Fundamental Properties of Hempcrete

Subjects: Others
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A bio-fiber composite made up of hemp hurd or shiv 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.

Keywords: hemp ; hempcrete ; insulation ; sustainable material

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. [1], 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. [2]. 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.

2. Compressive Strength

Murphy et al. [3] 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. [3] 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® [4][5] binder.

O’Dowd and Quinn [6] 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. [7] who indicate that the mechanical properties are improved when the binder proportions are limited. Research by Jami et al. [8][9] indicates that the characteristics and mix proportion of the binder affect the strength of the hempcrete. Furthermore, according to [10][11], 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. [12] 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. [13][14]. 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. [15], the use of a binder based on MgO leads to a hempcrete compressive strength that approaches 2 MPa. In the study conducted by Evrard [16][17], hempcrete mixtures were formulated and evaluated, resulting in compressive strengths ranging from 0.2 to 0.5 MPa. Arnaud et al. [18], on the other hand, reported compressive strengths ranging from 0.4 MPa to 1.2 MPa. According to Walker [19], 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. [20] 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. [21] 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. [22], 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 1**, 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 [23]. 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.

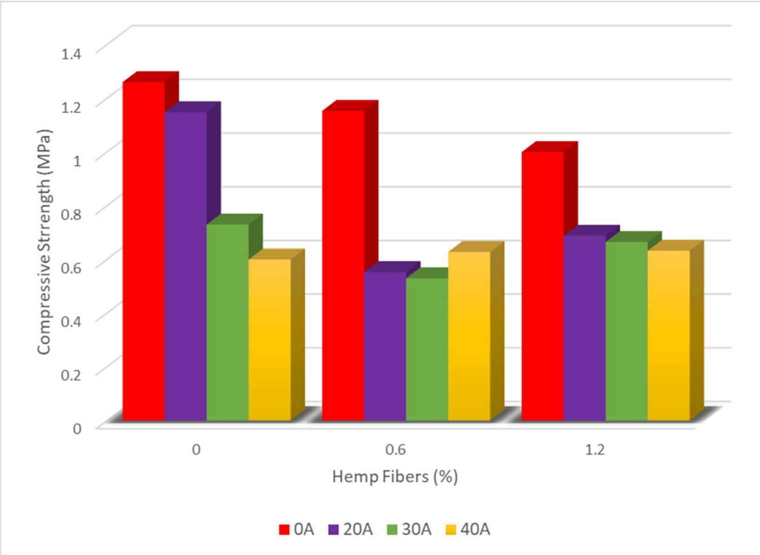

Figure 1. An examination of the effects of clayey soil and fibers on compressive strength after 7 days. (Adapted from references [22][24]).

Awwad et al. [25] 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 [26]. Chabannes et al. [27][28][29] 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 [30][31]. 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.

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

- 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.
- 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.
- 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.

- 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.

- 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.

- 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 [32][33]	**2005**	**1.88~1.98 MPa**	**610–830 kg/m^3**
Cerezo [34]	**2005**	**0.3~0.7 MPa**	**356–504 kg/m^3**
Elfordy et al. [12]	**2008**	**0.06~1.2 MPa**	**291–485 kg/m^3**
Nguyen et al. [11][35]	**2009**	**0.2~2.5 MPa**	**670–850 kg/m^3**
Hirst et al. [36]	**2010**	**0.2~1.2 MPa**	**220–342 kg/m^3**
Sutton et al. [37]	**2011**	**0.1~0.2 MPa**	**270–330 kg/m^3**
Arnaud and Gourlay [38]	**2012**	**0.1~0.34 MPa**	**460–500 kg/m^3**
Nozahic et al. [39]	**2012**	**7.11 MPa**	**1100–1300 kg/m^3**
Chabannes et al. [28]	**2014**	**0.45~0.51 MPa**	**400–650 kg/m^3**
Walker et al. [13]	**2014**	**0.29~0.39 MPa**	**360–400 kg/m^3**
Sassoni et al. [40]	**2014**	**0.1~0.2 MPa**	**330–640 kg/m^3**
Sinka et al. [2]	**2014**	**0.125~0.266 MPa**	**330–540 kg/m^3**
Chabannes et al. [29]	**2015**	**0.47~0.68 MPa**	**460–505 kg/m^3**
Tronet et al. [7][41]	**2016**	**1.36~4.74 MPa**	**580–843 kg/m^3**
Sassu et al. [42]	**2016**	**0.146~0.622 MPa**	**638–753 kg/m^3**
Nadezla Stevulova et al. [43]	**2018**	**0.9~5.75 MPa**	**960–1160 kg/m^3**
Niyigena et al. [44]	**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 [45][46]. According to Asrar et al. [47], 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 [48], 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 [49].

The compressive strength of hempcrete varies widely from about 0.03 to 1.22 MPa, depending on age and its mixture design [18]. The study by Evrard [17] 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 [17]. 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 [50].

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

- It is lightweight yet boasts significant thermal mass [51].
- Streamlines the construction process by reducing layers and steps, especially in timber-frame structures [52].
- Notable thermal insulation attributes [12][17][18][34][53].
- Capitalizes on agricultural renewable resources, specifically hemp.
- Can utilize locally sourced materials, including hemp and lime.
- Has minimal environmental repercussions [51][54][55].
- Offers commendable acoustic insulation [56].
- Achieves excellent airtightness, especially when paired with a render system [51].
- Demonstrates strong fire resistance [57].
- Exhibits distinct porosity characteristics [23][38].

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 [17] 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. [18], 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 [6], 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 [18][53], 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 [18][38] 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.

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 [11][12][58][59][60][61][62][63][64][65][66][67]. 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 [68][69].

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 [56][70][71].

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 [72][73]. 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 [74][75][76][77].

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) [78].

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.

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 [3]. A fire test by Fernea et al. [79] 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® [80] 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 [81], 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 [40][79].

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% [82] 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 [56], especially when smaller hemp shives [56] and lime–pozzolanic binders [82] 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 [34]. Recent research indicates the amount of hemp aggregate in the concrete is a key determinant of acoustic performance when compared to clay and lime [83]. 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 [34][83].

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. 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 [84][85].

Ip and Miller [86] 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 [86], 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 [86], 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 [87]. According to reference [66][67], 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 [65]. Hempcrete demonstrates a favorable climate change indicator, as it effectively sequesters carbon dioxide within its plant-derived aggregate [88][89]. The binders that pose the most risk are those commonly utilized in commercial settings, with particular emphasis on Portland cement [39].

Multiple research studies [18][38][53] 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 [86]. According to the cited source [87], 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 [86]. 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 [90]. 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 [91], transportation of materials, dosage, construction method, and application technique [92]. According to research findings [93], 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 [94], 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.

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. [13][14] 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. [13][14] 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 [19][95].

Walker et al. [13][14] 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 [96][97]. 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 [96][97].

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 [98][99]. 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 [100][101].

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 [102][103][104][105].

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 [8][9][105].

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