reactive vegetable protein in flour form. Sassoni et al. [54] only briefly discussed the production process, but they did not provide any information about the curing time or type. $Al_2(SO_4)_3$ aluminum sulfate was investigated by Pantawee et al. [55] for possible usage in hempcrete. It was found that increasing the amount of $Al_2(SO_4)_3$ in the matrix can speed up the setting and hardening of the matrix and that adding $Al_2(SO_4)_3$ to the composites can increase their compressive strength.

Hempcrete's strength can be further enhanced by using magnesium-based binders for lime. When compared to calcium binders, magnesium binders are far more compatible with organic fillers [46]. When calcium binders are added to a mixture, an alkaline environment is produced, which aids in the release of lignin and other organic components from bio-based products during the mixing process. This slows the setting of lime [45]. Binding agents made from magnesium oxychloride and magnesium phosphate are the two most used magnesium-based binders. The final qualities of the material, the conditions under which it must harden, and the specific chemicals used in the mixture are all susceptible to change. Although these binders are not novel, lime has garnered far more interest than it has these alternatives. Yet, due to their high strength, fire resistance, and compatibility with organic aggregates [56–58], both magnesium binders are viable alternatives to lime binders.

Research into the use of lime in conjunction with a variety of other materials, including pulverized fuel ash, ground granulated blast furnace slag (GGBS), metakaolin, silica fumes, pumice, and clays, has yielded promising results. According to Walker [52,53,59], the performance can be increased by around 25% by including both hydraulic and pozzolanic material. In their hempcrete study, Walker [53,59] examined nine different pozzolans for their reactivity with hydrated lime, all of which were conveniently located in or near Ireland. According to their findings, calcium silica hydrates are the components responsible for the durability of lime pozzolana concrete. However, as compared to the other products, such as pulverized fuel ash, the hydrated lime showed a better reaction to GGBS and metakaolin. Calcium chloride and sodium sulfate (Na_2SO_4) are two activators that can be used to boost lime's and PFA's reactivity ($CaCl_2$). The activators aid in the production of C-S-H, ettringite, and mono-sulpho-aluminate, which in turn boost early and 28-day strength as a result of the pozzolanic reaction between lime and PFA [52,53,59,60].

While lime-based binders are the most commonly used binders in hempcrete, alternative binders can also be used to increase the compressive strength of the material. Some of the alternative binders that have been used in hempcrete include:

1. Cement: A mixture of Portland cement and hydrated lime can be used as a binder in hempcrete. This binder can improve the compressive strength of the material, but it can also increase the embodied energy of the material and its carbon footprint.
2. Gypsum: Gypsum can be used as a binder in hempcrete, although it is not as commonly used as lime or cement. Gypsum is a relatively low-carbon binder, and it can improve the fire resistance of the material. However, it may not be suitable for all applications due to its lower compressive strength compared to cement or lime.
3. Magnesium oxide (MgO): Magnesium oxide is a natural binder that is made from mined magnesium carbonate. It has a high compressive strength, and it is considered a more environmentally friendly alternative to cement.
4. Pozzolanic materials: Pozzolanic materials, such as fly ash, can be used to improve the compressive strength of hempcrete. Pozzolanic materials are by-products of industrial processes, and they can help reduce the carbon footprint of the material.
5. Natural hydraulic limes (NHLs): Natural hydraulic limes are lime-based binders that are made from naturally occurring materials, such as limestone. They have a higher compressive strength compared to traditional hydrated limes, and they can be used to improve the compressive strength of hempcrete.

The optimal mix ratio of hemp fibers to different types of binders depends on several factors, including the desired properties of the material, the type of binder being used, and local building codes and regulations. Generally, the weight mix ratio of hemp fibers to binder ranges from 1:1 to 1:3, and lime-based binders typically have a mix ratio of 1:1.5, while cement-based and NHL-based binders have a mix ratio of 1:2. Pozzolanic materials have a mix ratio of 1:2 as well [61–68].

Hemp shives have a high capacity for both absorbing and releasing water due to their porous and cellular structure. When using hydraulic binders, hempcrete units are at risk of breaking binds due to the material's high water content. However, mechanical performance is enhanced when C-S-H is incorporated into hydraulic binders. For this reason, it is essential to study novel binders and additives that improve the hempcrete's setting properties. Previous work has investigated the impacts of different binders and developed novel binders to boost the mechanical strength of hempcrete. Though studies have shown that pulverized fuel ash is not very reactive with lime, it remains a popular choice among those looking to use lime–pozzolana binders. However, GGBS and metakaolin are good choices for making a lime–pozzolana binder as a result of their high reactivity with lime and equally abundant availability. One of the major requirements for hempcrete binders is that they cannot be entirely hydraulic. A great deal of promise has been shown by MgO-based binders in the studies that were considered. However, further research is required to fully understand the durability through time and the interfacial zones between aggregates and binders.

6. Fundamental Properties of Hempcrete

6.1. Density

When compared to the density of conventional concrete aggregates, hemp shives are significantly lighter. Since hemp is less dense than cement, hempcrete is significantly lighter than standard concrete. Regardless of the quality of the concrete, the weight density comparison holds true. According to Ohmura et al. [69], the orientation of particles making up the volume of the hempcrete can affect density. Needless to say, compaction and moisture content also affect the density, which will then affect hempcrete's thermal performance according to Sinka et al. [70]. More specifically, for every 50 kg/m^3 increase in density, the authors point out that hempcrete's thermal conductivity increases by 0.005 W/m.K. Despite the fact that hempcrete's thermal performance and its mechanical properties are affected by the density and humidity content, the mixture is frequently portrayed as a lightweight material.

6.2. Compressive Strength

Murphy et al. [71] have reported the mechanical characteristics of hempcrete made from commercial binders and hydrated calcitic lime. According to their research, composites made with commercial hydraulic binders showed higher compressive strengths than those made with calcitic lime. They also report that the binder concentration in hempcrete increases compressive strength. Murphy et al. [71] use the following designations CL90H10, CL90H50, and CL90H75 to denote, respectively, 10%, 50%, and 75% hemp content, all with 90% calcitic lime binder. On the other hand, the samples TH10, TH50, and TH75 denote, respectively, 10%, 50%, and 75% hemp with Tradical® [72,73] binder.

O'Dowd and Quinn [74] report on hempcrete with compressive strengths ranging from 0.65 to 1.9 MPa. The compressive behavior of hempcrete blocks was also investigated by Tronet et al. [75] who indicate that the mechanical properties are improved when the binder proportions are limited. Research by Jami et al. [13,14] indicates that the characteristics and mix proportion of the binder affect the strength of the hempcrete. Furthermore, according to [76,77], compaction can enhance the compressive strength of hempcrete. Accordingly, the strength and resistance to deformation before failure can be increased by reducing the amount of binder used. Confirming such a result, Elfordy et al. [78] show that compressive strength increases with density and compaction.

The impact of different binder types on the mechanical strength of hempcrete was investigated by Walker et al. [59,60]. The results of their study indicate that while enhancing the hydraulicity of the binder can enhance the initial strength, the compressive strengths of the mixtures being evaluated reached a similar level after a period of one year. According to the findings of Cigasova et al. [41], the use of a binder based on MgO leads to a hempcrete compressive strength that approaches 2 MPa. In the study conducted by Evrard [79,80], hempcrete mixtures were formulated and evaluated, resulting in compressive strengths ranging from 0.2 to 0.5 MPa. Arnaud et al. [81], on the other hand, reported compressive strengths ranging from 0.4 MPa to 1.2 MPa. According to Walker [53], the compressive strength of the material was around 0.2 MPa after 28 days, and this value grew to 0.4 MPa after a period of one year. In their study, Haik et al. [82] investigated the effects of varying clay substitution percentages for lime in hempcrete mixtures, maintaining a constant weight ratio of 1:2. The strengths of mixtures including clay percentages of 90%, 50%, and 0% were found to be 0.07 MPa, 0.09 MPa, and 0.04 MPa, respectively. The empirical evidence suggests that partial substitution of lime with clay can lead to a modest improvement in strength, primarily attributed to the development of hydraulic compounds.

Abdalla et al. [83] reviewed the impact of various natural fibers, including hemp, coconut, banana, and basalt, among others, on fresh and hardened concrete. They provided a comprehensive review of using these natural fibers for reinforcing cement-based materials, focusing on their properties, mechanical performance, and durability.

In a study led by Ngo et al. [84], the influence of different amounts of clay and hemp in soil-based concrete was explored. The research focused on how clayey soil combined with hemp fibers affected the compressive strength over curing durations of 7, 28, and 180 days, maintained at 20 °C and 90–100% relative humidity. Data from the 7-day test, illustrated in Figure 2, showcased a standard deviation under 0.025 MPa, or roughly 4%. This variability is attributed to the differences between sandy and clayey soils, compounded by the effects of the porous multi-scale structure [47]. After 7 days, there is a slight dip in compressive strength, ranging from 0.6 to 1.2 MPa, due to the addition of clayey soil. This value transitions to between 1 and 2.4 MPa at 28 days and spans from 2.5 to 5 MPa by 180 days. Interestingly, elevating the clayey soil content from 20% to 40% has a subtle effect on compressive strength, especially when the deviation stays below 0.3 MPa. Once the mixture stabilizes by the 180th day, the effect of additional clay content on strength diminishes. The study also highlighted that introducing fibers into the concrete mixture reduces its compressive strength progressively. For concrete without clayey soil, the strength diminishes over the three tested periods, with the 28 and 180 days showing a more pronounced reduction of around 0.8 MPa. Conversely, when complemented with clayey soil, the fibers' impact on the strength varies only slightly. A mere 1.2% fiber addition results in a notable strength reduction of about 0.5 MPa at both 28 and 180 days.

Awwad et al. [85] suggest that voids and discontinuities, stemming from reduced density, alterations in the soil concrete structure, intergranular void, and dispersion of pores, might lead to diminished compressive strength. It has been documented that the incorporation of hemp fibers in soil concrete samples can mitigate lateral strain during compressive stress [86]. Chabannes et al. [87–89] propose that an increased friction angle on the shear crack surface might be attributed to these fibers. When focusing solely on linear elastic responses, some experts have highlighted behaviors observed up to approximately 10% strain under compression [55,90]. Although hempcrete's limited compressive strength means it is not designated as a primary load-bearing material, its contribution to the structural integrity of conventional timber wall frames or double-stud framing, such as in stud confinement, is undeniably acknowledged.

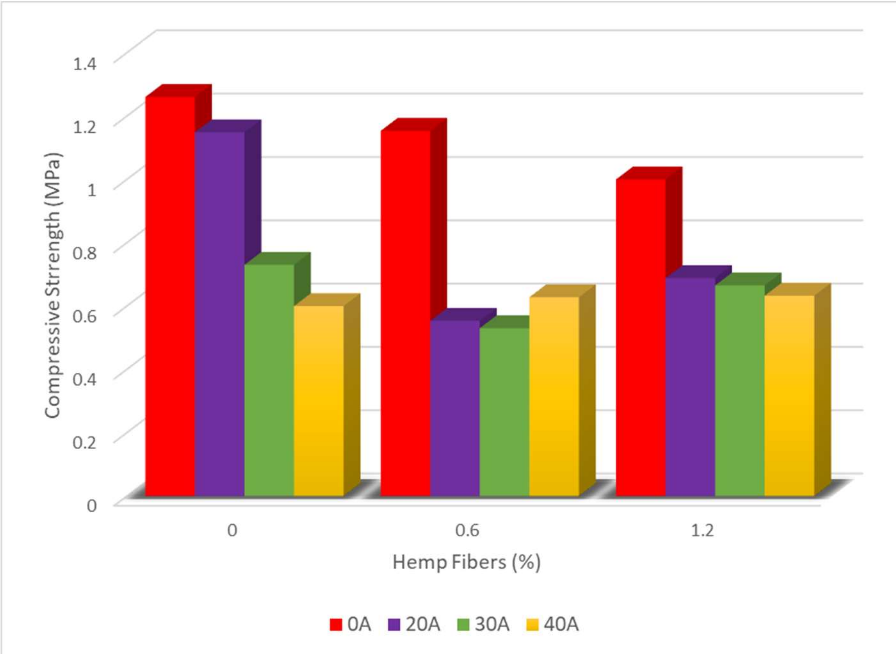

Figure 2. An examination of the effects of clayey soil and fibers on compressive strength after 7 days. (Adapted from references [20,84]).

Based on the literature review study presented on compressive strength, to improve the compressive strength of hempcrete, the following steps can be taken:

1. Use high-quality hemp fibers: The quality of the hemp fibers used in the mixture can significantly affect the compressive strength of the material. High-quality fibers should be long, strong, and free of contaminants.
2. Use a high-quality lime binder: A high-quality lime binder with a high proportion of calcium hydroxide will help increase the compressive strength of the material. Additionally, the binder should be well cured to ensure maximum strength.
3. Optimize the mix ratio: The mix ratio of hemp fibers to binder is critical to the compressive strength of the material. A higher binder content will result in a stronger material, but it will also reduce the insulation properties of the material. A weight mixture ratio of around 1:1 is typically used, but it can be adjusted based on the desired properties of the material.
4. Use a denser mixture design: A denser mixture of hempcrete will have a higher compressive strength compared to a more porous mix. To achieve a denser mix, the fibers should be well-distributed and compacted during mixing and casting.
5. Avoid moisture damage: Moisture can severely damage hempcrete, leading to reduced compressive strength. To avoid moisture damage, it is important to properly design and detail the building envelope, including roofing, walls, and foundations. Additionally, a vapor-permeable render or paint should be used to protect the surface of the material.
6. Cure the material properly: Proper curing of the material is essential to developing its full compressive strength. The material should be kept moist and covered during the curing process to prevent the evaporation of water, which would reduce the strength of the material.

Mixture percentage values in the reviewed literature exhibit a wide range as a result of the variety of composition, production methods, and physical qualities of the raw materials. The gain in compressive strength increases with increasing binder percentage, while flexural strength peaks at 50% hemp content. The reviewed literature shows that both flexural and compressive strengths are affected by the binder, hemp percentage, and level of compaction. Furthermore, the binder composition greatly affects the pace of strength increase. Additionally, the studies cited have shown that the dimensional stability of hempcrete could be of concern. Compressive strength is low, and the lateral strain is often over 7.5 percent. Hemp shives are flexible, and the lime-based binder allows them to be rearranged inside the mixture. Hempcrete, in its current strength form, is better suited for insulation than load-bearing applications in walls.

Table 1 presents a summary of the compressive strength of Hempcrete, as reported by various authors in their research studies. The table shows that the compressive strength of hempcrete can vary widely depending on the specific mixture design, binders, and curing conditions.

Table 1. An overview of hempcrete's reported compressive strength and density from previous studies.

Authors	Year	Reported Compressive Strength	Reported Density
Kioy [91,92]	2005	1.88~1.98 MPa	610–830 kg/m^3
Cerezo [93]	2005	0.3~0.7 MPa	356–504 kg/m^3
Elfordy et al. [78]	2008	0.06~1.2 MPa	291–485 kg/m^3
Nguyen et al. [77,94]	2009	0.2~2.5 MPa	670–850 kg/m^3
Hirst et al. [95]	2010	0.2~1.2 MPa	220–342 kg/m^3
Sutton et al. [96]	2011	0.1~0.2 MPa	270–330 kg/m^3
Arnaud and Gourlay [97]	2012	0.1~0.34 MPa	460–500 kg/m^3
Nozahic et al. [98]	2012	7.11 MPa	1100–1300 kg/m^3
Chabannes et al. [88]	2014	0.45~0.51 MPa	400–650 kg/m^3
Walker et al. [59]	2014	0.29~0.39 MPa	360–400 kg/m^3
Sassoni et al. [54]	2014	0.1~0.2 MPa	330–640 kg/m^3
Sinka et al. [70]	2014	0.125~0.266 MPa	330–540 kg/m^3
Chabannes et al. [89]	2015	0.47~0.68 MPa	460–505 kg/m^3
Tronet et al. [75,99]	2016	1.36~4.74 MPa	580–843 kg/m^3
Sassu et al. [100]	2016	0.146~0.622 MPa	638–753 kg/m^3
Nadezla Stevulova et al. [101]	2018	0.9~5.75 MPa	960–1160 kg/m^3
Niyigena et al. [102]	2018	0.2~1.1 MPa	385–480 kg/m^3

Increasing Mechanical Strength

Hempcrete with a higher compressive strength than that stated in the literature can be produced using one of several different methods. This could be attained by adjusting the mixture's ingredients, such as by employing different sets of binding agents and by adding suitable pozzolans or additives. Common examples of pozzolans used in the manufacturing of concrete include fly ash and silica fume. When used in concrete, these ingredients increase the mixture's mechanical strength [12,103]. According to Asrar et al. [104], un-densified microsilica's extremely fine grain size makes it highly reactive with the free lime in concrete, leading to the production of a paste that is both dense and impermeable. Hence, the mechanical strength of hempcrete may be improved by combining non-densified microsilica and lime. To improve the mechanical properties, gypsum can be used as a binder in conjunction with hemp. In a study by Karni and Karni [105], it was found that the compressive strength of unrestrained gypsum was 12.0 MPa. Calcined gypsum is used as a binding substance. By combining gypsum and hemp, perhaps a building material with greater compressive strength can be created than when using limes. The authors discussed the potential of using a mixture of hemp and gypsum as a sustainable building material.

They mentioned that gypsum has a higher compressive strength compared to lime, and that combining it with hemp can result in a material with even greater strength [106].

The compressive strength of hempcrete varies widely from about 0.03 to 1.22 MPa, depending on age and its mixture design [81]. The study by Evrard [80] shows that the compressive strength can vary between 0.2 and 0.5 MPa. In comparison to concrete, which has a strength of between 20.7 and 34.5 MPa, these values indicate that conventional hempcrete is not a good option for use as a load-bearing material. Thus, a wood frame or other gravity load-resisting device is needed to support the loads being applied. Since hempcrete can undergo large deformation without brittleness, hempcrete walls can undergo considerable strain before cracking. Despite the fact that hempcrete has a low compressive capacity, it is nevertheless used for nonstructural applications [80]. It should also be noted that hydrated lime takes in carbon dioxide as it hardens, and this makes it a more durable product. Therefore, adding more hydrated lime to the mixture raises the material's compressive strength. Since this is a long-term process, the material may take years, perhaps decades, to reach its final maximum compressive strength [107].

The benefits of incorporating hempcrete in wall construction include the following:

- It is lightweight yet boasts significant thermal mass [108].
- Streamlines the construction process by reducing layers and steps, especially in timber-frame structures [109].
- Notable thermal insulation attributes [78,80,81,93,110].
- Capitalizes on agricultural renewable resources, specifically hemp.
- Can utilize locally sourced materials, including hemp and lime.
- Has minimal environmental repercussions [108,111,112].
- Offers commendable acoustic insulation [50].
- Achieves excellent airtightness, especially when paired with a render system [108].
- Demonstrates strong fire resistance [113].
- Exhibits distinct porosity characteristics [47,97].

One unique aspect of hempcrete is its strength gain with time, in addition to the ingredients in the mixture that influence the compressive strength. Regarding the latter, Evrard [80] investigated a variety of hempcrete mixtures and found that their compressive strengths ranged from 0.2 to 0.5 MPa, whereas Young's modulus values ranged from 3 to 26 MPa. Furthermore, according to Arnaud et al. [81], the compressive strength values ranged from 0.4 to 1.2 MPa, depending on the amount and type of ingredients, and Young's modulus values ranged from 40 to 90 MPa. These hempcrete mixtures do not have a sufficient level of compressive strength for the material to be load bearing in its current state. According to O'Dowd and Quinn [74], the compressive strength of a mixture consisting of hemp shiv and lime at a weight ratio of 3:1 by volume had a value of 0.71 MPa. They also reported that a ratio of 3:1 hemp to lime has a strength that is comparable to mixture ratios of 4:1 and 5:1. With respect to strength gain with time, lime is known to slowly absorb carbon dioxide, thus gaining more strength over time. According to Arnaud and Cerezo [81,110], the compressive strength may reach its plateau after a period of a few months to a few decades, depending on the amount of slaked lime in the mix.

Arnaud and colleagues [81,97] report another unique characteristic of hempcrete related to its capability to withstand a significant amount of strain before breaking. Their test results indicate that there is no cracking in the material for a 10–15% compression rate. Of course, currently, this behavior results from a mixture design meant to be used for nonstructural, and likely insulation purposes. However, this is a desirable property if a structural load-bearing mixture design could similarly carry excessive deformation without collapsing. At this time, however, because of its low elastic modulus and very low failure stress (e.g., 0.15 to 0.83 MPa), hempcrete cannot be considered for load-bearing functions. In order for hempcrete to support sustained loads, its compressive strength will need to be significantly increased to values between 3 and 5 MPa, and its elastic modulus will also need to be significantly increased. Compressive strength, Young's modulus, and splitting tensile strength have all been shown to increase when mixtures contain an adequate proportion of cement.

Despite certain studies increasing the hydraulic lime content in the binder mixture from 50% to 75% by weight, no noticeable enhancement in the material's mechanical strength was observed. However, when the cement content in the binder mixture rises from 29% to 50% by weight, the compressive strength doubles. A binder mixture composed solely of cement achieves a compressive strength close to 3 MPa, meeting the minimum requirement for the material to bear loads.

6.3. Thermal Properties

Hemp shives' variable composition and structure affect hempcrete's thermal conductivity, which can increase by up to 30% when heat flows perpendicular to compaction. Its heat conductivity can be influenced by factors like orientation, compaction, and application method, impacting mechanical properties as well. While binder choice does not significantly affect thermal properties, it can impact mechanical performance. Increased wetness, temperature, and density can enhance thermal conductivity and mechanical characteristics, respectively. Recent research suggests that silica sol binder in hempcrete allows for maintained mechanical strength with thermal conductivity similar to hemp shives. Interestingly, smaller hemp shiv particles enhance mechanical strength without affecting thermal conductivity. Yet, in contrast, smaller particles in hemp plaster reduce thermal conductivity, necessitating further study [64,77,78,114–122]. The performance of hemp-plaster coatings is more influenced by anisotropic aggregates' orientation than particle size. Evaluating the thermal performance of hempcrete concretes requires considering dynamic characteristics like Q24h, in addition to U-values [123,124].

Hempcrete can bridge the gap between standard insulating panels and structural walls, leveraging passive solar energy gain for thermal comfort. Variations in specific heat values of similar-density hempcrete may result from different plant components or new measurement methods. Recent efforts aim to improve thermal insulation and increase thermal conductivity, paralleling shiv material properties, thus creating a balance between conventional insulation attributes and hygrothermal performance [50,125,126].

In France, the increased thermal inertia of hempcrete walls helped mitigate intense summers, highlighting the importance of local climate-adapted concrete mixes. Layered hempcrete walls may offer a viable solution to location-specific adaptation challenges [127,128]. Thermal conductivity that increases linearly with temperature and density also changes with relative humidity and water content shifts. Density impacts thermal conductivity more significantly than moisture content. A 67% density increase enhances thermal conductivity by around 54%, while going from dry to 90% relative humidity only boosts it by 15–20%. Such findings highlight that heat conductivity is impacted more by density than by moisture content [49,129–131].

A study of 11 polyester–hemp Expanded Perlite (EP) mixes found numerous results. EP and hemp reduced composite thermal stability. In H25P5 and H45P5, EP increased compressive strength by 20.11% and 5.68%, respectively. The H25P5 mixture had the maximum compressive strength (35.175 MPa) and the lowest thermal conductivity (0.1093 W/mK) [132].

Research studies have confirmed that hempcrete exhibits phase change characteristics, akin to other phase change materials, including latent heating, high thermal mass, and low thermal conductivity. In terms of heat conductivity, hempcrete is nearly on par with Autoclaved Aerated Concrete (AAC) blocks of identical density. However, hempcrete has been shown to offer greater energy savings compared to cellular concrete. This advantage is attributed to hempcrete's ability to permit the free movement of water vapor and moisture, ensuring a balanced indoor relative humidity and minimizing the potential for unwelcome fluctuations.

6.4. Fire Resilience of Hempcrete

The fire safety of a building that directly affects its permit and insurance hinges on its response time. Despite the availability of several studies on hempcrete's fire safety aspect, the consensus in available research points to hempcrete's substantial fire resistance [71]. A fire test by Fernea et al. [133] substantiated the safety of using hempcrete. The study used three different samples, all having the same cement volume but varying hemp-to-cement ratios, to explore its potential as an acoustic absorbent material. These ratios were 1:1, 2:1, and 3:1, crafted from white cement, lime, and water. The research primarily focused on the 2:1 ratio sample. In terms of fire performance, Hemp-TODAY® [134] reports that hempcrete achieved an ideal '0' on ASTM fire testing in the USA, the apex score on a 0 to 450 scale. The fire resistance test involved a propane gas-powered blow torch against a fully set and dried hempcrete wall. The area's burning progress was observed through photographs taken every minute over the eight-minute test. According to Allin [135], the burnt area expanded minimally over time. Ten minutes in, the darkened spots were still hot, but the flame could only leave a half-inch indent from the surface. These observations underscore hempcrete's suitability as a construction material with robust fire resistance [54,133].

6.5. Acoustic Properties

The acoustic properties of hempcrete are unique due to its porous nature. However, its noise-dampening capabilities decrease significantly after production. The sound absorption of untreated hempcrete varies widely, from poor to excellent, depending on the binder type, formulation, and manufacturing processes utilized. Generally, hempcrete can absorb around 40–50% [51] of sound across various frequencies. The surface permeability influences the absorption coefficient, which varies between 0.3 to 0.9 depending on the binder's concentration and frequency of application. Materials less than 20 cm thick show absorption peaks at low and medium frequencies (below 400 Hz and 1200 Hz, respectively). The binder concentration affects the amplitude and width of these peaks. Comparatively, hempcrete demonstrates better sound absorption than concrete made with hydraulic binders [50], especially when smaller hemp shives [50] and lime–pozzolanic binders [51] are used. As wall thickness increases, absorption peaks above 500 Hz become more distinct and shift towards lower frequencies. The absorption peaks of low-density mixtures decline as wall thickness increases, while medium-density formulations have a stable second peak until an absorption level between 500 to 2000 Hz is consistently achieved. The sound absorption decreases in high-density formulations [93]. Recent research indicates the amount of hemp aggregate in the concrete is a key determinant of acoustic performance when compared to clay and lime [136]. As the density rises to 500 kg/m^3, the transmission loss reduces, suggesting the manufacturing process's crucial role in determining acoustic behavior. The acoustic absorption can also be influenced by further retting, aging, and weather effects on hemp shives. Hemp–clay has superior air resistance compared to hempcrete due to its denser binder. The study reveals that open porosity significantly impacts acoustic absorption [93,136].

Discussion of Fire Safety and Acoustic Properties of Hempcrete

The notable fire resistance and acoustic properties demonstrated by hempcrete underscore its potential utility as a sustainable and robust building material. In terms of fire resistance, hempcrete's impressive ASTM test rating implies its superior performance, suggesting its potential to enhance fire safety in building construction. The controlled expansion of the burnt area during testing might suggest that hempcrete can contribute to fire containment, offering additional time for evacuation procedures in the event of a fire. This characteristic could prove pivotal in reducing insurance premiums and reinforcing overall building safety.

Simultaneously, the acoustic performance of hempcrete determined by a combination of factors, including binder concentration, aggregate size, manufacturing process, and environmental influences like aging and weather conditions, underscores its potential as a noise-control material. Its unique sound absorption attributes, derived from its porous nature, potentially make it an appealing choice for noise-sensitive applications in building construction. Observations related to the shift of absorption peaks towards lower frequencies with increased wall thickness suggest the existence of potential optimization strategies for enhanced acoustic performance. The superiority of air resistance in hemp–clay, in comparison to hempcrete, implies that careful selection of binders could be crucial to meet specific acoustic requirements.

Together, these properties highlight hempcrete's potential to revolutionize construction, offering safer, quieter, and more sustainable building solutions. This multifaceted performance of hempcrete may open new avenues for its application in the construction industry, fostering the adoption of more sustainable and performance-driven practices.

6.6. Environmental Sustainability

Bio-composites, such as hempcrete, possess intrinsic advantages in comparison to conventional cement-based materials like concrete. Exploring the composition of hempcrete unveils the fundamental chemical principles that enhance its mechanical strength and structural stability. Fundamentally, hempcrete is a composite material that combines hemp hurds, which refers to the fibrous inner core of the hemp plant, with a binder composed of lime. The chemical process responsible for the transformational properties of this binder involves the carbonation of lime. Not only does this highlight the CO_2 sequestration capabilities of hempcrete, but it also imparts its distinctive attributes. When lime, also known as calcium hydroxide ($Ca(OH)_2$), reacts with carbon dioxide in the atmosphere, it undergoes a transformation into calcium carbonate ($CaCO_3$). This process gradually strengthens and enhances the durability and strength of hempcrete. In addition to its ability to enhance structural integrity, the process of carbonation observed in hempcrete serves as evidence of its environmentally sustainable characteristics. Hempcrete actively engages in the collection of carbon dioxide, establishing itself as a constituent with carbon-negative properties [137,138].

Ip and Miller [139] conducted a life cycle analysis (LCA) of hempcrete walls, taking into account the wood frame and sealing off the hempcrete. The study's procedures and surroundings were diverse, with varying hempcrete densities, thicknesses, and wood frames used in France and the UK. Despite the differences, the average lifespan of the hempcrete wall was over 100 years. The study concluded that hempcrete is environmentally beneficial due to its ability to store carbon. According to Ip and Miller [139], hempcrete walls can store up to 82.71 kg CO_2eq. per square meter of wall.

The cost and widespread availability of plant fibers have rendered them a viable alternative to synthetic materials. According to a study by [139], the energy needed for hemp production is 11,400 MJ/ha, which is approximately 50% lower compared to other comparable crops. While the growth of hemp necessitates both area and fertilizer, it is possible to mitigate these limitations through the implementation of crop rotation and organic farming techniques [140]. According to reference [121,122], the manufacturing process of hemp shiv yields carbon dioxide emissions ranging from 0.085 to 0.19 kg per kilogram. Nevertheless, the aforementioned drawback is counterbalanced by the fact that hemp cultivation results in the sequestration of 1.5 to 2.1 kg of CO_2 per kg of hemp during its growth period [120]. Hempcrete demonstrates a favorable climate change indicator, as it effectively sequesters carbon dioxide within its plant-derived aggregate [141,142]. The binders that pose the most risk are those commonly utilized in commercial settings, with particular emphasis on Portland cement [98].

Multiple research studies [81,97,110] concur that hempcrete exhibits a negative carbon footprint, with values ranging from -0.3 to -1.0 kg CO_2 per kilogram of hempcrete. A single square meter of hempcrete with an unrendered thickness of 30 cm exhibits a density of 275 kg/m^3, hence providing a carbon dioxide storage capacity of 82.7 kg. The aforementioned mechanism facilitates the retention of 36.1 kg of carbon dioxide (CO_2), thereby compensating for the emission of 46.4 kg of CO_2 resulting from the utilization of materials and associated procedures [139]. According to the cited source [140], the lime binder utilized in non-load-bearing hempcrete, which is accompanied by a wooden support structure, accounts for 49% of primary energy consumption, 68% of water usage, and generates 47% of air pollution. Calcitic lime (CL) has the capacity to capture around 90% of carbon dioxide (CO_2) per kg of CL [139]. However, the process of carbonation may not result in the same level of reabsorption as observed in mineral aggregate mortars, mostly due to the setting challenges commonly encountered in plant-based concretes [45]. Nevertheless, the life-cycle assessments conducted on the hempcrete concretes failed to consider this factor.

The carbon footprint of hempcrete is influenced by various factors related to its design, including the selection of low-impact binder types [143], transportation of materials, dosage, construction method, and application technique [144]. According to research findings [145], in order to attain a comparable consistency, hempcrete plaster necessitates a greater amount of binder compared to sand–lime coating, thus leading to a more substantial carbon footprint. While plant-based construction materials have a favorable overall life cycle balance and contribute positively to health [146], their drawback lies in their comparatively greater cost when compared to conventional materials. Despite the numerous ecological, environmental, and energy-saving advantages associated with plant-based products, the present consumer preference remains skewed towards non-plant-based alternatives, with just a minority opting for the former. According to the Organization for Economic Co-operation and Development (OECD), the building industry accounts for 10% of the worldwide Gross Domestic Product (GDP), employs 28% of the entire workforce, and has notable environmental consequences. The implementation of legislative measures aimed at fostering the development of plant-oriented economies is important in order to effectuate a transformative shift within the building sector.

6.7. Durability

The durability of construction materials is paramount to ensure both the longevity of structures and economic efficiency. There have been numerous studies investigating the resilience of hempcrete across different metrics. Walker et al. [59,60] analyzed the mechanical characteristics and durability of various mixtures of hempcrete concretes, employing binders constituted from blends of lime, GGBS, metakaolin, and commercial binders. Three crucial durability factors were evaluated: resistance to freezing and thawing cycles, salt exposure, and biological degradation.

In the context of freeze–thaw resilience, it was determined that hempcrete's resistance was subpar due to mass loss throughout the cycle, leading to a decrease in compressive strength. Conversely, when subjected to sodium chloride salt exposure, hempcrete exhibited substantial resilience, attributed to the unsuitability of its large pores for salt crystallization. Furthermore, hempcrete demonstrated immunity to biological degradation due to the absence of necessary nutrients for microorganism growth. Some instances of mold growth were observed beneath hand-mixed exterior coatings on hempcrete walls after a year of outdoor exposure. However, a seven-month study by Walker et al. [59,60] suggested that despite having similar binder compositions and mixture designs, hempcrete resisted microbial invasion due to factors such as the alkaline nature of lime, lack of sustenance for microbial growth, and adverse environmental conditions [52,53].

Walker et al. [59,60] recommended enhancing the strength and durability of hempcrete manufactured with a lime–pozzolan binder. The study addressed concerns over the natural decay of plant materials, finding that hemp shives within the composite did not fully degrade due to a mineralization process resulting from calcium carbonate precipitation on elementary fibers following an alkaline degradation mechanism. This process rendered the hemp particles in the composite inert but also brittle, less porous, and weak in tension [147,148]. Aging tests such as wet–dry cycles and full immersion–drying cycles, particularly with calcic lime binders, resulted in binder leaching and a decrease in mass and compressive strength over time. However, composites utilizing hydraulic binders experienced an increase in compressive strength following repeated soaking and drying [147,148].

Upon further examination of its stability characteristics, hempcrete's composition, which is mostly centered around lime, creates an alkaline environment that effectively deters pests and hinders the growth of mold. The implementation of proactive humidity regulation measures in hempcrete walls effectively mitigates the dangers associated with mold growth, thus ensuring the protection of individuals from potential respiratory health issues. Another highly desirable characteristic of hempcrete is its fire resistance, which, in conjunction with its strong thermal and sound insulation properties, contributes to the creation of a secure and healthy indoor atmosphere [149,150]. The durability of hempcrete is enhanced by its ability to withstand common factors such as pests and mold. The continual carbonation of lime contributes to its distinctive capacity to repair micro-cracks, hence, enhancing its ability to maintain airtightness. Additionally, the ability of hempcrete to absorb and release moisture without compromising its mechanical qualities is of significant importance in maintaining an optimal indoor humidity level, which contributes to the comfort and well-being of the occupants [151,152].

Enriched by the alkaline characteristics of lime, hempcrete showcases a remarkable resistance against biogenic degradation initiated by microorganisms, insects, or pests. This inherent trait sets it apart from many other bio-based materials, especially those bound with different kinds of binders, as they often require added protective agents. Sand lime bricks mirror some of these benefits: they are not only fully recyclable but also deter mold and microorganism growth, thanks to their pronounced alkaline reaction. This parallels hempcrete's attributes, where its elevated pH levels, higher than 10, promote an alkaline milieu [153–156].

Moreover, hempcrete structures boast resilience against the erosive effects of salt exposure. The relatively expansive size of the pores in hempcrete impedes the crystallization process that is typically instigated by salts. The lime's alkaline nature curbs the proliferation of mold and insects, while the material's nutrient-deficient composition further halts the propagation of harmful microorganisms. As per recent studies and findings, such unique properties of hempcrete are pushing it to the forefront of sustainable construction materials, combining durability with ecological responsibility [13,14,156].

7. Discussion of Hempcrete Practical Opportunities and Challenges

7.1. Applications of Hempcrete

Hempcrete research began in the 1980s and has since explored various formulations by altering binders and mixing proportions with hemp shives. This resulted in mixtures with diverse physical–mechanical properties suitable for an array of applications, from load bearing to thermal insulation and sound absorption [76,77,94,119]. Originally designed as a sustainable alternative to traditional insulation materials like glass wool, fiberglass, and dense-packed cellulose [21,157], the use of hempcrete expanded to wall construction. In the UK and recently the US, this material has been incorporated into the full construction of timber-framed buildings [21,157]. Furthermore, researchers have tailored hempcrete for specific uses by adjusting mix proportions [71].

7.1.1. Hempcrete Walls

Hempcrete, known for its non-toxic properties [21], is predominantly utilized as a material for wall construction. An exhaustive guidebook by Stanwix and Sparrow [157] offers insights on using hempcrete for home wall construction. The application of hempcrete for wall construction can vary; it can be directly sprayed or cast on site, or alternatively, precast into blocks offsite for later assembly using standard masonry techniques. However, the authors warn of hempcrete's susceptibility to rain. To shield hempcrete walls from moisture and heavy run-off during rainfall or storms, they recommend substantial roof overhangs. In cases where this overhang does not align with architectural designs, alternative protective measures are necessary. For example, coating the hempcrete walls with breathable materials like lime helps to repel moisture. Moreover, the installation of a roof drain can help to prevent dampness from infiltrating the walls [21,157].

7.1.2. Wall Insulation

Hempcrete, particularly those with a density between 250 to 350 kg/m^3, is suitable for insulating exterior walls in most low-rise constructions. This insulation can serve as an infill within the structural frame of the wall (e.g., between studs) or be applied to the outer or inner surface of the frame. For larger-scale projects, hempcrete panels have been employed as curtain walls in buildings as tall as six stories [21]. A specific study conducted by Sassoni et al. [54] delved into low-density hempcrete made from their patented binder [158]. This type of hempcrete is used particularly for wall insulation. The research aligns with the reference [21], indicating that the tested hemp composite featured a density of 330 kg/m^3.

7.1.3. Other Applications

With densities ranging from 200 to 250 kg/m^3, hempcrete is favored for roof insulation. It is versatile enough to be spread as loose-fill insulation on flat ceilings or gently compressed into arched roof designs. The advantages of hempcrete as a roofing insulator encompass its resistance to pests, volumetric stability (ensuring it will not warp, shift, or settle), and heightened moisture resistance in contrast to conventional insulations [21]. Another, albeit rarer, application is sub-slab insulation. Here, hempcrete with densities between 375 to 500 kg/m^3 proves advantageous. Though its increased density results in slightly reduced thermal resistance, it effectively insulates beneath floor slabs when set on a sturdy, well-drained foundation with a vapor barrier separating it from the earth [21]. For window insulation, adding hemp fibers to hempcrete mixtures can seal the spaces between window structures and their frames, creating a tight barrier. This approach avoids the need for petrochemical derivatives and can be molded to construct both external and internal window trims [21].

Hempcrete renders are specifically designed mixtures with increased binder quantities. They enhance the structural integrity of the binder and reduce its quantity while providing slight thermal and acoustic insulation. These eco-friendly renders are generally dense due to their higher binder content, and their application in wall rendering and floor screed varies the resulting thermal and physical properties [21,72]. Lastly, precast blocks of hempcrete have been validated by numerous studies and are increasingly favored in the industry overcast hempcrete walls [13,14,72,73]. Some advancements even facilitate mortar-less block stacking through physical interlocking [159]. In summary, hempcrete's adaptable nature allows for its use in a variety of residential building applications, providing an eco-friendly alternative to traditional insulation and construction materials. Its benefits, including pest and moisture resistance, airtight sealing, and acoustic insulation, make it an attractive choice in the construction industry.

Featuring a variety of ecological and functional benefits, hempcrete is a testament to the growing commitment to sustainability in the construction industry. In the realm of green construction, its properties, which include significant carbon mitigation and a versatile range of applications, make it an indispensable substance.

However, there are many obstacles on the road to making hempcrete a standard building material. The increased sensitivity of hempcrete to moisture is a major concern, as highlighted in the literature review and previous investigations. In particular, precipitation can present a formidable challenge. Because of this susceptibility, preventative measures must be implemented, such as installing large roof overhangs to provide shelter from precipitation. Lime coatings on hempcrete walls become vital in situations where these overhangs cannot be incorporated into the building design.

There is also the issue of structural integrity, which poses its own unique set of difficulties. In its current form, hempcrete's compressive strength is inferior to that of regular concrete. Because of this discrepancy, hempcrete cannot be used as a principal load-bearing material. There are many new developments in the industry that strive to address this issue, but for the time being, it is still a real problem. Because of its one-of-a-kind make-up, this material cannot be used in the same way as other construction materials. Due to the specialized nature of working with hempcrete, there may be a shortage of qualified workers in the future. Time limits are also an important consideration. Due to the length of time needed for hempcrete to dry, the warmer months make for the best building window. Particularly in climates with extended winters and wet springs, this could affect construction schedules.

In addition, hempcrete's versatility is a plus, although it calls for painstaking care in every aspect. Hempcrete's density must be adjusted to suit its intended use. Insulating a roof or a sub-slab has different needs than insulating a wall. This variety demonstrates the adaptability of hempcrete but also highlights the complexity of its qualities that must be understood for its best use. Hempcrete's use in construction can also lead to new ways of thinking about building design. Some plans may call for roof drains, for instance, to eliminate the possibility of mold growth on the walls. These modifications can enhance hempcrete's performance, but they could also increase the complexity of the design or expense. The list of difficulties would be incomplete without also mentioning the cost. Though it offers long-term benefits like energy savings, the initial cost of hempcrete might be high in comparison to more conventional materials. Although hempcrete has long-term benefits, its high initial cost may prevent its widespread adoption.

Hempcrete is poised at an interesting juncture, bridging the past and future of construction. Its significant benefits and the interest shown in this emerging construction material mark it as the harbinger of a sustainable construction era. However, to navigate its course effectively, a comprehensive understanding of both its potential and challenges is essential. As architects, builders, and stakeholders venture further into the world of hemp and hempcrete, they will discover many possibilities and benefits that this crop can introduce in the building construction sector.

8. Advantages and Disadvantages of Hempcrete

Hempcrete, or hemp–lime composition, presents a myriad of advantages that make it a compelling choice for sustainable construction. One of its primary benefits is its ability to significantly reduce heat loss by effectively sealing any potential breaches, ensuring optimal airtightness. Furthermore, its high thermal mass combined with impressive insulating properties ensures enhanced energy efficiency. A standout characteristic of hempcrete is its lightweight nature, which simplifies the construction process by requiring fewer moving components and steps. This lightness also means that the foundational burden is reduced, enabling the use of materials with less embodied energy than conventional concrete. Moreover, hempcrete is composed of renewable, carbon-storing materials that have the potential for repeated use. It also acts as a vapor-permeable envelope, enhancing the breathability of structures.

However, while the opportunities are vast, there are challenges tied to hempcrete's use that need consideration. One significant hurdle is the requirement for designers and builders to collaborate with individuals possessing profound knowledge of hempcrete to ensure its correct application. Optimal construction conditions for hempcrete are during the summer months, given the reduced drying time. While winter construction is possible, it mandates extensive protection measures. Proper shielding and ample time must be allocated for on-site drying before any finishing tasks can be undertaken. Additionally, the application of hempcrete is limited to areas above the damp-proof course or its equivalent. A noteworthy challenge that arises in the context of broader adoption is the construction cost, which may be higher than traditional materials, potentially acting as a deterrent for some builders.

The utilization of hempcrete in construction merges the structural integrity and superior thermal insulation properties of a structure into a unified solution. While the initial cost of this material may be rather high in comparison to conventional materials, it offers exceptional long-term thermal efficiency, resulting in substantial energy bill savings. Furthermore, in contrast to alternative insulating materials that may experience degradation or sagging, hempcrete exhibits exceptional durability, demonstrating continuous performance over extended periods. In addition to its financial impacts, the advantages of hempcrete encompass the creation of a more healthful residential environment and the adoption of a construction methodology that is both sustainable and environmentally benign. The decision to invest in hempcrete may initially appear to be a high-quality option, but it is a choice that holds value for the future due to its long-lasting thermal advantages and positive impact on creating an environmentally sustainable living environment.

9. Conclusions

The building industry is progressively acknowledging the possibilities of bio-aggregate concretes, with hempcrete being prominently recognized. The potential inclusion of bio-aggregate concretes in the building regulations of several countries is being contemplated, as it has garnered significant support from industry experts. In the contemporary realm of sustainable construction, hempcrete has emerged as a focal material of interest. According to existing research, it has been suggested that the utilization of hempcrete has the potential to play a significant role in mitigating carbon emissions within forthcoming constructed settings. The findings derived from these investigations have the potential to facilitate the commercial feasibility of hempcrete.

The stated primary objective of this paper is to provide a comprehensive review of hempcrete as a construction material, delving into its varied characteristics and potential implications for the building industry. We not only have outlined the fundamental definition and rationale for employing hempcrete in construction but have also presented an in-depth analysis of its salient features. From its inherent advantages and limitations to the profound impact of different binders such as cement, NHL, pozzolanic materials, gypsum, MgO, and other admixtures on its mechanical properties, this study has addressed most of the important issues. Particular emphasis has been laid on the critical attributes of hempcrete, including its density, compressive strength, fire resistance, longevity, thermal and acoustic attributes, and most notably, its environmental sustainability. By integrating insights from previous studies, this study illustrates innovative strategies to enhance the compressive strength of hempcrete, with an aspiration to transform it from a subsidiary, non-load-bearing material into a robust, weight-supporting alternative. The motivation driving this study is the need for a better understanding of various attributes from the construction perspective that will help the design professionals seeking materials with ecological responsibility. In this pursuit, hempcrete stands out as a promising candidate that could redefine the benchmarks for sustainable construction in the imminent future.

Researchers are currently advocating for the exploration of a wide range of different and new applications for hempcrete, including sandwich panels, modular systems, and fillers within filler slabs. The existing body of literature indicates that hempcrete exhibits a high degree of versatility, rendering it a highly promising option as an environmentally sustainable construction material with wide-ranging applications. By making slight adjustments to both the composition and manufacturing method, it is feasible to generate a wide range of variances in the final product. The final product must meet several essential characteristics, including adequate mechanical strength, high thermal efficiency, environmental compatibility, and long-lasting durability. As a material with the ability to capture carbon, hempcrete demonstrates exceptional potential in properly managing temperature and moisture levels within structures. The capacity of this material to be molded into various configurations amplifies its attractiveness.

Nevertheless, a notable obstacle impeding the extensive use of hempcrete is the limited availability of a proficient workforce for its application. The primary areas of emphasis should encompass: (a) the provision of specialized training for a greater number of individuals in the application of hempcrete, (b) the implementation of policy measures aimed at promoting the utilization of materials that capture carbon, and (c) comprehensive evaluations comparing hempcrete to conventional construction techniques. It is worth mentioning that the maximum documented compressive strength achieved by hempcrete is 3.5 MPa, a value significantly lower than the typical strength of conventional concrete, which is approximately 17 MPa. The aforementioned constraint renders hempcrete unsuitable as a principal load-bearing material in the field of construction. Despite the acknowledged limitation in terms of compressive strength, a considerable body of research has put forth various approaches aimed at augmenting the compressive capacity of hempcrete.

According to the literature review in this paper, the following areas need further investigation and are identified as research gaps:

1. Investigate the physical treatment of hemp and lime–pozzolana combinations for improved mechanical strength;
2. Examine the effect of physical treatment on the reactivity of hemp–lime–pozzolana mixtures;
3. Expand research on increasing hempcrete's mechanical performance;
4. The current focus has been mainly on hempcrete's mechanical characterization;
5. A need for accurate equations to predict hempcrete's structural capacities;
6. Address the question of hempcrete's microbiological durability;
7. Explore hempcrete's decomposition mechanisms;
8. Study the relationship between durability and compaction;
9. Investigate the effect of compaction on hydraulic properties of lime–pozzolana-based hempcrete;
10. Research related to compaction or pre-compression of the mixture is limited;
11. Delve deeper into the relationship between phase-changing properties and hempcrete's mechanical properties;
12. Explore hempcrete's fire resistance in line with various countries' standards;
13. Validate hempcrete properties across different regions and climates given the local nature of building materials;
14. Most current studies have been conducted in Europe; global validation is necessary;
15. Investigate hempcrete's ductility and energy absorption for potential use in earthquake-resistant structures;
16. Identify other applications based on hempcrete's unique properties.

While hempcrete offers numerous advantages, it is important to acknowledge its present limitations, notably its compressive strength, which remains inferior to traditional concrete. Yet, the breadth of available research points to the potential to enhance this inherent limitation.

There are several avenues for future exploration outlined in this paper, highlighting gaps in our current understanding of hempcrete. This spans from its mechanical characterization and structural properties to broader global validations, especially given that most current studies are rooted in European contexts, which may need to be adjusted to different regions, particularly if the hemp is to be locally grown in those regions. It is crucial to foster an environment of continued research and training, emphasizing the need to bolster the workforce proficient in hempcrete application and addressing the challenges it faces.

This review emphasizes the role of hempcrete as a desirable bio-based construction material, which with continued research and innovation, could play a pivotal role in the sustainable future of construction.

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