A Comprehensive Review on the use of Hemp in Concrete

Salim Barbhuiya[1], **Bibhuti Bhusan Das**[2]

[1] Department of Engineering and Construction, University of East London, United Kingdom

[2] Civil Engineering Department, National Institute of Technology Surathkal, India

Corresponding author: Salim Barbhuiya

Email: s.barbhuiya@uel.ac.uk

Abstract:

A simple mixture of hemp hurd, water, and lime is used to make hemp concrete. It is indeed one of the few materials that can continue to absorb carbon after being employed in construction, storing more carbon in the atmosphere over the building's lifetime than was emitted during construction. Furthermore, hemp can be harvested in as little as 60 days. Hemp concrete is a "carbon-negative" or "better-than-zero-carbon" substance because the hemp plant absorbs more carbon from the atmosphere than it emits during its production and application on site. It is a bio-composite material that can be utilised as an alternative to concrete and standard insulation in building. Hemp concrete is also recyclable at the end of the building's lifespan. This study summarises the fast-developing body of knowledge about hemp concrete, which was recently developed.

Keywords: Hemp, hurd, binder, concrete, compressive strength, durability

1. Introduction

Long-term changes in temperature and weather patterns are referred to as climate change. These changes could be due to natural causes, such as oscillations in the solar cycle. However, human activities have been the primary cause of climate change since the 1800s, owing to the combustion of fossil fuels such as coal, oil, and gas. Fossil fuel combustion produces greenhouse gas emissions, which act as a blanket around the Earth, trapping the sun's heat and boosting temperatures. Carbon dioxide and methane are two examples of greenhouse gas emissions that contribute to climate change. These are produced by, for example, utilising gasoline to drive a car or coal to heat a building. Carbon dioxide is released when land and forests are cleared. Garbage landfills are a major source of methane emissions.

The world's population and standard of living are both steadily expanding. As a result, worldwide energy consumption, carbon emissions, and garbage generation have increased. The construction industry accounts for a significant share of these in developed countries. This is responsible for about 40% of overall energy use and CO_2 emissions [1–5]. When embodied carbon [EC] and embodied energy [EE] are included in, these percentages rise to roughly 50% [6,7]. As a result, it is indeed vital to find ways to reduce the building sector's high energy and carbon demands so that it may become more sustainable and have a lower environmental impact.

Concrete is the most widely used material in the construction industry, with 10 billion tonnes manufactured each year and used in a variety of applications. Cement-based products, on the other hand, are sometimes seen as non-sustainable due to the high EE of cement, which is manufactured in a kiln at 1450°C. Cement also has a high EC since each tonne of cement produced emits roughly one tonne of CO_2 into the atmosphere [8,9]. Furthermore, insulating materials are required to achieve low OC and OE levels in structures, which typically have high levels of EC and EE that are not compensated by the OC and OE reductions achieved over the life cycle of the building [10,11].

As a result, sustainable construction materials must be developed in order to reduce the building sector's environmental impact. Hempcrete, also known as Lime-Hemp Concrete (LHC), is a ground-breaking concept that is gaining traction. LHC is a new sustainable construction material made out of hemp shives as bio-aggregates and lime as a binder [12]. Hemp shives are a by-product of the hemp fibres industry. They produce 65-70 percent of the hemp plant's total output (by mass). They are lightweight and have a low thermal conductivity, which implies they have a good thermal insulation ability due to their high porosity.

Lime is a binder made at 950 °C in a limestone kiln, which is 500 degrees Celsius lower than the temperature used to make cement (1450 °C), and so has a lower EE. Furthermore, during the carbonation process that occurs during its hardness, the bulk of the CO_2 emitted as a result of the chemical reaction that creates it is absorbed back into the system. Therefore, its EC is significantly smaller than that of cement. As a result of the carbon sequestration by hemp during its growing cycle, LHC's EE is low, and its EC is actually negative [13–16].

In addition, because LHC has a low thermal conductivity, it can lower the OC and OE of a building. The hemp-lime ratio, on the other hand, determines the thermal conductivity of LHC; lower lime concentration indicates lower conductivity and density. This study focused on a 1:2 ratio, which results in a thermal conductivity of 0.09-0.11 W/mK and a density of 330 kg/m^3 [17]. When constructing energy-efficient structures, thermal conductivity isn't the only aspect to consider. A building's heat capacity is a significant aspect in determining its thermal performance. Due to large diurnal and seasonal changes, the outside temperature could be high.

The study by Evrard (2006) [18] analyzes drying process, final density and vapour permeability of different type of LHC-wall mixtures to point out influence of mixing, implementation and water input on material's final properties. The effect of using different binding agents in combination with hemp shives and fibres in Lime-Hemp Concrete (LHC) building material was examined by Paulien et al., (2009) [19]. Pochwala et al., (2020) [20] reported the results of certain hemp–lime composite studies and the potential for using hemp–lime composite for the structural construction industry. Hemp–lime composite heat transfer coefficient, fire resistance, and bulk density properties are compared to those of other commonly used construction materials. The obtained results show that the material together with supporting beams made of other biodegradable materials can be the perfect alternative for other commonly used construction materials.

Thermal mass affects a building's thermal behaviour by storing heat during the winter and releasing it at night or acting as a heat sink in the summer and passively cooling itself at night. The heat capacity of the LHC is 0.7 MJ/m^{3}K, which is moderate. The LHC's capacity to restrict the impact of outside temperature variations is due to these two properties. The internal amplitude was just 4 °C in one investigation, but the exterior amplitude was 16 °C [21]. LHC can also regulate exterior humidity swings with an internal amplitude of roughly 5% RH compared to a 70 percent RH external amplitude.

Other research [22, 23] found that the LHC's thermal performance is highly promising. The thermal comfort of the building improves as a result of LHC's properties. As a result, the thermal qualities of LHC are its principal value to the building user; yet, because its mechanical properties are limited, it can only be employed for non-structural applications [24–26]. It is for this reason it is widely utilised as a wall, ceiling, and floor insulation layer. It is also utilised to replace traditional construction materials like Hollow Concrete Blocks and Autoclaved Aerated Concrete. If LHC is utilised instead of these materials, and common insulating materials (e.g., polystyrene), the EC and EE of these materials can be greatly lowered. This paper reviews what is currently known about hemp concrete, their properties and performance, as well as the important areas where more study is needed.

2. Binder

The binder is the most important component of every concrete. Hemp concrete is made with a lime-based binder. This is because of its plentiful supply and low production emissions. Lime, on the other hand, is better than cement for hemp shiv [27]. Lime absorbs a large amount of water and obstructs hydraulic movement. The interior parts of the concrete will not set as a result of this. Hemp concrete's mechanical, thermal, hygrothermal, and acoustic qualities are all affected by the binder used and the dose [28-32]. In hemp concrete, the most common binding agent is hydrated lime ($Ca(OH)_2$).

Lime's hydraulicity is an important feature. To improve the strength and setting qualities of hydrated lime, researchers have employed pozzolanic elements such as fly ash, GGBS, and silica fume [32]. The combination of lime and pozzolana is not new. The potential of lime to build strength through time has been demonstrated in ancient structures that have remained structurally sound. Walker (2013) [27] found that hydrated lime performed better than fly ash when combined with GGBS and metakaolin. Activators such as sodium sulphate and calcium chloride can be used to overcome the limited reactivity of lime and fly ash. The activators help to promote the pozzolanic reaction between lime and fly ash by assisting in the formation of C-S-H, ettringite, and mono-sulphoaluminate, which all help to improve early and 28-day strength.

Sassoni et al. (2014) [33] proved that hemp concrete, which was made with a patented binder, had exceptional mechanical properties. A reactive vegetable protein in a flour-like form, MgO, $MgSO_4$ or $MgCl_2$ solution were used to make the binder. While Sassoni et al. (2014) [33] did not disclose anything on the curing time or kind, the manufacturing method was briefly covered. Pantawee et al., (2017) [34] looked into the use of aluminium sulphate $Al_2(SO_4)_3$ in hemp concrete. It was observed that adding $Al_2(SO_4)_3$ to composites improved their compressive strength, and that increasing the amount of $Al_2(SO_4)_3$ in the matrix expedited the setting and hardening of the matrix.

Magnesium-based binders can also be used to increase the strength of hemp concrete by replacing lime. Magnesium binders have a substantially higher compatibility with organic fillers than calcium binders [35]. During the mixing process, the calcium binders create an alkaline environment, allowing lignin and other organic components to be released from bio-based products. The setting of lime is slowed as a result of this [36]. There are two types of magnesium-based binders: magnesium oxychloride cement and magnesium phosphate cement. The amount of chemicals added to the combination, the hardening conditions required, and the material's eventual properties all alter. Despite the fact that they are not new, these binders have received far less attention than lime. Nonetheless, both magnesium binders are feasible alternatives to lime binders due to their great strength, fire resistance, and compatibility with organic aggregates [37-39].

Studies on the use of lime mixed with pulverised fuel ash, ground granulated blast furnace slag (GGBS), metakaolin, silica fumes, pumicite, and clays in hemp concrete have been conducted. Walker (2013) [27] found that adding about 25% of hydraulic and pozzolanic material increases performance. Walker (2013) [27] tested nine different pozzolans for their reactivity with hydrated lime in their hempcrete investigation, all of which were readily available in and near Ireland. Calcium silica hydrates are the compounds that contribute to the strength of lime-pozzolana concrete, according to their research. The hydrated lime, on the other hand, exhibited a better reactivity with GGBS and metakaolin than the other products, such as pulverised fuel ash.

Activators such as sodium sulphate (Na_2SO_4) and calcium chloride can be used to increase the reactivity of lime and PFA ($CaCl_2$). The activators improve the pozzolanic reaction between lime and PFA by assisting in the synthesis of C-S-H, ettringite, and mono-sulphoaluminate, all of which improve early and 28-day strength. Walker (2013) [27] made hemp concrete from binders with the following compositions:

Lime-Metakaolin: 80% calcite + 20% metakaolin, and 80% calcite + 20% metakaolin + 0.5 percent methylcellulose

Lime-GGBS: 70% lime + 30% GGBS, and 70% lime + 30% GGBS + 0.5 percent methylcellulose

3. Mechanical properties

3.1 Density

The density of hemp shivs is lower than that of typical concrete aggregates. Hemp concrete, as a result, has a far lower density than normal concrete. Almost all of the time, ordinary OPC concrete has a density of 2400 kg/m^3.This is true regardless of the concrete's grade. Hemp concrete comes in a variety of densities. Table 1 shows the density of hemp concrete as reported by several investigations. As can be observed, there is a wide variety of density. The mass composition of composites determines the product's mass, which is why there is such a wide variation.

The density of a product, according to Ohmura et al. (2002) [40], is determined by the product's spatial orientation in the volume. In the case of hemp concrete, both the material composition and the manufacturing process are altered. As a result, the density varies. The density is also affected by compaction. As a result, higher-density hemp concrete has a higher strength. The quantity of humidity trapped in the walls has an effect on density as well, though only to a minor degree. The thermal performance of hemp concrete is heavily influenced by density fluctuations. Sinka et al. (2014) [41] conducted studies that back up this claim. The thermal conductivity of hemp concrete increases by 0.005 W/m.K, according to the authors for every 50 kg/m^3 density gained.

Table 1: Density of hemp concrete

Binder Composition	Density (kg/m^3)	Reference
NA	850	[42]
Natural Hydraulic Lime	460	[43]
NA	610	[44]
Commercial pre-formulated lime-based binder	270	[45]
Patented MgO based binder	330	[33]
60% Dolomitic Lime + 40% Metakaolin	540	[41]
Hydrated Lime	377	[31]
Hydrated Lime + Pozzolanic additive	508	[46]
MgO-cement	1040	[47]

3.2 Compressive strength

Murphy et al. (2010) [48] investigated the mechanical characteristics of hemp concrete made from commercial binders and hydrated calcitic lime. According to the data, composites created with commercial hydraulic binder had higher final compressive strengths than those made with calctiic lime. Increasing the binder concentration in hemp concrete increases the compressive strength, according to Murphy et al. (2010) [48]. (Fig. 1). CL90H10 denotes ten percent hemp; CL90H50 denotes fifty percent hemp; CL90H75 denotes seventy percent hemp with ninety percent calctic lime binder; TH10 denotes ten percent hemp; TH50 denotes fifty percent hemp; TH75 denotes seventy percent hemp with Tradical® binder.

O'Dowd and Quinn (2005) [49] minimal effect on compressive strength. The authors produced hemp concrete with compressive strengths ranging from 0.65 to 1.9 MPa. The compressive behaviour of hemp concrete was investigated by Tronet et al. (2014) [50]. The mechanical properties of hempcrete blocks are improved when the binder proportions are limited. According to Jami et al. (2016) [51] the characteristics and mix proportion of the binder employed for the formulation determine the strength of hardened hemp concrete.

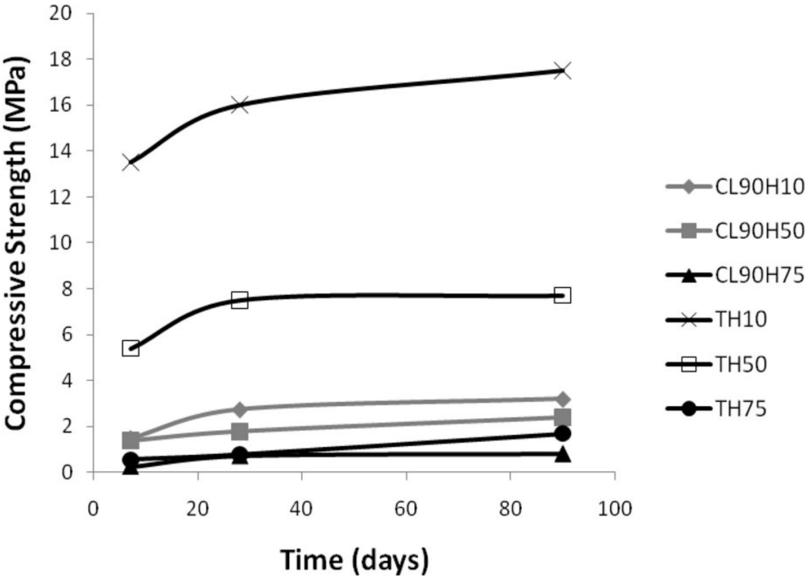

Fig. 1: Compressive strength development of hemp concrete [48]

Compaction significantly boost the compressive strength of hemp concrete, according to researchers [52]. This method not only improves the material's mechanical strength by reducing the amount of binder used, but it also improves its ability to resist deformation before failure. Elfordy et al. (2008) [53] have also confirmed this. There is a link between density, compressive strength, and compaction, according to the experts. They reported that a mix with a higher density had higher compressive strengths, demonstrating a link between density and compaction.

The effect of binder type on mechanical strength of hemp concrete was examined by Walker et al., (2014) [54]. Early strength development is aided by increasing binder hydraulicity; yet, regardless of binder type, all concretes acquired identical compressive strengths after one year. Cigasova et al. (2014) [55] reported that hemp concrete with a MgO-based binder had a compressive strength of roughly 2 MPa. Hemp concrete mixes with compressive strengths ranging from 0.2 to 0.5 MPa were created by Evrard (2003) [56]. Arnaud et al. (2006) [57] found values ranging from 0.4 MPa to 1.2 MPa. According to Walker (2013) [27], compressive strength can be 0.2 MPa after 28 days and 0.4 MPa after a year.

Haik et al. (2017) [58] investigated hemp lime mixes in a 1:2 hemp-lime ratio, with two samples generated by substituting Israeli clay for 50% and 90% of the lime, respectively. Compressive strengths of 90 percent clay, 50 percent clay, and 0 percent clay mixes were 0.07 MPa, 0.09 MPa, and 0.04 MPa, respectively. According to the findings, a 50% substitution of lime for clay resulted in the formation of hydraulic compounds, which improved the strength marginally. Ngo et al., (2020) [59] did research on designing a soil concrete utilising hemp. The influence of clay and hemp amounts on soil concrete was investigated by the authors. Figures 2–4 depict the effects of clayey soil and hemp fibres on compressive strength after 7, 28, and 180 days of curing at 20°C and 90–100% relative humidity. After 7 days, the data shows a standard deviation of less than 0.025 MPa, which is around 4%. The differences in sandy and clayey soil influence this variation. It is also affected by the porous multi-scale structure [60]. After 7 days, the compressive strength drops somewhat with the addition of clayey soil, ranging between 0.6 and 1.2 MPa (Fig. 3). After 28 days, the compressive strength varies between 1 and 2.4 MPa, and after 180 days, it varies between 2.5 and 5 MPa (Figs. 3 and 4). However, the influence of clay percentage on compressive strength is low when the volume fraction of clayey soil is increased from 20% to 40%. (less than 0.3 MPa). Once the compressive strength has stabilised at 180 days, the effect is minor. The compressive strength of soil concrete with 0% clayey soil falls after 7, 28, and 180 days when fibres are added. At 28 and 180 days, the effect is more obvious (about 0.8 MPa of variation). When clayey soil is added, however, the influence of fibres is only slightly different.

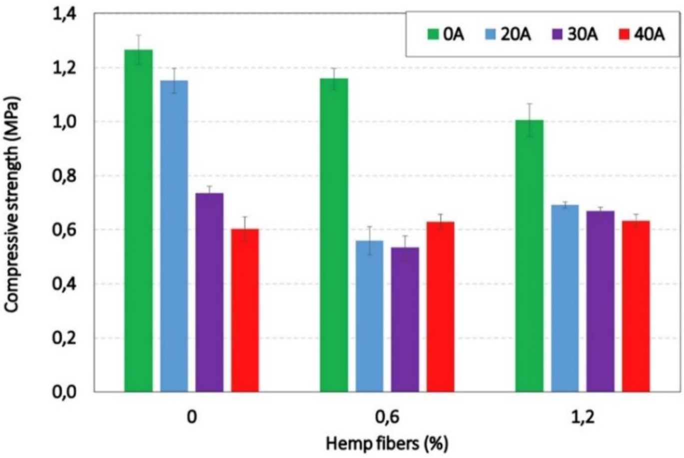

Fig. 2: Effect of clayey soil and fibres on the compressive strength at 7 days [59]

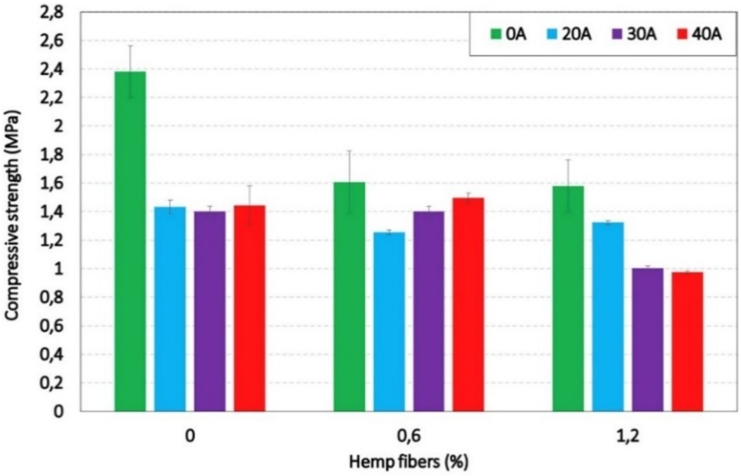

Fig. 3: Effect of clayey soil and fibres on the compressive strength at 28 days [59]

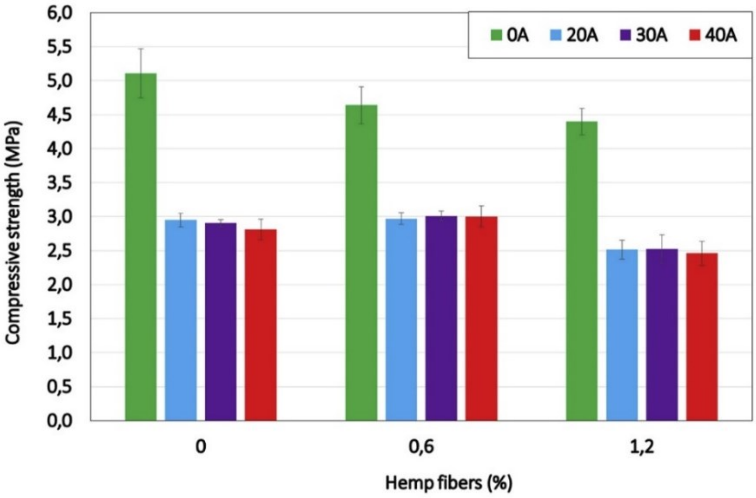

Fig. 4: Effect of clayey soil and fibres on the compressive strength at 180 days [59]

Only 1.2 percent of the fibre has any effect at 28 and 180 days, when the compressive strength drops by roughly 0.5 MPa. Reduced density, changes in soil concrete structure, intergranular void and pore dispersion, all of which produce voids and discontinuities, may all contribute to fibres' detrimental impact on compressive strength [61]. Fibres used as reinforcement in soil concrete specimens have been found to reduce lateral strain during compressive loading [62], which could account for the ductility shown in soil concrete with fibre stress-strain curves. The greater friction angle at the shear cracking surface could be due to fibres [63]. When it comes to the behaviour of hemp concrete under compression, it's vital to remember that it responds linearly and elastically until it reaches 10% strain. As a result, when researching the behaviour of hemp concrete under compressive pressure, several researchers terminate studies at 10% strain [26, 34]. Hemp concrete's low strength prevents it from fully supporting roof loads, although when formed over standard timber wall framing or double-stud framing, it does play a limited structural function in the construction

3.3 Flexural strength

According to Abbott, the commercial hempcrete product from The Limecrete Company Ltd has a flexural strength of 0.30-0.40 MPa (2014). Over a 90-day period, Murphy et al. (2010) [48] examined the flexural strength of various hemp composites (Fig. 5). At varied volumetric lime-hemp ratios, the composites were prepared with hydrated lime and commercial binder with hydraulic and pozzolanic additives (1:9, 1:1 and 3:1). Flexural strength was observed to improve by 25% to 50% when the binder content was raised by 25% to 50%. The flexural strength was almost unaffected by increasing the binder percentage to 90%. This suggests that the lime-hemp linkages may contribute to the mix's flexural strength. The commercial composites have much higher flexural strength than the CL90-made composites. After 28 days, the flexural strength of composites manufactured with 75% hemp and Tradical® binder was 1.20 MPa and 1.19 MPa, respectively. In terms of composition and density, these values are identical to the hempcrete blocks studied by Elfordy et al., (2008) [53]. With the exception of the TH50 specimen, all samples had reached more than 90% of their complete 90-day flexural strength by 28 days.

Due to the earlier development of hydraulic products, commercial samples reached early flexural strength slightly earlier than CL90s samples. The samples with a high hemp level increased their flexural strength far more slowly than those with a low cannabis percentage. The flexural strength of TH75 and CL90H50 decreased slightly between 28 and 90 days. The production of hydration products was blamed for the loss in flexural strength in hydraulic binder mixes after 28 days.

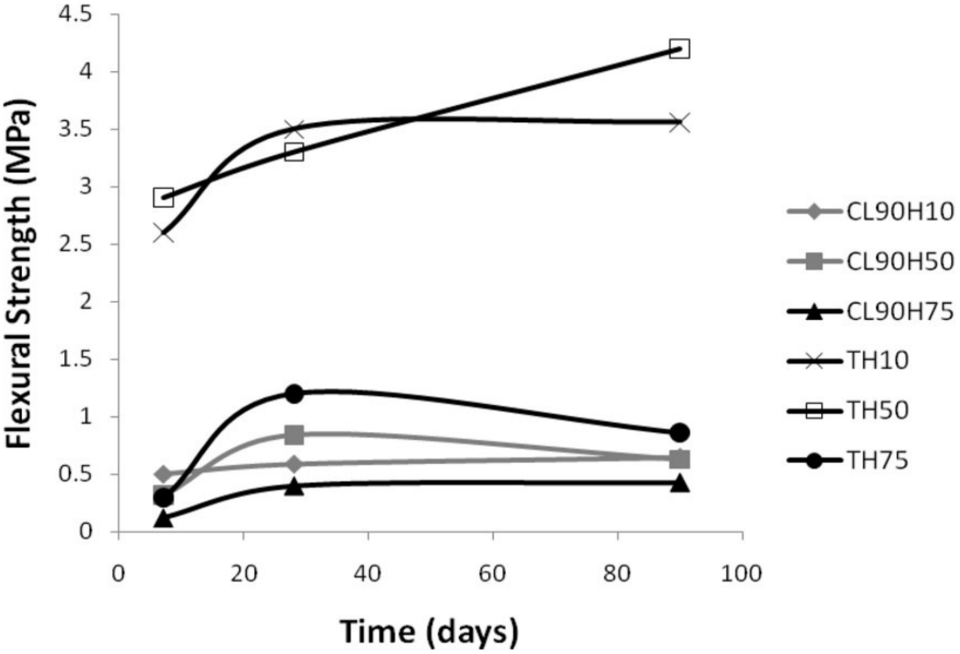

Fig. 5: Flexural strength development of hemp concrete [48]

Hemp fibres were studied to see how they affected the flexural strength of lime, cement, and gypsum binders in several investigations [64, 65]. The load is initially held by the matrix, but if macroscopic damage develops, the load is moved to the matrix-fibre interfaces, resulting in stiffening reduction and a slight increase in stress uptake. When the peak load is attained, unlike brittle composites, the load steadily diminishes. The matrix/fibre bonds are gradually failing, which causes this.

4. Thermal Properties

The structure of hemp shives is anisotopic. As a result, in the perpendicular direction of compaction, hemp concretes might have up to 30% greater thermal conductivity [66] (See Fig. 6). The orientation, compaction, and application procedure used to optimise the mechanical properties of hemp concretes might also alter their thermal conductivity [67]. The choice of binder has little effect on the thermal properties of hemp concretes created with different formulae, but it can have a substantial impact on the mechanical performance [52].

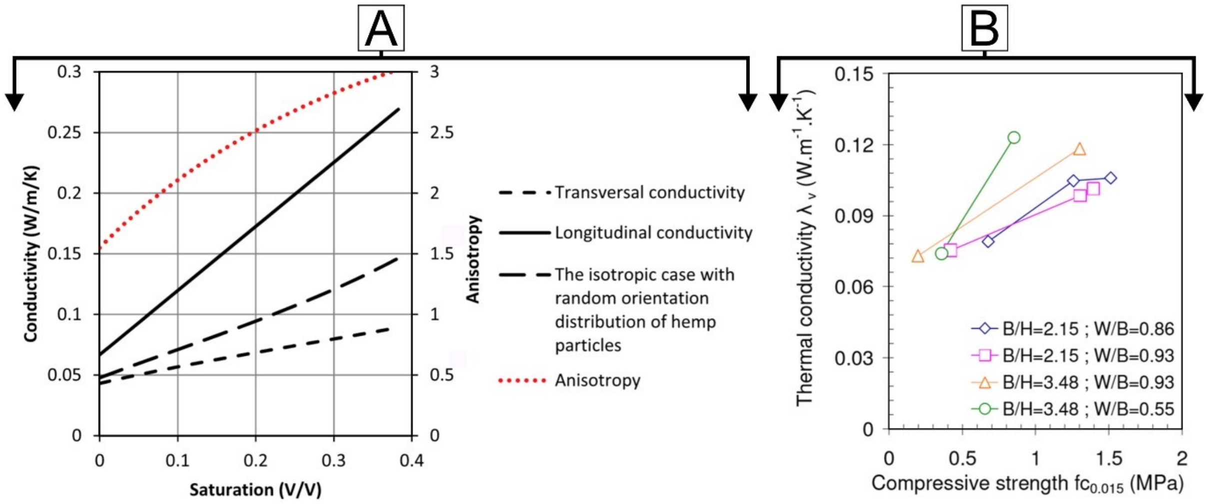

Fig. 6: (A). Relationship between conductivity of hemp shives and degree of saturation [66]. (B). Relationship between compressive strength and thermal conductivity of hemp shives [52].

Thermal conductivity increases with moisture and temperature, whereas mechanical properties improve with density [68-71]. Organic binders, such as sapropel, can also be used to achieve decreased thermal conductivities [72]. A recent investigation of a hemp concrete with a silica sol binder [73] indicated that it has a thermal conductivity of 0.05 W/mK, similar to hemp shives, while preserving mechanical strength. Smaller particle size hemp shives improve the mechanical strength of hemp concretes while having no effect on heat conductivity [74]. Thermal conductivities were found to be lower with smaller particles in a hemp plaster [21]. More research is needed to explain why. The application of hemp-plaster coatings may be influenced more by the orientation of anisotropic aggregates than by the use of smaller particles. U-values alone are not an appropriate measure for evaluating the thermal performance of hemp-lime concretes, according to research conducted on walls exposed to real-world weather conditions. Q24h, as well as other dynamic features, should be assessed for this [75].

Hemp concrete is a semi-structural insulation material that can be used to bridge the gap between standard insulation panels and structural walls [76], as well as to manage thermal comfort through passive solar energy gain [77]. Anomalies in the plant materials themselves could explain the disproportionally wide range of specific heat values found in the existing body of literature for hemp concretes with comparable densities. The introduction of other measurement methods or issues with measurement procedures could have resulted in such substantial discrepancies between the same type of binder and commercial hemp shives. For densities of 300 kg/m^3, specific heat values recorded in different publications ranged from 300 to 1700 J/kgK [76]. Thermal insulation and reaching thermal conductivity values as near to those of the shive material have been the focus of work in the previous decade. Also, according to the climatic needs of the regions where hemp construction originally developed, this should be comparable to traditional insulation materials, with the added benefits of hygrothermal performance and water vapour permeability.

A research of a hemp concrete wall indicated that adding a larger thermal inertia component helped reduce overheating in summer temperatures in different regions of France [78]. This illustration shows how concrete compositions must be adjusted to the climate in which they are used. Low thermal diffusivity is necessary to slow the transmission of external heat, whereas high thermal effusivity may enhance the amount of stored energy. Because it is difficult to make hemp concrete that meets both criteria, layered hemp concrete walls could be a good way to adapt this material to different environments. The hot wire and GHP thermal conductivity are compared to published values in Fig. 7 [79]. The fundamental approaches of the various authors are color-coded. These are green means hot box, light blue means hot ring/hot plane, dark blue means hot wire and red means GHP. Some authors distinguish between heat fluxes that are parallel to the aggregate (labelled "parallel" in Fig. 7) and heat fluxes that are perpendicular to the aggregate (labelled "perpendicular" in Fig. 7).

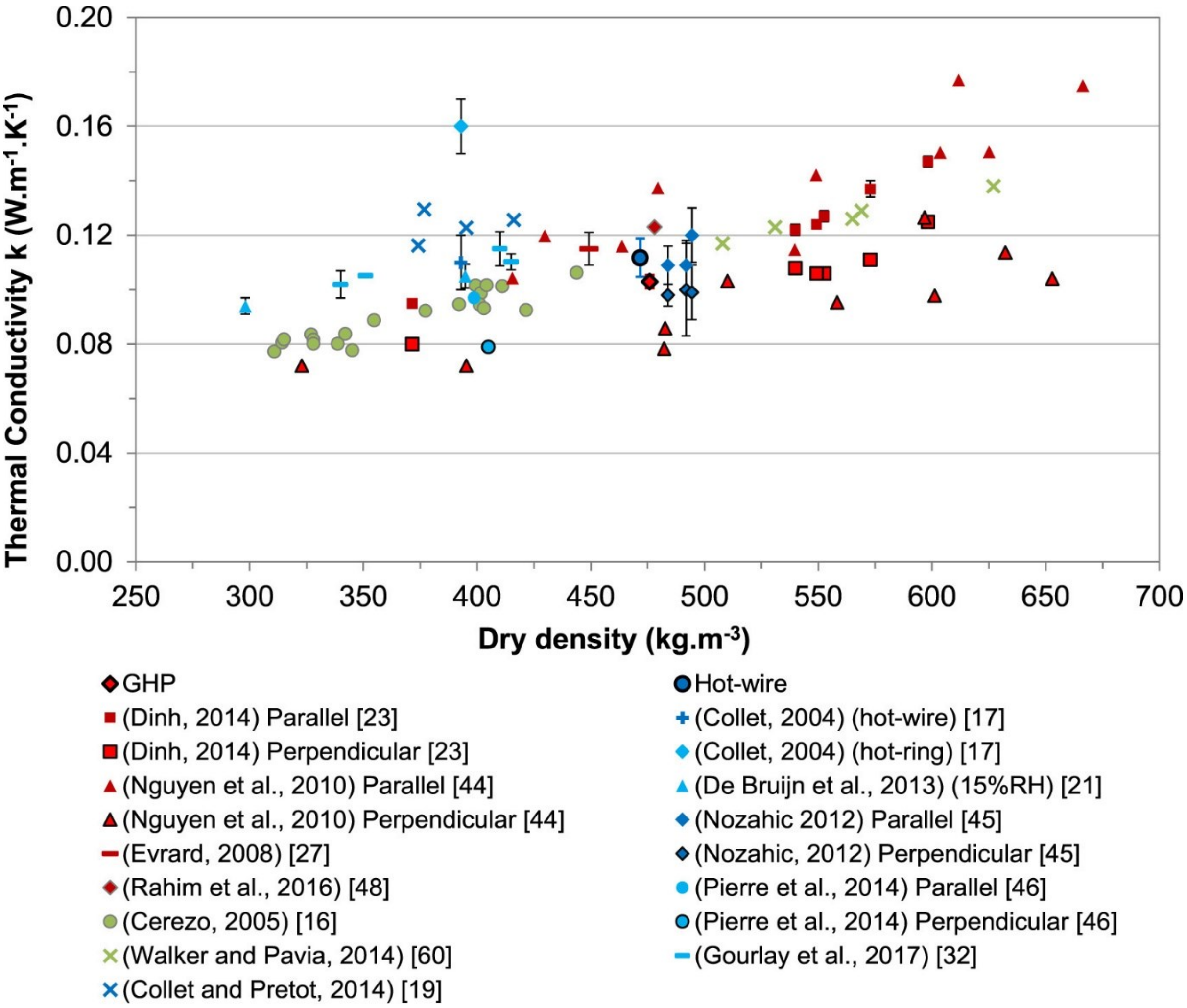

Fig. 7: Relationship between thermal conductivity and dry density [79]

Figure 8 depicts the effect of temperature on thermal conductivity. The data reveal that thermal conductivity increases linearly with temperature. K_{dry} increases by 12% between 10 and 40 degrees Celsius. As previously demonstrated experimentally [80, 81] k(T) = 0.0004 T + 0.0948 for hemp concrete, there is a linear relationship between thermal conductivity and density. In "parallel" configuration, the rise in thermal conductivity with temperature of the examined material recorded by Pierre et al., 2014 [80] and Rahim et al., 2016 [81] is twice as great, while in "perpendicular" configuration, it is close to Pierre et al., 2014 [80]. The thermal conductivity as a function of humidity, as measured by the hot wire instrument, is shown in Fig. 9.

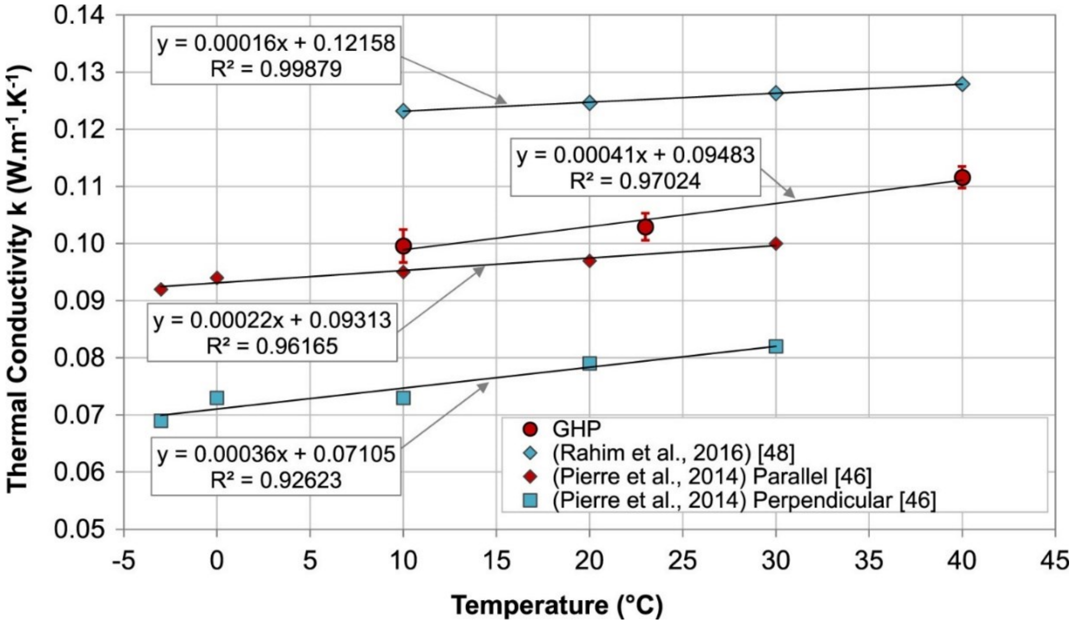

Fig. 8: Relationship between thermal conductivity and temperature [79]

Thermal conductivity rises almost linearly with water content, according to Gourlay et al., (2017) [82], although thermal diffusivity and specific heat capacity evolve in distinct ways. The influence of formulation, density, and water content on the thermal conductivity of hemp concretes was examined by Collet and Pretot (2014) [83]. Experimental observations and self-consistent scheme modelling are used in the research. At (23 °C; 50% RH), the thermal conductivity of the materials examined ranged from 90 to 160 mW/(m K). The influence of density on thermal conductivity is far greater than that of moisture content. When the density is increased by 67%, the thermal conductivity increases by roughly 54 percent, but it increases by less than 15–20 percent from dry condition to 90 percent RH.

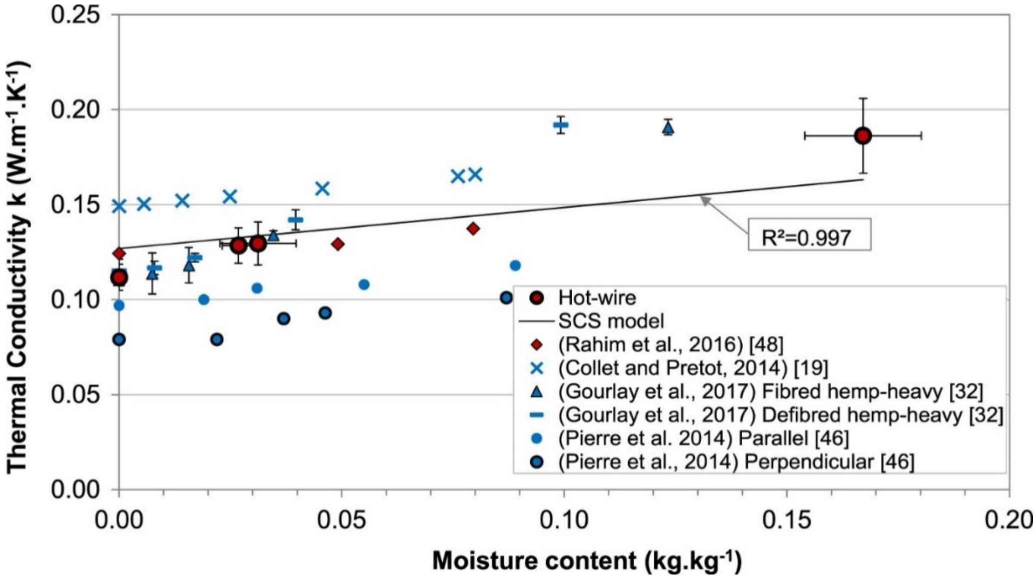

Fig. 9: Relationship between thermal conductivity and moisture content [79]

5. Acoustic properties

Hemp concretes' acoustic properties are determined by their porous structure. The sound absorption coefficient of hemp concretes decreases dramatically as they are rendered. Hemp concretes that have not been rendered have varied absorption qualities. The type of binder, formulation, and production techniques all play a role. They do, however, have an average sound absorption of 40–50% [84] over a wide frequency range. The surface permeability, which varies based on the texture, influences the absorption coefficient (α). This can range from 0.3 to 0.9 depending on the binder dosage and frequency [85].

Furthermore, as long as the material is less than 20 cm thick, absorption peaks at low (f ~400 Hz) and medium (f ~1200 Hz) frequencies can be seen. When compared to other construction materials studied under similar conditions, the results found by this author [85] were promising. With increasing binder concentrations, the amplitude of the peaks and the width of their bands diminishes as the pore size shrinks. Sound absorption was higher in concretes made with smaller hemp shives [77] (Fig. 10) and concretes made with lime-pozzolanic binders than in hydraulic binders [84].

The magnitude of absorption peaks above 500 Hz increased as the wall thickness grew. As a result, the frequencies of the peaks have changed to lower frequencies. Low-density formulations exhibit a net shift in absorption peaks towards lower frequencies, as well as some stabilisation as thickness increases. The first absorption peak in the medium density formulations shifts in frequency, whereas the second peak stabilises until a consistent absorption level of 500 to 2000 Hz is obtained.

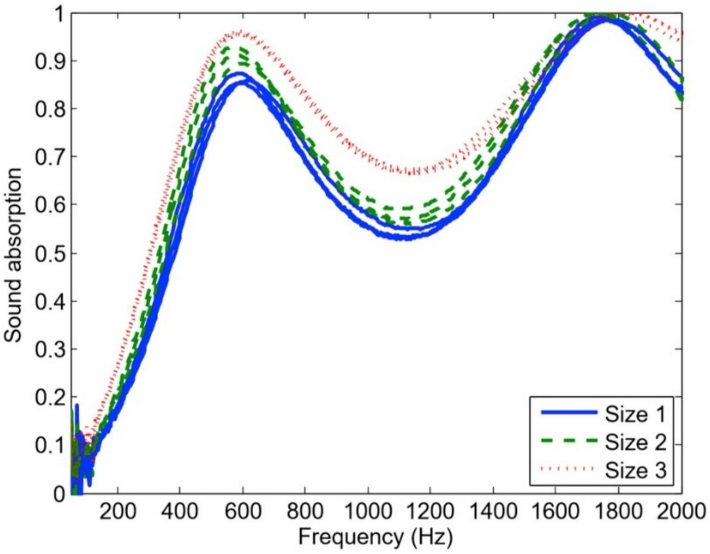

Fig. 10: Relationship between sound absorption of hemp shiv and various sizes of the particles and degree of compaction [77].

As the frequency of high-density formulations increases, absorption decreases steadily [85]. Recent research has revealed that the amount of hemp aggregate in the concrete determines acoustic performance the most, with binder type having little effect (when comparing clay and lime) [86]. In hemp concretes including either of these binders, a very absorbent initial peak forms between 500 and 1200 Hz below 375 kg/m^3, with only minor differences in the absorption peak widths, indicating increasing hemp-lime roughness. The manufacturing process appears to be the most critical component in acoustic behaviour up to a density of 500 kg/m^3, while transmission loss increases as density reaches 500 kg/m^3. Due to its higher binder density, hemp-clay has a higher air resistance than hemp-lime. By altering the pore size distribution, further retting and ageing can influence the hemp aggregate's acoustic absorption performance [70]. Hemp shives swell up as they age due to exposure to real-world weather conditions. Acoustic absorption was shown to be significantly influenced by open porosity.

6. Hygrothermal performance

Hemp concrete is a green building material because of its capacity to regulate heat, moisture, and relative humidity, as well as its low embodied carbon. It has a high moisture diffusion coefficient and water vapour permeability of around 2.3 x10-11 kg/(Pa.m.s) for low to mid relative humidity and is practically constant. The moisture buffer value (MBV) of hempcrete is 2 g/(m^2. percent RH) (m^2. percent RH), while the MBV of concrete is 0.37 0.04 g/(m^2. percent RH) (m^2. percent RH) [87, 88].

When a material is repeatedly subjected to various degrees of relative humidity, MBV refers to its ability to accumulate or release moisture. The ability of a substance to modify ambient relative humidity is proportional to its moisture buffer value. Under outdoor climatic conditions, Piot et al. (2017) [89] evaluated the hygrothermal behaviour of a wall composed of a proprietary hempcrete mix with a dry density of 350 kg/m^3. A computer model was used to calculate heat conduction and storage, as well as vapour diffusion, liquid capillary movement, and moisture storage.

The hempcrete wall's overall dryness was observed to be affected by the external rendering chosen. Hempcrete's hygric inertia causes "perennial moisture" within the wall, which is bad for the building's heat conductivity and durability on two fronts. The authors also found that using a water-absorbing outside coating or plaster improves the thermal conductivity of hempcrete walls by making them more conductive. Figure 11 depicts the link between relative humidity and a hempcrete wall's thermal capacity. As a result, whereas thermal bridges caused by mortar joints boost heat fluxes, moisture transport suppresses them when humidity is high. The amount of suppression caused by moisture migration, on the other hand, is uncertain [90, 91].

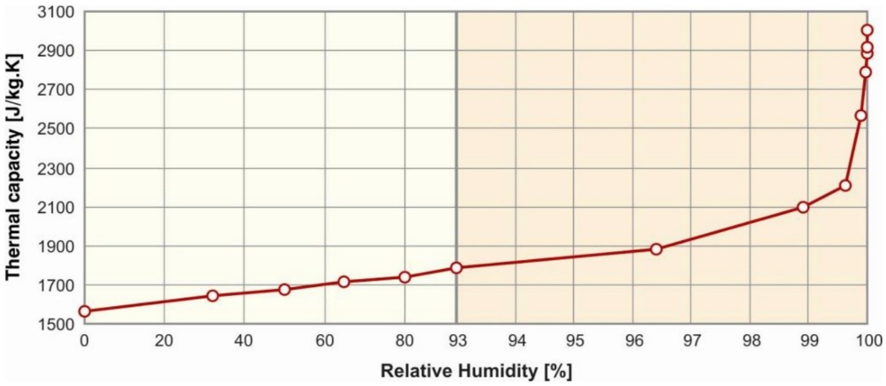

Fig. 11: Relationship between relative humidity and thermal capacity of hemp concrete [92].

The experimental hygric characterisation of hemp concrete is still up for debate. As a result, the chosen parameter and/or measurement method may differ depending on the author. There are numerous approaches to characterise moisture transfer phenomena when dealing with high humidity levels, for example. Hemp concrete should be used to fill a timber frame and protected from liquid water with cladding and a capillary barrier because it is not a structural building material. As a result, hemp concrete should not be exposed to extremely high humidity in routine use. The sorption isotherm, water vapour permeability, and sometimes a value based on capillary absorption are all hygric qualities that have been extensively studied in the literature on bio-based building materials.

Several tests were conducted at various scales to evaluate the hygrothermal behaviour of bio-based materials such as wood fibre materials [93] and hemp concrete [94, 95]. The findings were utilised to evaluate numerical heat and mass transfer models [96, 97]. The water content, temperature, and relative humidity inside the examined media exposed to controlled boundary conditions can all be measured using these experimental methods. The calculated and measured outcomes are frequently in sync. However, most tests are carried out in controlled temperature and relative humidity environments, which may not fully reflect hygrothermal behaviour in real-world uncontrolled situations with more complex simultaneous heat and mass transfer phenomena.

7. Durability properties

Another characteristic of hemp concrete that has received little attention is its durability. Except for freeze-thaw, the few studies that have looked into hemp concrete suggest that it works well in most cases. Hemp concrete must be strengthened against freeze-thaw and cycle wetting and drying with a good grade, suitable hydraulic binder. When it comes to the production of mould as a result of moisture, there is some ambiguity.

Despite the fact that more research on termites' influence on hemp or hemp concretes is needed, a study using hemp shives treated with mineral oxides found that termites could traverse the material but did not survive long [98]. One of the few examples of weather exposure tests in buildings constructed using unrendered hemp concretes is a tower finished in Switzerland in 1999 [99]. The tower referred to here is actually a block if flats in Yverdon-les-Bains which have been given an external insulation layer of hemp lime and a protective coating of linseed oil, so althoug it is indeed ‘unrendered’ it is not unprotected. Hemp concretes made with "quick" natural cement and treated to accelerated ageing by 8 wetting/drying cycles at 30 °C over 75 days, there were no differences in thermal conductivity or acoustic characteristics [100] (For more detail, see Fig. 12.)

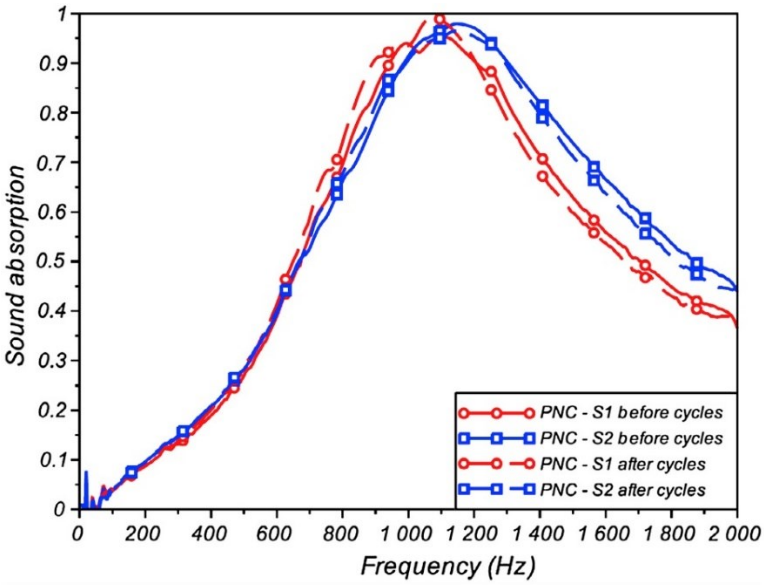

Fig. 12: Comparison of sound absorption before and after W/D cycles [100].

Mould formation was only discovered on the same concrete samples when the relative humidity (RH) reached 98 percent and the pH dropped below 10. Unlike hemp concretes, loose hemp shives deteriorated severely under real-world weather conditions following two years of wetting/drying cycles at 30°C (every 5 days under RH 95 percent, followed by 2 days under RH 40 percent) [70]. The cellulose and lignin content of the shives decayed in the laboratory, while the hemicellulose content remained unchanged. Real-world weather circumstances caused more severe decay, including hemicellulose breakdown, as well as a far larger mass loss of 35.9% compared to 24.2 percent in the lab.

Water vapour sorption was found to be influenced by mass loss, volume fluctuations, and increased open porosity. These effects were more noticeable in shives exposed to real-world environmental conditions, as pore size changes were greater. Although the binder protects the material from microorganisms that could degrade the microstructure of the hemp shives, it also needs to be protected from capillary absorption and excessive rain. Although capillary absorption decreased over time in all specimens prepared with aerial lime, hydraulic lime, or Portland cement, it can be slowed by increasing the hydraulicity of the binder and adding a water retainer [101].

Hemp concrete samples were put through a 25-freeze-thaw cycle test in Sweden, which included 12 hours at +20 °C and 12 hours at -20 °C [102]. Prior to the freeze-thaw cycles, a cement-lime formulation generated the best mechanical results, but thereafter, a pure cement binder formulation produced the best results, indicating that the test aided rather than impeded mechanical performance. According to recent research [103], during a long-term durability test, alkali-tolerant fungus and bacteria developed on various hemp-lime plaster samples.

Furthermore, the amount of the material and its appearance remained unaltered in most samples, with the exception of minor mass uptake after heavy rain and yellowing of exposed surfaces. According to this and previous studies, salt weathering did not affect any of the samples in the long run [106]. Hemp concrete walls that have not been properly dried before being rendered with lime mortars might have chromatic changes as well as microbiological, textual, and morphological disorders. Clay-bounded hemp concrete supports show more of these characteristics than lime-bounded hemp concrete supports. Natural hydraulic lime renders, on the other hand, are less prone to deterioration than aerial lime renders [104]. (Fig. 13).

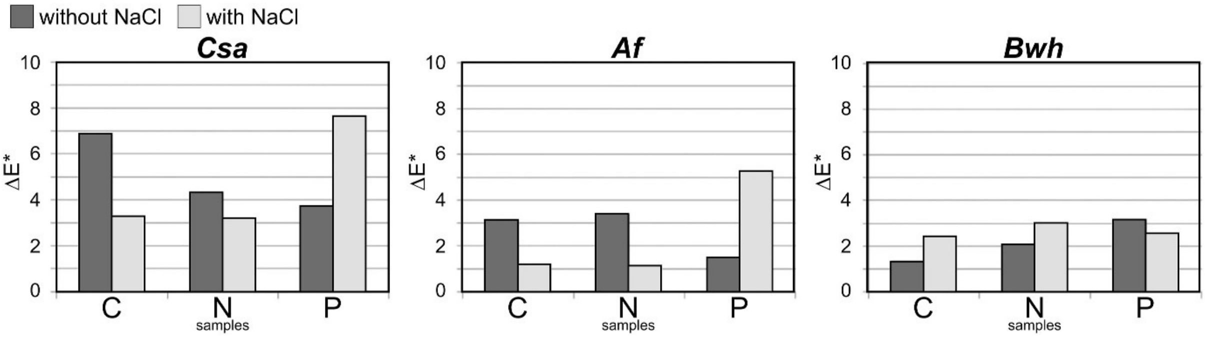

Fig. 13: Colour difference (ΔE*) of hemp–lime samples during and after Mediterranean (Csa) Tropical (Af) and Semi-arid (Bwh) weathering tests [104].

Walker et al. (2014) [54] investigated the mechanical characteristics and durability of hemp-lime concrete mixes made with commercial binders as well as binders made from lime, GGBS, and metakaolin. Due to mass loss during the freeze-thaw cycle, hemp concretes were shown to have low freeze-thaw resilience. The compressive strength of the material was reduced as a result of this. Because the wide pores prevented crystallisation, the hemp concretes were resistant to sodium chloride salt exposure. Despite repeated hedging, it was revealed that biological deterioration was non-existent due to a shortage of nutrients to fuel microbial development.

Delannoy et al., (2018) [105] studied the behaviour of hemp shiv over the course of two years in three different environments: a reference environment, accelerated ageing settings based on humidification and drying cycles, and external ageing. The possible evolution of particle functional characteristics is tracked through time and in relation to ageing conditions. For both storing settings, the study found that there was no variation for the reference circumstances, but four ageing processes may be observed for accelerated and external ageing conditions: mass loss, particle volume fluctuations, and aggregate porosity opening. The last one is a change in pore size distributions, which is only seen with external age.

Benmahiddine et al. (2020) [107] employed Thermogravimetric analysis (TGA) to determine the distinct breakdown phases of hemp concrete using weathered and unweathered hemp shives and binder. The goal was to compare the different stages of hemp concrete before and after it had aged. Figures 14(a) and 14(b) illustrate the TGA and dTG curves of weathered and unweathered hemp shives, respectively. Figure 8(b) demonstrates that between 50 and 150 °C, a phase shift peak in hemp shives occurs, which corresponds to free water evaporation. A substantial peak owing to cellulose breakdown can also be seen between 300 and 380 °C [108]. The shoulder upstream of this huge peak, around 250 °C, is typical of hemicellulose thermal depolymerisation. Furthermore, the TGA curve in Fig. 14(a) demonstrates that weathered hemp shives lose somewhat more mass than the control. The peaks, on the other hand, appeared at the same temperatures but with slightly different amplitudes, showing that the amount of dehydrated molecule in issue varied.

Similarly, Fig. 15 compares the TGA and dTG curves of weathered and unweathered binder. Figures 15(a) and 15(b) show TGA and dTG curves that are nearly identical in look and behaviour, with modest changes in peak amplitudes. The temperature ranges of these peaks are also equal. Between 100 and 400 °C, the first peak corresponds to free water leaving the pores and water chemically linked to C–S–H hydrates in continuous form [109]. A second peak was discovered at 480 °C. The latter is due to $Ca(OH)_2$ dehydroxylation. Finally, between 750 and 850 °C, a final peak occurred. This is caused by $CaCO_3$ decarbonation

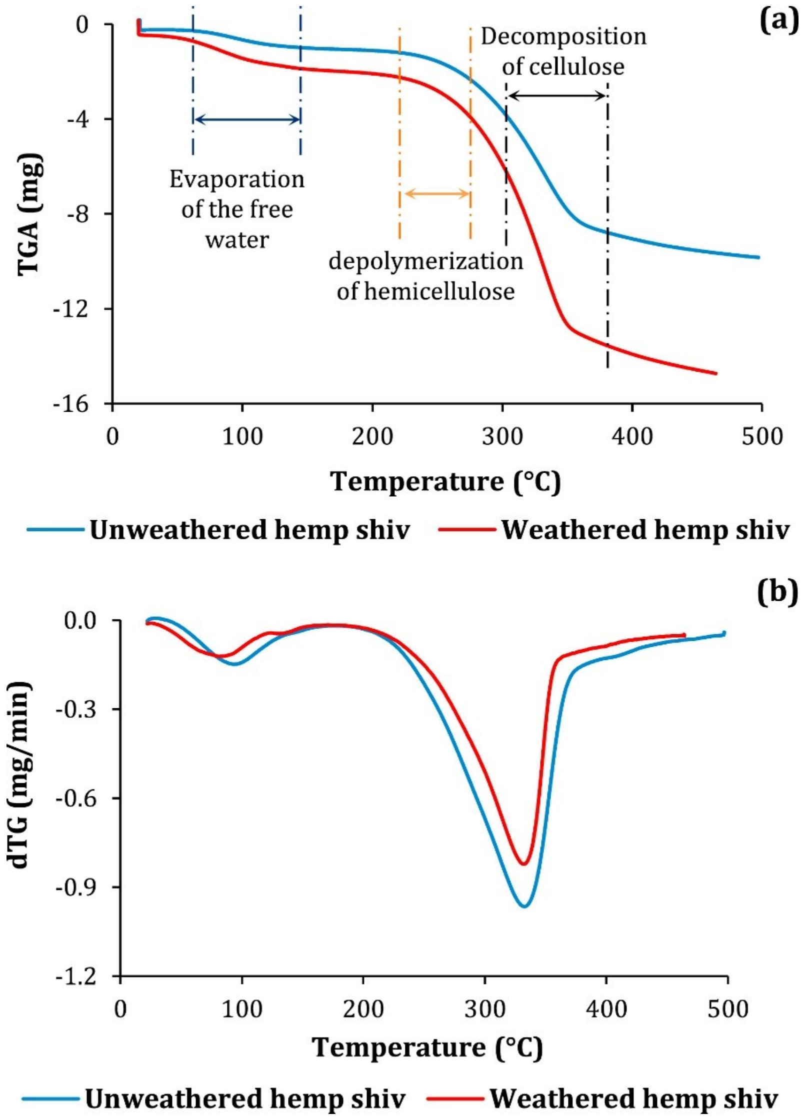

Fig. 14: TGA (a) and dTG (b) of the weathered and unweathered hemp shives [107]

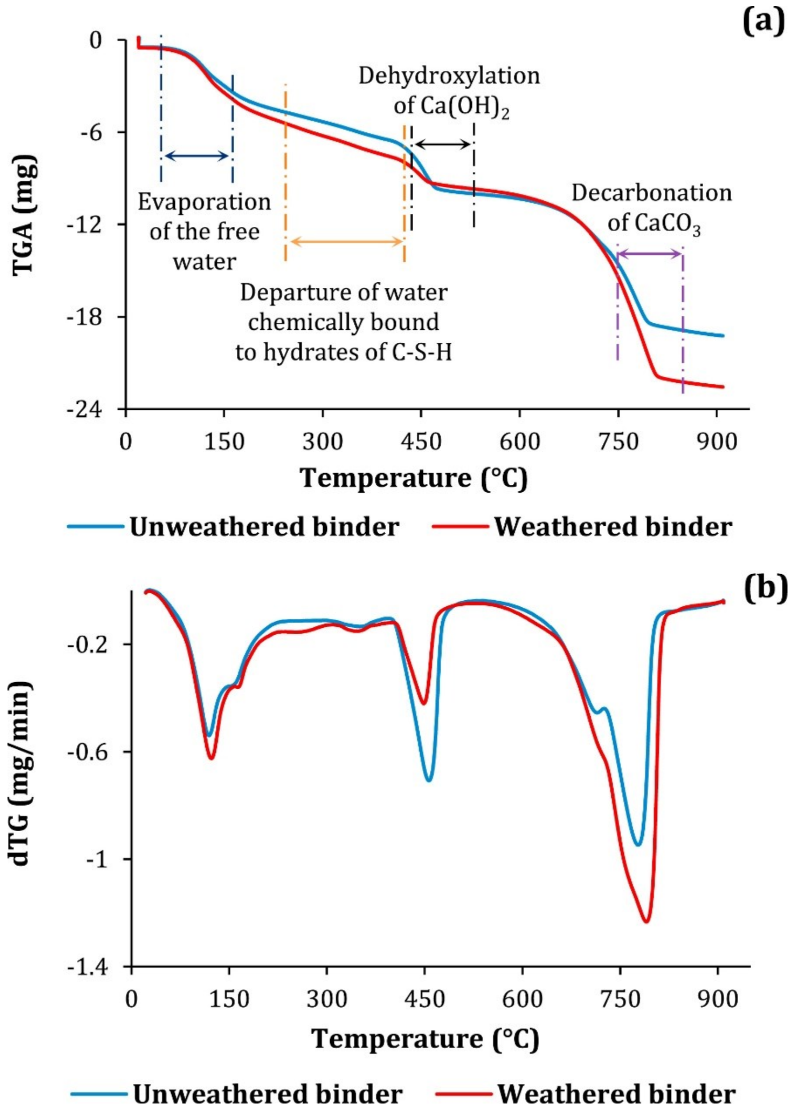

Fig. 15: TGA (a) and dTG (b) curves of the weathered and unweathered binder [107]

Baduge et al., 2019 [110] investigated the effectiveness of three different types of cenosphere as a lightweight supplemental cementitious material for alkali-activated binder in carbon-negative hemp-concrete for non-load bearing applications. The mechanical performance of hemp concrete exposed to three temperatures: room temperature (RT), 300 °C, and 600 °C is investigated using mechanical testing, thermogravimetric analysis (TGA), and Fourier-transform Infrared Spectroscopy. According to the study, alkali activated cenosphere binders could be a long-term replacement for lime. Figure 16 shows an image of hemp concrete blocks prepared for compressive strength testing.

Fig. 16: An image of hemp concrete blocks prepared for compressive strength testing

8. Environmental sustainability

Ip and Miller, 2012 [15] investigated the hemp concrete wall's life cycle impact. The hemp concrete is closed in both circumstances, and the timber frame is considered. The average lifespan is over 100 years. The composition of the wall (hemp concrete density, thickness, and wood frame) as well as the settings and methodologies used in these researches varied (France and UK). The results all point to the same conclusion. Because hemp concrete allows for carbon storage, it has been shown to have a positive environmental impact (according to Ip and Miller, 2012[15]: 82.71 kg CO_2eq. per square metre of wall).

Plant fibres are less expensive than synthetic fibres and are frequently available locally due to low processing costs. Hemp production uses only 11,400 MJ/ha of energy, which is around half of what other similar crops require [111]. Crop rotation and organic farming could help to mitigate the negative features of hemp growing, such as the usage of land and fertilisers [112]. Carbon emissions per kg of hemp shive production range from 0.085 to 0.19 kg of CO_2 [113], while this is more than offset by 1.5–2.1 kg of CO_2 sequestration during growth [21].

Because of the carbon dioxide storage in the plant-based aggregate, hemp concrete has a normally positive balance in its climate change indicator [114, 115]. Commercial binders, notably Portland cement, are the most hazardous binders [116]. Several research [115] agree on values of -0.3 to -1.0 kg CO_2 per kg of hemp concrete as a rough guideline. With a density of 275 kg/m^3, a 1 m^2 unrendered 30 cm thick hemp-lime formulation sequesters 82.7 kg of CO_2. This offsets the 46.4 kg of CO_2 emitted by the materials and during processing, allowing for the storage of 36.1 kg of CO_2 [111].

In a non-load-bearing hemp concrete with a wooden support structure, the lime binder consumes 49 percent of primary energy, 68 percent of water, and emits 47 percent of air pollution [112]. Although calcitic lime (CL) can absorb up to 90% of the 0.7 kg of CO_2 per kg of lime [111], the CO_2 may not be reabsorbed by carbonation in the same proportion as in mineral aggregate mortars due to the setting difficulties that are typical in plant-based concretes [117]. This was not taken into account in the life-cycle assessments of the hemp-lime concretes we looked at. A design that considers low-impact binder types [118], material transportation, dosage, building method, and application technology [119] is crucial in deciding the ultimate carbon footprint of hemp concrete. Because more binder is required, a hemp-lime plaster formulation can have a greater impact than a sand-lime coating [128].

Despite the fact that plant-based building materials have a favourable overall balance in all phases of their life cycle [112] and have a positive health impact [120], one obvious disadvantage is their higher price when compared to the traditional materials that currently dominate the market [112]. This is why, at the moment, only a small fraction of customers choose plant-based goods because of their ecological and environmental benefits, as well as their energy-saving properties. According to the OECD, the building industry accounts for 10% of global PIB and 28% of employment, and has a substantial environmental impact. Only the implementation of correct laws that support the development and promotion of new, plant-oriented economies can bring about changes in the construction sector

9. Applications of hemp concrete

Because hempcrete lacks the strength required for foundation building and is instead supported by the frame, it has been used to construct non-load bearing insulating infill walls in France since the early 1990s, and more recently in Canada. Hempcrete has also been used to repair old stone and lime structures. In France, hempcrete is still frequently utilised, and its popularity is growing year after year. Hempcrete has become a growing innovation in Ontario and Quebec, following France's lead in the organic construction technologies industry. Hempcrete is being implemented using two basic construction approaches. The first method involves casting or spraying hempcrete directly on the construction site using moulds.

The second approach involves stacking prefabricated blocks that are carried to the job site, comparable to masonry construction. For aesthetics and durability, drywall or plaster is placed once the hempcrete technology has been constructed between the timber framing. The compressive strength is typically around 1 MPa, or about 5% of the compressive strength of residential concrete. It is excellent for use in earthquake-prone areas because it's a low-density material that doesn't crack when it travels. Because hempcrete has a density of 15% that of ordinary concrete, it must be used in conjunction with another material in building construction to support the vertical load.

The vast majority of hemp fibres are only available in dry form. These days, loose wools for hand [121] or sprayed application [122] are difficult to come by. Bark fibres are commonly used to make rectangular, thermo-welded insulating panels for roofs, attics, walls, and suspended ceilings. 85–90% hemp fibre, 8–10% polymeric PET-based fibres, and 2–5% soda as a fire retardant make up the final product [123]. Plant-based binders, such as corn starch, are sometimes used to make these insulating panels [124]. Thermal characteristics are available as panels (or rolls) with densities ranging from 25 to 45 kg/m^3 [125]. About 40% of semi-rigid, thermo-welded insulating panels with densities of 90–100 kg/m^3 [126] are made up of hemp fibres, hemp shives, and PES-binder. After being connected to the façades, they are rendered with specially prepared mortars. Nonwoven felts made of 75% hemp and 25% recycled jute fibre are used as a levelling and acoustic underlay for flooring and to buffer impact between hard surfaces. Hemp-fibre reinforced composites are made with thermoplastics like polypropylene and polyethylene, as well as thermoset fibres like polyester. Plant-based resins from soy, canola, or corn can now be used to create 100 percent bio-composite products.

Automobile interior substrates, furniture, and other consumer products are examples of typical applications [127]. Hemp fibre reinforced composite sandwich panels have lately been developed for façades, building skins, and curtain walls [128]. Larger hemp shives are crushed in slabs after being combined with dry soil. When mixed with dry soil and softly compressed, larger hemp shives produce a practical, loose filling material, whereas dust-free hemp shives make a practical, loose filling material. Hemp shives, on the other hand, are commonly employed in the creation of concrete and mortar. Lightweight hemp concretes have been used in manually cast or sprayed applications for the past 25 years, with densities ranging from 200 to 840 kg/m^3 [86], as well as lower [73, 129] and higher [130] densities. According to studies conducted in the United Kingdom, the performance difference between 230 mm and 300 mm walls is negligible.

Hempcrete walls are soundproof, moisture-transmitting, mold-resistant, and fireproof. According to British/EU regulations, Limecrete, Ltd. (UK) provides a fire resistance rating of 1 hour. In order to use hemp in construction in the United States, you must first obtain approval. The R-value (heat transfer resistance) of hempcrete can range from 0.67 to 1.2 cm, making it an excellent insulator (the higher the R-value, the better the insulation). Hempcrete has a porosity range of 71.1 percent to 84.3 percent by volume.

10. Concluding remarks

The authors believe that hemp concrete is close to being mature enough to be accepted by the mainstream construction industry, and that bio-aggregate based concretes should be included in all countries' building laws. According to the research, hemp concrete has the potential to have a positive impact on future built environments by lowering carbon emissions. The commercial success of hemp concrete will be determined by the research findings related to the highlighted research gaps.

According to the researchers, other types of hemp concrete, such as sandwich panels, modular systems, fillers for filler slabs, and so on, should be researched. The bottom line is that hemp concrete is a versatile green building material that can be adapted for a range of uses, according to the published literature. Only modest modifications in the composition and production procedures, on the other hand, result in a large number of variances in the final product. In any event, the end product must have sufficient mechanical strength, minimal heat conductivity, high environmental credentials, and sufficient durability.

The authors advocate utilising new terminology (for example, bio-based materials with carbon capture and storage (BMCCS)) to emphasise the carbon capture and storage capabilities of materials like hemp concrete in order to increase acceptance and visibility. This carbon sequestering material offers remarkable temperature and moisture management characteristics when utilised correctly. Its adaptability simply adds to its appeal. Hempcrete construction is currently only practised by a small number of persons in the United Kingdom. More workers need expert training, government policy should support the use of carbon sequestering materials, and more research comparing its efficacy to normal approaches is needed.

The low rate of compressive strength is perhaps the most significant disadvantage of hemp concrete. Hempcrete has a compressive strength of 3.5 MPa at its maximum. Concrete's lowest compressive strength, on the other hand, is around 17 MPa. As a result, hempcrete cannot be used in load bearing structures.

Based on the review of the works on hemp concrete, following areas have been identified for further research:

- Physical treatment of hemp and lime-pozzolana combinations has yet to be investigated. It aids in the improvement of the end product's mechanical strength.

- There are very few studies that focus on increasing the mechanical performance of hemp concrete. Only the mechanical characterisation of hemp concrete is currently being investigated. Theoretical compressive strength predictions have yet to be proven accurate. It is necessary to develop equations for predicting the same.
- There is an unresolved question regarding the microbiological aspect of hemp concrete durability. Hemp concrete's decomposition mechanisms need to be investigated further. While there have been studies on the mechanical qualities of lime-pozzolana-based hemp concretes, their combination with compaction or pre-compression of the mix is rarely investigated. The majority of the studies were conducted in Europe, and because building materials are a locally sourced commodity, they must be validated in the location where they will be used.
- Because hemp concrete is ductile and can withstand a greater amount of strain before failing, its energy absorption properties should be investigated for use in the structural design of earthquake-resistant structures. This research could potentially aid in the discovery of new LHC applications.

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