Review of Hempcrete as a Sustainable Building Material

Wafaa Zuabi¹ and Ali M. Memari²,*

¹Department of Civil and Environmental Engineering, The Pennsylvania State University, University Park, PA 16802, United States
²Department of Architectural Engineering and Department of Civil and Environmental Engineering, The Pennsylvania State University, University Park, PA 16802, United States

Abstract: The rate of carbon emission into the atmosphere has hit a record high in the last 20 million years. In planning, designing, and construction disciplines, sustainability is of utmost importance. With their carbon neutral and carbon negative properties, bio-composite materials have been getting more attention in the construction industry. One example is a bio-aggregate concrete known as hempcrete. This bio-composite is made up of hemp hurd, the inner woody core of the hemp plant, along with a lime-based binder. This paper discusses the main advantages of hemp and its use in making a type of concrete for construction. Besides their mechanical, insulation, durability, and other properties, the paper discusses the process of making hempcrete, various tests involved in determining the properties, and some applications in construction.

Keywords: Hempcrete, bio-based composite, sustainability, carbon neutral, affordable home construction

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1 INTRODUCTION

The construction industry uses natural resources to improve the quality of life by making buildings and infrastructure systems. Today, most professionals in fields related to material manufacture, design, and construction are committed to ensure the safety and wellbeing of people while protecting the environment. According to the American Society of Civil Engineers (2017), civil engineers have the ability to prolong the quality of life without harming nor exploiting environmental, social, and economic resources. With the shared vision to protect the environment, innovative technological advances can offer proper solutions to address the current problem of using environmentally damaging materials for construction.

Concerns are on the rise as current atmospheric carbon dioxide levels are increasing alarmingly compared to past decades. Ancient air bubbles trapped in the ice provide information about what Earth’s climate was like in the distant past. During ice age periods and warmer interglacial periods, carbon dioxide levels were estimated to be 200 and 280 parts per million, respectively. For the first time in recorded history, the current level of carbon dioxide in the atmosphere has exceeded 400 parts per million (Luthi and Etheridge 2019).

In relation to the construction industry, it has been reported that residential and commercial structures make up about 40% of the United States’ energy consumption, which is responsible for nearly 38% of all carbon dioxide emissions (Tatari and Kucukvar 2012). Due to such statistics, the construction industry has been developing methods to reduce as well as reverse CO₂ generation.

Demand to reduce or stop construction practices that harm the environment are driving scientists, architects, and engineers to search, develop, and implement the use of alternative materials, such as bio-aggregates. One of the recently rediscovered materials in the industry is hemp because of its high sustainability properties and attributes, serving over 25,000 different products in the global market (Johnson 2018).

For building purposes, the hemp crop’s inner woody core is mixed with a lime-based binder forming a bio-aggregate concrete, known as “hempcrete”, which is a light-weight concrete primarily composed of lime and hemp shives (waste products in fiber production). The hemp-lime composite material is mainly used to make walls, although floor slabs, ceiling, and roof insulation can be made as well. The relatively denser hempcrete mixture is poured above a base layer into the floor to make floor slabs (WWH 2020). However, Hempcrete Direct (2019) explains that hempcrete blocks can also be used for roofs as well as the more conventional wall applications since their implementation is easier than other types. Its cost-reducing and sustainable properties make it a promising material in both new projects and those involving renovation. If a basic 300 mm wall of hempcrete is used, the
cost may be on the order of $135/m² (Alo 2018), involving only 5–6 laborers on-site (Hemp Technologies Global 2020). This price is an estimate and subject to change depending on the location and type of the project.

2 MATERIALS IN HEMPCRETE

2.1 Hemp

Planting hemp has numerous advantages that makes it easy to work with. According to SUBATC (1924), the hemp plant becomes ready to harvest 100 to 120 days after it has been planted; it does not need much caring, weeding, or cultivation, and it can grow on new or old soil. It can withstand extreme temperatures like frost and only requires modest amounts of water. Furthermore, according to Hemp Basics (2020), hemp has the potential to grow in all 50 states of the U.S., i.e., in different environments and climates. Monitoring the growth process requires minimal effort as the plant solely requires fertilizer without the need for pesticides and herbicides. Moreover, harvesting hemp can be more favorable for the use of land; not only it allows the soil to be used for other crops after harvesting hemp, compared to growing trees, but it also reduces logging and soil erosion drastically, and thus decreases topsoil loss and soil runoffs that may cause pollution in water.

The process of making hemcrete starts with extracting the interior of a cannabis plant – an interior woody core that is separated from the flower, seed, and the rest of the plant. This extraction is difficult due to the strong chemical bonds called pectin present in the hemp stem (Canadian Hemp Trade Alliance 2020). To overcome these bonds, a process known as retting is performed on the stem where water, enzymes, or microbes are applied to separate the bast fiber (Figure 1) surrounding the stem from the inner woody core (Hempgazette 2020).

Figure 1. Separation of outer hemp fiber bast and inner hemp hurd/shiv through retting (Hemp Traders 2020)

When harvested as such, it is given the name hemp “hurd” or “shiv”. The hemp hurd is then chopped into lengths of approximately 6–25 mm, often using a decor-ticator. The hemp itself has a high silica content, which makes it suitable for binding with lime. The fiber content in hemp increases hemp’s density and improves strength; however, this worsens the thermal performance of hemcrete. Accordingly, it is preferable to have minimal fiber or no fiber at all present in hemcrete mixtures. Figure 2 shows the effect of fiber content on hemp’s quality.

Figure 2. Hemp with different degrees of fiber content: (a) high, (b) moderate, (c) low (Magwood 2016a)

2.2 Lime

Lime plays the role of a binder as it preserves the natural fiber in hemp, making it durable and resistant to fire, mold, and vermin. The mineral has numerous advantages listed below that makes it a promising material for construction (Rhydwen 1999):

(1) High porosity and permeability
(2) Autogenous healing - water dissolve free lime and seal the crack
Workable for plastering - a high degree for lime mortars is considered to stay cohesive, smooth, and moldable (workability can be determined by different flow diameters achieved by varying water contents of lime mortars)

High pH of 12.4 - lime washing surfaces can repel mosquito larvae and prevent mold growth

Recyclable - safely decomposable in soil or burnable to produce hydrated lime

Long-lasting; 50–100 years

3 HEMP PRODUCTION AND USE

Hemp has been cultivated and used since 8000 BCE (Schluttenhofer and Yuan 2017). One old urban legend says that the U.S. Declaration of Independence was written on Dutch hemp as the material was known to have high quality and lasted longer when compared to cotton. The 1924 document (SUBATC 1924) talks about growing hemp in California as we are today. Hemp’s usage in North America started in 1611 (Freeman 2019) and was legal in the 1700s. The Ministry of Hemp (2019) emphasized that hemp was commonly grown amongst farmers for multiple reasons varying from paper to lantern oil to ropes. Hemp’s uniqueness in quality gave rise to the following applications or products:

1. Medicine - painkillers and cancer treatment
2. Fabrics in textile
3. Biofuel
4. Paper
5. Bullet-proof vests, bunkers, and clothes
6. Cellulose plastics
7. Hempseed food and edible oil
8. Construction - hemp concrete and composite boards

As the list of products suggests, hemp has a variety of applications. According to the Hemp Industries Association (2016), hemp product retail sales were nearly $700 million in 2015 and can be illustrated as shown in Figure 3. Various parts of the plant (fiber, stalk, leaf, flower, or seed) can be used for different purposes, including food, medicine, and construction (Vivek 2019).

4 OVERALL PROCESS

The process begins with the mixture of hemp hurds with water followed by the lime-based binder. The order in which these ingredients are added is very important as the reactions occur rapidly. Some hempcrete producers choose to mix the hurds using a mortar mixer (or by hand) with the lime-based binder, followed by misting water until the desired consistency is reached (Magwood 2016b). A chemical reaction known as “bonded cellulose insulation” occurs between the water and the lime-based binder, which adheres to the hurd particles together (Contributing Writers 2020). According to Christensen and Beckerman (2016), the most common ingredient ratio among hemp hurd, lime-based binder, and water is 4:1:1. Changing the mixture proportions influences several properties of hempcrete, such as its workability. The authors further report that hemp: binder: water ratios (by volume) with 1:9:22.2 (10% hemp and 90% binder) needed an extra 5 minutes above the initial 10 minutes of mixing to reach the necessary workability as opposed to those with ratios of 1:0.33:3.3 (75% hemp and 25% binder) and 1:1:3.3 (50% hemp and 50% binder), which needed only 10 minutes of mixing (Murphy et al. 2010). Such results led to the conclusion that increasing the lime content improves the workability of the hemp concrete.

With respect to the effect of water content on hempcrete’s properties, one needs to note that the hurd’s porous nature allows for excess absorption of water, which can lead to a considerable amount of water absorption during application (Green Building Materials 2017). Such a high moisture content can result in a high-density mixture, which drastically elongates both the setting and drying time. Of course, once the mixture is left to set and cure, excess water naturally dries out, but the following two extreme conditions are to be avoided: the mixture should not fall apart into tiny fragments (dry sign) nor be too damp (wet sign) (Fawcett 2019). An ideal mixture should break into 2–3 pieces if shaped into a ball and poked. The amount of water in the mixture is also dependent on the temperature and humidity of the day hempcrete is made. Following all these steps carefully should yield good quality hempcrete.

5 CONSTRUCTION METHODS

5.1 Monolithic Cast Walls

Cast in place method needs structural framing to be built in accordance with the pre-installed electric pipes and plumpling system (Centropleux Projects 2019). Wooden
or plastic forms are then used that will enclose the structural framing (Figure 4), although they can be spaced out. There are several ways of constructing the walls, varying from floor to the roof at once (Figure 5) or “sectioning” as hempcrete is being poured into the void spaces in the formwork (Figure 6). Hempcrete is then mixed and poured (or carried by hand) into the forms. The mixture should properly surround the already-fastened pipes and mechanical work, and not voids left (Centropleux Projects 2019). The hempcrete’s surface should also be leveled and flattened for efficient surface integrity, but leaving the mixture’s interior surface loose to allow for proficient insulation (Centropleux Projects 2019).

After 24 hours, the forms are removed and placed at a higher position for the next batch to be poured. Depending on the environment and mixture ratios, drying times may take between six to eight weeks (Stanwix and Sparrow 2014) to allow hempcrete to achieve its full strength. Overall, the cast-in-situ method is highly flexible for construction and suitable for many types of building applications, but not for cases in contact with soil or water (Sparrow 2014).

5.2 Hempcrete Bricks and Blocks

Hempcrete bricks (Figure 7) are produced on a large-scale, serving primarily for insulation and infill wall purposes, where the framing is erected before constructing masonry hempcrete, i.e., stacking and mortaring the bricks. The bricks are either placed inside (infill) or in front of the framing to complete the wall assembly. Block production consists of four different steps: mixing the three basic ingredients hemp, lime, and water, molding, open-air curing, and palletizing (IsoHemp Natural Building 2020b). According to the method described in IsoHemp Natural Building (2020b), 30 cm wide block-shaped molds are used to fill and compact hempcrete, which are then placed in a storage space (Figure 8) to dry and harden. With the desired hardness reached, the bricks are placed on pallets and stored to dry for an additional 6 to 8 weeks (Figure 9).

The dried blocks are then trucked to the construction
5.3 Complete Structural Wall Panels

A custom wall system, known as structurally insulated panels, can also be made using hempcrete, as shown in Figure 12, where such panels are produced in a factory through a combination of sprayed hempcrete panels and a structural frame comprised of fabricated zinc-coated steel members. Once the steel framing is assembled, hempcrete mixture is then sprayed into the steel frame, forming a structurally insulated panel. It should be recognized that there are a variety of structural insulated panels involving other materials. Assembling occurs after the panels are sent to the site resulting in a finished building envelope on top of a pre-built foundation (Centropleux Projects 2019).

5.4 Spraying Hempcrete

Spraying hempcrete requires the use of industrial spraying equipment, as shown in Figure 13, to build a hempcrete wall where the hempcrete is pumped from a cement mixer through a hose and a spraying nozzle, saving time when compared to hand-packed hempcrete. According to Magwood (2014), this method is not yet employed in North America but is rather commonly used in Europe. One reason could be the lack of skilled labor in this field and also the cost of equipment. Depending on the model and the capacity capability, these spraying machines can generally spray up to 100 liters of hempcrete per minute (Baumer Hempcrete Solutions 2020).

The use of hempcrete as masonry is labor-friendly, saving time, and lowering costs (Canna Systems Canada Incorporation 2015). Another advantage of hempcrete brick or block use is that they are delivered to job sites with much of the drying already done, leading to a curing process that is sustainable as the blocks are left out to dry naturally without energy consumption. The disadvantage is that this method is less monolithic and cohesive than the cast-in-place method.
6 HEMPCRETE PROPERTIES

While there are many types of insulation materials, most involve the use of much energy in their production. An ideal insulation material would be renewable and durable, which can be produced from waste streams or as a by-product of other processes. Hempcrete has much of such attributes, besides the potential of creating healthy buildings. Hempcrete’s construction flexibility allows architects and builders to come up with customized designs (Tradicall 2020).

Hempcrete walls offer several finish options, varying from a rough cast surface to a smooth finish. A Highland Hemp house built in 1969 in Bellingham, Washington, was recently remodeled where the owner is quoted as saying that the house is a “physical testament to the beauty and potential in hemp building” (O’Connel 2018). The material’s density provides airtightness, guaranteeing uniformity within the structure. In contrast, it is argued that these walls are too thick, subsequently leaving residents with less carpet space.

Hempcrete does not require agrochemicals like the common endosulfans, DDT’s, and other nitrogenous fertilizers in its cultivation. The hemp plant absorbs up to 15 tonnes/hectare (Wilson 2020) of carbon dioxide from the air, thus reducing the greenhouse gas effect on the planet. Additionally, hempcrete has high levels of cellulose; hemp plants and hurds are composed of 65%–70% (Wilson 2020) and 40%–48% of cellulose, respectively (Stenvulova et al. 2014). The high levels of cellulose prevent carbon from releasing into the atmosphere (Falak 2019). The required amount of hemp needed to make a full-sized 1,500 square-foot house is around one-thousand 33-pound bags (Kennedy 2018), which saves around 130 kg/m³ of atmospheric carbon (Koms1 2018).

Figure 14 outlines the stages involved in hempcrete production and its contribution to carbon dioxide emission. The raw production of the hemp plant itself releases carbon dioxide because non-renewable energy resources are used for cultivating purposes, consequently polluting water and air. In addition, due to the transportation required to move the material, it further has some negative effects, as shown in Figure 14. Nonetheless, hempcrete is 7 to 8 times lighter than concrete, hence significantly decreasing vehicle energy consumption and expenses (Koms1 2018). Needless to say, the thickness of the hempcrete wall is directly proportional to its carbon dioxide distribution.

Summarizing all these quantities categorizes hempcrete as a green material because it promotes the wellbeing and safety of the public and minimizes the impact of climate change whilst maintaining the efficiency and resilience of buildings (USGBC 2020). The overall total negative value is attributable to the decarbonation processes and photosynthesis of the hemp plant itself. Most importantly, the numbers show it has a negative carbon footprint making it a suitable material in the construction industry.

Depending on the complexity of the project and the availability in the region, currently, hempcrete may be more expensive than some other conventional construction materials/systems. Of course, as briefly mentioned earlier, transporting hempcrete is more economical compared to concrete, as it is a lightweight and low-density material. Furthermore, construction with hempcrete (as opposed to normal weight concrete) requires shallower foundations and thus more affordable foundations without necessarily requiring joints because of their distinctive properties.

Owing to hempcrete’s insulation properties, the Ministry of Hemp Basics (2020) valued the low cost of heating for an average household in Alaska during winter to be around $500 dollars. A case study (BCB Tradicall 2020) on the energy performance of a hemp home in Vidauban, France, has shown that the heating bill could be about $140 dollars, including VAT during the winter months of
November to the end of March. In general, due to their natural ability to trap heat, they can lead to a significant reduction of 50% to 70% in a heating bill (Falak 2019).

Although hempcrete homes can save on electricity, their construction is currently more expensive compared to the conventional wood frame with fiberglass batt insulation. Because hempcrete building construction is relatively new, not enough research and development (R&D) has been conducted on industrial hemp and hempcrete usage to lower the cost. However, as with any other innovative product, with more use and sales of the product, more economical options will evolve. Needless to say, more R&D can help hempcrete to be accepted by the builders (O’Connel 2019). The lack of architects, engineers, builders with an interest in hempcrete, and the current knowledge gaps require more training programs for design professionals and builders. In the long run, this will help lower the costs.

Life cycle assessment (LCA) can comprehensively analyze the sustainability of a hempcrete building’s material composition in terms of embodied energy, the effect of waste products during manufacturing and construction processes, as well as any material restoration over the building’s lifetime. The life span of hempcrete is not accurately known; however, the lifecycle assessments performed on the material estimated the lifespan of hempcrete walls to be around 100 years (Pretot et al. 2014), with hardness and rigidity increasing over time.

The life-cycle energy evaluation by Florentin et al. (2017) performed on hempcrete has shown that hempcrete can absorb more carbon than it releases during its production phase, hence having negative embodied carbon. An average hempcrete apartment absorbs 7.5 tons of carbon dioxide, which is equivalent to the energy consumed by an average concrete apartment for heating and cooling in five years (Florentin et al. 2017). A comparative life-cycle analysis by Florentin et al. (2017) suggests that hempcrete’s net carbon balance is 10% less than that of autoclaved aerated concrete. Overall, hempcrete is carbon negative which signifies Earth’s total net carbon savings.

Recycling is also an option to get rid of hempcrete building once it reaches the end of its life; however, hempcrete is still a relatively new material and not many hempcrete buildings have been built to reach their end of life. So, while R&D efforts are still ongoing for efficient recycling of hempcrete, landfill disposal is currently the best option with the caveat that the disposed of hempcrete will not emit carbon dioxide when decomposed.

7 THERMAL PERFORMANCE

Thermal conductivity is defined as the rate at which heat flows through a material depends on density, composition, and moisture content. With respect to density, as in most materials, with an increase in density, hempcrete’s conductivity increases because high density decreases the porosity between the shiv particles (Kinnane et al. 2015). For example, high-density mixtures of 450 to 550 kg/m$^3$ have conductivity values of 0.11 to 0.16 W/(m·K), whereas low-density mixtures of 220 to 275 kg/m$^3$ have conductivity values of 0.05 to 0.06 W/(m·K) (Collet and Pretot 2014), which is within the range of most other conventional insulation materials.

Overall, depending on the density, they have an average conductivity of 0.05 to 0.16 W/(m·K) (Collet and Pretot 2014).

Another parameter that affects thermal conductivity is the moisture content, which causes the conductivity to increase linearly with moisture content (Tran Le et al. 2010). The amount of water and the quantity of lime-based binder play a role in increasing the overall thermal conductivity of hempcrete (more binder leads to higher conductivity); however, this varies with the binder, as some may lead to lower conductivities (Cerezo 2005).

Specific heat and volumetric heat capacities reflect the potential of a material to store heat per unit mass and per unit volume, respectively, as it is subjected to varying temperature (Kinnane et al. 2015). The values of the heat capacity of hemp-lime composites have been reported to be between 1,000 J/kg·K and 1,560 ± 30 J/kg·K, depending on various densities (Tran Le et al. 2010; Evrard and De Herde 2010). When it is humid, the material exhibits a higher thermal storage capacity because of the higher volume of absorbed moisture within the wall.

Although hempcrete is a light-weight material, it also shows the high thermal mass and high heat inertia properties as it has a natural ability to diffuse accumulated heat (IsoHemp Natural Building 2020a) slowly. Maintaining a comfortable temperature range in a building is of utmost importance, which requires careful selection of building materials. The rate at which hempcrete wall stores and releases heat is influenced by temperature fluctuations. The thermal storage capacity of hempcrete allows it to store the generated interior heat and release it to the interior later (e.g., at night) when outside is colder (during winter). On the other hand, during the summer, it will absorb the outside heat and does not release it to the interior immediately, which will help avoid overheating, and therefore can reduce energy bills.

The thermal inertia of Hemp-lime walls can be defined under two categories. The first one is the thermal inertia under fluctuating outdoor conditions, which is attributable to thermal diffusivity, which is determined by dividing the heat conducted by heat stored as a measure of how fast heat can pass through a material (Kinnane et al. 2015). Hempcrete shows lower thermal diffusivity when compared to other materials like concrete, earth block, and solid brick (Maalouf et al. 2014).

Through building simulations, hempcrete’s thermal diffusivity in humidity levels of 0% to 100% ranged from 1.48 to 0.98 m$^2$/s (Evrard and De Herde 2005). Hemp-
lime composites with lower conductivities and higher specific heat capacities were reported to have higher values of thermal diffusivity, varying from 0.274 to 0.3 mm$^2$/s (De Bruijn and Johansson 2013). Another study reports a diffusivity value of 0.266 mm$^2$/s for hemp with a high density of 570 kg/m$^3$, low specific heat capacity, and conductivity of 0.15 W/m-K (Maalouf et al. 2011). According to Evrard and De Herde (2005), in their thermal assessment of hempcrete, a low thermal diffusivity of 250 mm$^2$/s can result in 98.5% dampening of a sinusoidal change in a 24-hour exterior temperature range of 20°C to 0°C.

The second type of thermal inertia is associated with fluctuating indoor thermal conditions, defined as thermal diffusivity, which is a measure of how easily a material can exchange heat with its surrounding (Kinnane et al. 2015). Materials identified with low diffusivity can be expected to provide thermal warmth or warm to touch. Hempcrete walls are reported to have a low diffusivity value of about 231 J/m$^2$Ks$^{-1}$ (Maalouf et al. 2014), as referred to in Table 1.

A better understanding of thermal inertia can help in realizing the practical implications of low thermal diffusivity (Van Der Maas and Maldonado 1997). In particular, it helps to explain the reason for a drastic change in a material’s temperature during the day if it has low thermal inertia and vice-versa.

The hemp shiv contains air spaces between its particles and microscopic pores within the material itself, which provide thermal resistance, i.e., the more air pockets, the higher the insulation. Compared to rigid foam insulation, hempcrete provides smaller thermal resistance per unit thickness, and thus larger wall thickness would be needed to meet the code requirements. For example, according to the UK building regulations (UK Hempcrete 2014), a 240 mm thick hempcrete wall would be needed as opposed to 160 mm thick polyurethane rigid insulation to meet the insulation requirements. On the other hand, hempcrete costs less than other synthetic insulation materials, and that can compensate for the larger thickness of hempcrete walls. The other attribute of hempcrete that helps energy saving is its airtightness due to being a monolithic and single layer (solid) material, which reduces heat loss through air leakage commonly seen with excessively large amounts through conventional wood-frame walls (Tradal 2020).

Due to the high vapor permeability of hempcrete walls, moisture can be stored from both sides and also dried to the interior or exterior without causing moisture damage due to condensation. Because of such permeability property, no moisture accumulation and thus no mold and fungi growth can occur, and this helps create a healthy indoor air quality.

8 COMPRESSIVE STRENGTH

The compressive strength of hempcrete ranges from 0.03 to 1.22 MPa and is dependent on its age and material composition (Arnaud et al. 2006). Evrard (2003) documented that they can also vary from 0.2 to 0.5 MPa. When compared to concrete strength of 20.7 MPa to 34.5 MPa, these ranges indicate that hempcrete is not suitable for use as a load-bearing material. Therefore, a separate gravity load resisting system, such as a wood-frame, would be needed to support the applied loads. Despite being weak to resist compressive loads, hempcrete offers flexibility as opposed to brittleness, and therefore hempcrete walls have large deformation capacity without rupturing (Evrard 2003).

On the other hand, hydrated lime slowly absorbs carbon dioxide as it sets and becomes a harder material with time. Accordingly, with an increase of hydrated lime in the mixture, the compressive strength of the material can be enhanced. Of course, this is a very slow process, and it would take several years or even decades for the material to reach its mature maximum compressive strength (Strandberg 2008).

9 EXPERIMENTAL TEST RESULTS ON MATERIALS

The tests discussed in this section have been reported in the literature as following specifications in IS 1624: 1986 (Methods of Field Testing of Building Lime).

9.1 Lime Properties

The types of lime used for building construction are classified into several categories: Classes A, B, C, and E (Indian Standard 712 1984). Class A limes are defined as “hydraulic” limes commonly utilized for structural purposes as they have a minimum compressive strength ranging from 1.25 to 1.75 MPa. Class B limes are considered “semi-hydraulic” commonly seen in mortars for work with

| Table 1. Values of hempcrete’s thermal responses from literature (Kinnane et al. 2015) |
|-----------------------------------------------|------------------|------------------|------------------|
| Thermal property | Thermal conductivity (W/m-K) | Volumetric heat capacity (J/K-m$^3$) | Thermal diffusivity (mm$^2$/s) | Thermal effusivity (J/m$^2$s$^{-1}$) |
| Literature values | $0.129 \pm 0.05$–0.16 | $\rho = 220$–550 kg/m$^3$ | $C_p =$ 900–4,700 J/kg-K | $0.14 /s (0.27$–0.3 for thermal conductivity | $231 \text{ for } C_p =$ 3,000–4,690 |

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<tr>
<th>Material property</th>
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<th>Volumetric heat capacity (J/K-m$^3$)</th>
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bricks or stone along with class E limes, the “kantar” limes. Like class A limes, class B limes have a minimum compressive strength ranging from 1.25 to 1.75 MPa. Finally, class C limes are known as “fat” lime or otherwise referred to as “quick” lime (non-hydraulic lime), mainly used for coating, plastering, and whitewashing purposes.

Numerous tests have been conducted on different types of lime, examining its visual appearances (Figure 15) such as color, state of aggregation, and texture (hard/soft/powder-like/granular). One sample type tested showed to be whiter in color and lumpier in the form (Manohari et al. 2016). On the other hand, a hydrated lime sample felt loose in texture and grain when held and rubbed in between fingers. The size of the grains measure was not larger than 2.50 mm (Manohari et al. 2016), and this led to the conclusion that the lime sample was a class C lime.

The objective of the ball test is to determine the type of lime. According to the test standard, 50 mm diameter balls of quicklime are mixed with water and left six hours to turn into a paste, which should then be submerged into a basin of water. If they show any indication of disintegration within minutes, they would be considered class C limes; otherwise, they would belong to class A. They would belong to class B or E if they do not show any expansion with no sign of surface cracks (Indian Standard, 1624 1986).

The density and specific gravity of lime can be determined by adding water-free kerosene to a Le-Chatelier Flask (Figure 16), and then placing it in a water bath – to keep the temperature constant throughout and maintain stable conditions (Helsel et al. 2016). After the initial reading of the meniscus, the lime sample is added, and the meniscus read again. With measurements at two different levels, the volume of the liquid displaced is determined, which leads to the density (mass divided by the volume) and the specific gravity of the lime sample (Manohari et al. 2016).

The aim of the impurity test is to analyze the purity and impurity of lime samples. Freshly burnt quicklime collected from a kiln is mixed with water and allowed to set for two hours. The mixture may then be strained using an 850 micron IS sieve as water is added. The residue consisting of unburnt or overburnt stone and sand (among other particles) is then rinsed with water to ensure lime-free residue. The residue is then spread on a metal tray and sprayed with a jet of water. The water is removed while settling, followed by drying off and cooling the residue. Then a process called “lime slaking” tends to occur, in which the calcium hydroxide in traditional lime turns into calcium oxide by the addition of water (Hassibi 1999). To avoid this, the residue is screened and left to dry for a period of eight hours. After the drying process is over, the residue is weighed (Manohari et al. 2016). According to Manohari et al. (2016), the ratio of the residue to the initial mass provides an index for burning efficiency. According to this method, classes B and F will not have more than 10% of residue, whereas classes C and D will not have more than 5% of residue.

The purpose of the plasticity test is to evaluate how easy a lime paste spreads, i.e., its plasticity. In this test, thick cream-like consistency of the water-lime mixture is left overnight, and then the paste is spread on highly absorbing blotting paper (Figure 17) using a blade or simple butter knife. A high-quality standard lime sample is used to compare with the lime sample undergoing the test. If the paste is spreadable compared to the standard lime sample and shows no presence of sandy materials nor rough strokes, then the desirable plasticity is established.

The workability property is determined by the plasterer based on his/her experience and knowledge as the material is applied to the wall using a trowel. To pass the test, the spread area should increase in size by about two times while sticking properly to the wall. It is necessary for a workability test to be performed on the same mortar that will be used in construction.
To evaluate the normal consistency of hydraulic lime, the amount of water needed for the paste is compared during the initial and final stages of the setting. This experiment makes use of the Vicat apparatus shown in Figure 18. The standard consistency is determined by how deep the lime sample permits the Vicat plunger to penetrate from the bottom of the Vicat mold.

Referring to Figure 19, the Vicat apparatus is comprised of a 6.33 mm-diameter brass rod B, adjustable by screw E (ASTM International 2016). A 12.5 mm-diameter plunger C free falls into the mold holding the paste, and the penetration depth is worked out using the vertical graduations on the scale, which should be linked to bracket A. If the required total weight of 30 g of the plunger and rod is not achieved, weight D could be attached to the rod, or an extra shot could be added (ASTM International 2016).

The first step involves adding lime to water and mixing it in a bowl containing a dry paddle. The mixer is initially set to 30 seconds and then changed to low speed for another 30 seconds to allow proper consistency. Afterward, the lime paste is shaped into spheres and thrown from hand to hand, distanced 15 cm apart, for about six times. The ball is then pressed vigorously into a 40 mm-high Vicat mold with a 60-mm diameter top gradually increasing to a 70 mm-diameter base, under a non-porous glass base plate. The paste is firmly pressed using a trowel and gently tapped from the side to level the surface of the paste with the top of the mold.

The mold is then positioned so that its center aligns with the plunger’s end, and the rod is lowered so that the plunger barely touches the surface of the paste. Once the indicator is moved to the upper zero marks, the rod is instantly released – this process should be done within 30 seconds after mixing. To achieve normal consistency, the process is repeated with lime and varying percentages of water until the plunger stops penetrating at a certain depth; the paste usually shows normal consistency after 30 seconds of release, when the rod reaches a point where the scale reads 10 ± 1 mm below the surface. The observations of a lime sample weighing 300 g are outlined in Table 2.


<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Percentage of water</th>
<th>Amount of water</th>
<th>Initial Reading</th>
<th>Final Reading</th>
<th>Penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>120</td>
<td>40</td>
<td>17</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>42</td>
<td>126</td>
<td>40</td>
<td>13</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>44</td>
<td>132</td>
<td>40</td>
<td>11</td>
<td>29</td>
</tr>
<tr>
<td>4</td>
<td>46</td>
<td>138</td>
<td>40</td>
<td>8</td>
<td>32</td>
</tr>
<tr>
<td>5</td>
<td>48</td>
<td>144</td>
<td>40</td>
<td>5</td>
<td>35</td>
</tr>
</tbody>
</table>
procedure focuses on the initial and final setting time to determine the overall setting time of hydrated lime using the same Vicat apparatus in Figure 19.

For the preparation of lime putty, 500 g of hydrated lime is soaked with an equivalent mass of water. Then as in the standard consistency test, the paste is loaded into a Vicat mold laying on top of a non-porous plate while ensuring a smooth finish. The Vicat needle is dropped to softly touch the surface of the putty and then released to penetrate the test block (Manohari et al. 2016; Padhi 2013). This process is repeated several times until the lime putty resists getting pierced by ± 5 mm (Padhi 2013). The initial setting time is considered as the time period between mixing the lime with water, and the test block resisting the piercing. The final setting time of lime is noted when an annular end attached to the needle does not make an indentation on the specimen, but the needle does. Results showed that the final setting times of lime were 60 and 720 minutes, respectively (Manohari et al. 2016).

9.2 Hemp Properties

While there are different definitions for specific gravity, in this paper only, the bulk specific gravity and the apparent specific gravity of hemp is of interest. The bulk specific gravity is defined as the “ratio of the mass of a unit volume of aggregate, including the water permeable voids, at a stated temperature to the mass of an equal volume of gas-free distilled water at that stated temperature” (Pavement Interactive 2019). On the other hand, the apparent specific gravity is defined as the “ratio of the mass of a unit volume of the impermeable portion of aggregate to the mass of an equal volume of gas-free distilled water at the stated temperature” (Pavement Interactive 2019).

The first step in determining such ratios is to soak the hemp aggregate in water for 24 hours (Manohari et al. 2016). The hemp is weighed at three different times: 1) initially (in the open air), 2) when dried in the oven, and 3) when saturated in water. The bulk specific gravity is calculated by dividing the weight of the hemp sample in the air by the difference between that same weight and the weight of the saturated sample. On the other hand, the apparent specific gravity is found by dividing the weight of the oven-dried sample by the difference between that same weight and the weight of the saturated sample. Consequently, the hemp fiber’s specific gravity was calculated to be 0.65.

The water absorption property of hemp aggregate is deduced by monitoring how its density changes as a sample is submerged into the water, as seen in Figure 20. Hemp shives are packed in an 8 cm-diameter perforated container (cage) bearing a rigid bar that is attached to a scale (Fourmentin et al. 2016). The container is then suspended 6 cm-deep in a water container whilst the scale begins to determine the mass of hemp over time. Although it is important to vigorously compress the shives, small voids should still be present, so air released from the hemp could escape. To aid with that process, the steel cage has pre-built 5 mm holes. Results showed that the mass read 40 g relative to an apparent volume of 200 to 350 cm³ (Fourmentin et al. 2016).

Generally, “hemp aggregates have a high-water absorption capacity” (Page et al. 2017). More specifically, the water absorption of hemp is 450% after 48 hours. Studies by Amziane and Arnaud (2014) explain this high value to be due to the porous structure of hemp shives. Water absorption has an inverse relationship with the hardening time for hybrid composites, with hempcrete achieving the highest value (Page et al. 2017)(Stevulova et al. 2018).

9.3 Hempcrete Properties

The density and strength of hempcrete are functions of the different mixture ratios. As typical mixture ratio examples, three different samples are outlined in Table 3.

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemp fiber</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Water</td>
<td>1.5</td>
<td>2.9</td>
<td>2.9</td>
</tr>
<tr>
<td>Lime</td>
<td>1.5</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Cement</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The hemp part of the mixture consists of chopped 5 cm-long aggregates, comprised of 62% shives and 35% fibers but should not have more than 3% dust particles. The fibers must be submerged in water for at least 24 hours to allow for efficient absorption. Usually, class C limes in powdered form are used. Water should have a moderate hardness (0–100 mg/L) and must be at a temperature of 27°C. Adding water to lime creates a highly exothermic reaction, where large amounts of heat produced cause water to evaporate quickly. Taking into consideration that hemp absorbs a great amount of water, the binder ratios
for the three samples are 100%, 120%, and 120%, respectively.

To obtain the compressive strength, an axial load is applied to cubic samples until failure. The maximum recorded load applied divided by the cross-sectional area of the cube sample yields the compressive strength. This is done for different samples at 40 days and 60 days in order to observe the gain of strength with time. Some test results have shown that the average compressive strength for hempcrete can be 0.97 MPa for the 45-day sample and 1.11 MPa for the 60-day sample (Designing Buildings Wiki 2017). In comparison to conventional concrete strength of 20.7 MPa, hempcrete compressive strength is approximately 5% than that of concrete.

This shows that with such very low compressive strength, hempcrete does not meet the criteria for being an ideal direct load-bearing structural material. More binder, e.g., lime, need to be added if higher compressive strength is required (Evrard 2003). On the other hand, hempcrete shows that it has a large deformation capacity before failure, which offers a somewhat ductile behavior, i.e., a large capacity to deform without brittle failure normal in concrete.

In summary, compressive strength depends upon multiple factors, including the ratio of the ingredients and the material’s stage in its lifetime (Strandberg 2008). Hemp shiv to lime volume ratios of 4:1 and 5:1 have shown comparable compressive strength behavior to that of a 3:1 ratio with compressive strength of 0.71 MPa (O’Dowd and Quinn 2005). Accordingly, it was reported that the compressive strength remained unaffected (no decrease) with increasing hemp ratios (O’Dowd and Quinn 2005). Elfordy et al. (2008) noticed a correlation between density and compressive strength, i.e., compressive strength increases as density increases (due to larger compactions). Generally, the average compressive strength of hempcrete is below 1.2 MPa (Murphy et al. 2010).

The tensile strength of hempcrete can be determined from the splitting cylinder test, as shown in Figure 21. Some reported test data by O’Dowd and Quinn (2005) show that the average split cylinder tensile strength of hempcrete is about 0.22 MPa and 0.268 MPa for 45 days and 60 days, respectively (O’Dowd and Quinn 2005). According to the splitting cylinder test, the tensile strength for a volume ratio of 3:1 was 0.15 MPa.

The volume and mass of several hempcrete blocks were taken in order to find out their densities. Given its average specific gravity of 0.817, that is smaller than that of water, hempcrete floats on water (Manohari et al. 2016). With respect to fire performance, according to Hemp-TODAY® (2020), “hempcrete scored a perfect ‘0’ under ASTM fire testing in the USA”. This is the highest possible rating on a scale of 0 to 450. To test hempcrete’s resistance to fire, a blow torch powered by propane gas was fired against a well-set and dried wall. A photograph was taken in one-minute increments for the whole test duration of 8 minutes, and the progression of the burnt area’s size was observed (Allin 2013). As seen in Figure 22, the burnt area barely expands over time. At 10 minutes, the darker areas were still hot. Further examining the burnt area, the flame only managed to indent half an inch from the surface. This demonstrates hempcrete as a suitable candidate for building proven by its strong fire-resisting properties.

Hempcrete walls have a high degree of sound insulation by trapping sound waves, thus reducing noise pollution. The acoustical performance of hempcrete is highly dependent on parameters like thickness and whether or not hempcrete is rendered. A 170 mm – 200 mm thick hempcrete block is thought to have appropriate sound insulation; the thicker the hempcrete block, the more sound it can absorb (Protchenko 2019), and the lower the density, the better the sound insulation. A study by Gle

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**Figure 21.** Outcome after splitting tensile test (Manohari et al. 2016)

**Figure 22.** Fire test against a hempcrete wall throughout 8 minutes (Allin 2013)
et al. (2011) reported that binder-free loose hemp with different levels of compaction showed “a peak in the 400–600 Hz range” for sound absorption. These values convey that the higher the level of compaction, the lower the frequency hemp is able to absorb.

Rendering a hempcrete wall interferes with its open surface porosity, greatly decreasing sound absorption (Kinnane et al. 2016). A 10 mm 1:25 lime-hemp render and a 10 mm 2:1 lime-hemp render hempcrete wall samples demonstrated nearly identical sound absorption behavior. Therefore, altering mixture proportions of hemp to lime has no effect on hempcrete’s sound absorption capabilities. The trend of the three hempcrete wall samples shows decreasing sound absorption coefficients with increasing frequency. Hempcrete’s acoustic properties and high absorption values are owed to its porosity (Aasrubi et al. 2012) and loose nature, which permits the absorption of sound within a range of frequencies.

10 BUILDING GUIDELINES

Hemp is not readily available everywhere and is even illegal in a few countries, so procuring the material for construction can be difficult or expensive. The number of hemp buildings are low, but there are some. With building materials comes standards and then building code, but since hemp is relatively new, it is very important to know which code one is working from.

There is a process that one has to go through to earn a permit application for a hempcrete building. It starts off with the applicant understanding the local code while taking into consideration the parts of the building that do and do not meet that specific code. The applicant’s overall goal is to prove that the material is suitable for construction, which can be done by evaluating the safety and serviceability performance criteria, including structural load resistance, thermal resistance, and fire resistance, among others. Hempcrete relies on framed structures for load resistance, which already follow building codes for engineered wooden structures (Magwood 2016a). However, the applicant must provide the necessary documents to the jurisdiction for the other performance expectations to be approved by the jurisdiction for the project.

Options that could be of use to the applicant is analyzing past performances of previous projects. The quality of these documents is of paramount importance and will be rejected if failed to meet the standards of the jurisdiction. Case studies from similar projects in different countries will not count as valid evidence, especially if climates are different. While some ASTM standards related to hempcrete are under development in the U.S., some tests can follow the European/British standards at this time if adopted by local jurisdictions (Magwood 2016a). Using independent tests, along with code-recognized standards such as ASTM, ANSI, or CSA, can be beneficial. Professional seals by licensed architects or engineers are significant and will certainly help the approval of projects by the governing jurisdictions.

11 CONCLUSIONS

With hemp’s nutritional benefits, along with its high stake in retail and lime’s multitude of chemical benefits, hempcrete becomes an important material in building construction practices. Hempcrete has a significant contribution to the construction industry as it involves planting, building, installing, and more, instilling opportunities in other sectors of business.

Making hempcrete can be straightforward without the need of complicated technologies and processes, from its initial stages of growing to its final stages of constructing. Growing the durable material requires limited use of fertilizers, while offering various construction methods such as in situ, wet-mixed hempcrete pouring, hempcrete bricks and blocks, structurally insulated panels, and spraying hempcrete.

Hempcrete is at a great disadvantage since it is not suitable for being a load-bearing material like concrete; however, its ability to resist fire, mold, fungus, and moisture along with its carbon-negative properties compensates for that. The material’s ability to absorb carbon dioxide makes it an ideal eco-material in lessening the negative environmental impact of the construction sector. It displays the good economic value as well as excellent thermal and insulative properties, ensuring comfortable living atmospheres. It holds an excellent lifespan and offers a low maintenance cost.

Seeing a shift in the global selection of concrete as a building material to utilizing hempcrete will be contingent on costs, hemp availability, awareness, and project suitability. Advocates must remember to take advantage of hempcrete and use it in well-planned and well-designed buildings.

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