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Evaluating the Environmental Performance and Constructive Potential of Hempcrete in Small-Scale Architecture

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Abstract

The study elaborates on hempcrete's ability to be used in small- scale construction and environmentally friendly architectural projects. It investigates on hempcrete's embodied carbon through life-cycle assessment, thermal insulation, durability, mechanical properties, and cost-effectiveness. The research compares three different building techniques: prefabricated panels, in-situ casting, and 3D printing. According to the results, hempcrete has a substantially lower embodied carbon than conventional materials and has the potential to capture net carbon because of the carbonation of lime and hemp biomass. It improves indoor thermal quality and energy efficiency by providing good moisture control and thermal insulation. Its load-bearing application is limited by structural restrictions but works well for insulation and non-load-bearing walls.

1.Introduction

The construction sector must reduce its impact on the environment due to the climate crisis. The high embodied carbon of materials like concrete significantly contributes to global carbon emissions. This issue is especially increasing in small-scale architecture projects, where eco-friendly choices can be positive alternatives to the environment. There are still few low-carbon options that can be used for smaller projects. There is an increase in demand for materials that have low carbon emission, energy-efficiency, durability, and affordability.

Hempcrete is a better low-carbon alternative. It is a plant-based composite composed of lime or mortars based on lime and hemp shives, which are the woody core of the hemp plant. Hempcrete has high sound absorption, moisture control, and thermal insulation which makes it a popular choice for insulation, and non-load-bearing wall systems. Its renewable characteristics and ability to absorb carbon through lime carbonation and hemp cultivation enhance its environmental benefits. However, hempcrete's structural limitations and variation in durability is largely influenced by the type of binder and construction details, making it challenging to use. It can be employed in small-scale projects where cost and usability are essential.

While recent studies have examined hempcrete's mechanical, thermal, and hygrothermal properties, research gaps remain in the study of its long-term durability, proper construction methods, environmental impacts, and cost-effectiveness in small-scale architecture. Evaluating hempcrete's suitability requires a life-cycle assessment (LCA) that considers thermal performance, structural behaviour, and embodied carbon. The objective of the research is to evaluate the construction potential and environmental performance of hempcrete in small-scale architectural applications. Through life-cycle assessment (LCA), it assesses the material's embodied carbon and examines its durability, structural properties, and thermal performance with various binder compositions. Cost effects as well as useful design and construction considerations are also examined in the study. By creating design strategies and comprehensive guidelines that improve hempcrete's usability and performance, the ultimate goal is to promote hempcrete as a feasible low-carbon material option for sustainable small-scale buildings, addressing the climate challenges we face today.

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2.Literature Review

2.1.Material composition and variants

In India, hempcrete typically consists of water, lime-based binders, locally sourced hemp shives, and a few mineral additives. The hemp shives, which are derived from industrial hemp stalks grown in areas such as Uttarakhand, are lightweight and insulating due to their high porosity and low density (90–150 kg/m³). Hydrated lime, hydraulic lime, or lime–pozzolan mixtures containing fly ash, metakaolin, or GGBFS are the most often used binders; all of these are readily available in India. Limestone powder or river sand are examples of additives that improve workability and assures dimensional stability. They are suitable for non-load-bearing walls that offer superior thermal and moisture regulation capabilities because their typical mixing proportions range from 1:1.5:3 to 1:2:4 (binder:water:shiv), producing densities between 300 and 600 kg/m³.

Fig.1. Hemp hurds produced from Hemp plant
(image source: link.springer.com)

2.2.Mechanical properties & structural role

Although hempcrete has a relatively low compressive strength, usually between 0.2 and 2.5 MPa, its elastic behavior is characterized by significant deformability and a high strain capacity before failure. By discovering that hempcrete made with commercial hydraulic binders had higher compressive strengths than hempcrete made with hydrated calcitic lime, Murphy et al. brought attention to the significance of binder type and concentration in improving mechanical performance. While Evrard recorded a lower range of 0.2 to 0.5 MPa, O'Dowd and Quinn reported compressive strength values ranging from 0.65 MPa to 1.9 MPa, further demonstrating the material's dependence on mix formulation and curing conditions. By controlling binder proportions and optimizing binder-to-hemp ratios, studies by Tronet et al. and Jami et al. also showed that strength can be increased without significantly compromising the material's insulating properties. Compaction is crucial for improving structural integrity, as Elfordy et al. showed that higher density and compaction are directly associated with higher compressive strength and less deformation before failure. Walker et al. also highlighted the influence of binder chemistry, demonstrating that while long-term mechanical values tend to converge after a year of curing, early-age strength is improved by increased binder hydraulicity. Advanced binder systems, such as MgO-based formulations, produced compressive strengths that were nearly 2 MPa, according to Cigasova et al., whereas the addition of clay to lime binders resulted in moderate improvements due to the formation of hydraulic compounds (Haik et al.).

A review by Abdalla et al. suggests that adding natural fiber reinforcement, like hemp, coconut, banana, and basalt, could improve the durability and tensile resistance of cementitious composites. Studies employing clayey soils and hemp fibers (Ngo et al.) demonstrated strength development from 0.6 MPa to 5 MPa over 180 days, despite the fact that the addition of fiber somewhat reduced compressive values.Collectively, these studies demonstrate that hempcrete is a significant structural element of hybrid wall systems, particularly in timber-framed or confined infill assemblies, despite still being primarily non-load-bearing due to its capacity to provide lateral restraint and enhanced composite action (Chabannes et al. [87–89], Walker). Mechanical enhancement techniques involving denser mix designs, optimized binder content, and natural fiber reinforcement are being researched in order to enable limited load-bearing applications in low-rise, sustainable construction. Improved compressive strengths appropriate for minor structural applications have been demonstrated in studies employing lime–GGBFS or lime–metakaolin binders and denser mix ratios (binder:shiv ≈ 1:1.5). Reinforcement with natural fibers, hemp-lime blocks treated with lime, or bamboo grids has been proposed to increase stiffness and durability. Pilot projects in Tamil Nadu and Uttarakhand demonstrate that hempcrete can perform load-bearing functions in low-density, single-story buildings, despite the fact that it is still primarily utilized for non-load-bearing projects in India.

2.3 Thermal & hygrothermal performance

Hempcrete offers remarkable moisture management and thermal insulation properties due to its high porosity and vapor permeability. The stated thermal conductivity values, which normally range from 0.09 to 0.16 W/(m·K), are influenced by two factors: density (250–600 kg/m³) and moisture content. Lighter compositions (approximately 300 kg/m³) achieve lower conductivity rates of approximately 0.09 W/(m·K), whereas more compact mixtures can reach values as high as 0.16 W/(m·K). The corresponding effective R-values for wall thicknesses between 150 and 300

mm are roughly 1.5 to 3.0 m²K/W, providing sufficient insulation for temperate and humid conditions.
Because hempcrete is highly vapour permeable and has a significant moisture buffering capacity (MBV ≈ 2–3 g/m²·%RH), it can be used for passive humidity control in interior spaces [Rahim et al., 2016; Collet & Pretot, 2014]. These hygrothermal characteristics significantly lower the likelihood of mold growth, delay condensation, and stabilize interior temperatures and relative humidity. Consequently, hempcrete improves indoor air quality and occupant comfort, especially in environments with fluctuating humidity and temperatures that are typical of temperate or maritime climates.

2.4 Environmental assessment (LCA, carbon sequestration)

The environmental benefits of hempcrete are attributed to its carbon-absorbing ability, carbonation process, and relatively low emissions. The hemp plant absorbs carbon dioxide from the atmosphere and transforms it into biomass during its four-month growth period. The hurds are then mixed with a binder and water. The energy required to produce the lime binder is high due to the quarrying and calcination processes. This step accounts for the majority of greenhouse gas emissions. Some sources claim that hempcrete can absorb "over 100 kg CO_2 per m²" or "19 lb CO_2 per cubic foot," meaning that under the correct conditions, it can absorb more carbon dioxide than is needed to produce it.

According to studies that examine life cycle assessments, such as those by Arrigoni et al. 2017 and Lecompte et al. 2017, emissions from creation to a shipping point usually range between roughly -500 and +50 kg CO_2-eq per cubic meter. When considering the full lifecycle, emissions can drop to between -700 and +10 kg CO_2-eq per cubic meter if we account for the carbon recapture (30– 90%). Thus, for a 300 mm wall, the total balance can be anywhere between -200 and +5 kg CO_2-eq per square meter. Among the factors influencing this are the binder mixture, transportation distances, mixing energy, curing time, and disposal methods.

2.5 Construction methods & technologies

Prefabricated panels, in-situ casting, and the recently developed 3D printing method are all methods used in hempcrete construction. Hemp-lime mixtures are placed into temporary formwork on-site during the in-situ casting process. Although it permits wall geometry flexibility, it necessitates a significant amount of labor and oversight to guarantee consistent and uniform compaction.
Depending on the temperature and humidity levels, curing usually takes two to eight weeks. However, because curing takes place off-site under controlled conditions, prefabricated hempcrete panels and blocks allow for improved quality control and less time spent on-site. New developments in 3D-printed hempcrete demonstrate promising buildability at densities of about 660 kg/m³, doing away with the need for formwork but necessitating careful control over layer curing and mixture rheology.

3.Hempcrete as Sustainable Material

As the climate change crisis is alarmingly increasing, there is a growing demand to rethink and transform how we live sustainably. Construction plays a crucial role here, especially with increasing global populations demanding more housing and infrastructure. In this context, hempcrete has emerged as a promising bio-composite building material gaining attention for its potential in sustainable construction, particularly in small-scale architecture.

Hemp hurds, the woody inner core of the hemp plant, are combined with water and a binder based on lime to make hempcrete. As it grows, the hemp plant absorbs a lot of carbon dioxide, making it a valuable resource. Because of this property, hempcrete is a carbon-negative substance. Hemp matures in about four months, and it grows quickly. It is then harvested and turned into hemp hurds. Kiln-heated limestone powder is used to make the lime binder. Because it requires mining and crushing, this process—known as calcination—uses a lot of energy. Even then the entire process of combining hemp hurds, lime, and water is still easier and requires less energy than using conventional building materials.

The production process begins with the mixing of hemp hurds with water. Following this, the lime will be added slowly. This slow incorporation of the lime prevents the reaction from occurring prematurely to affect the consistency of the material. Once combined, the hempcrete is placed into a mold and allowed to cure for six to eight weeks. After curing, the hempcrete hardens into light-weight, ready to be used as either a block or panel in construction. In addition to the hydrated lime binder's antifungal, antimicrobial, and fire-resistant properties, hemp is natural and high in cellulose, which stores carbon. Its porous structure provides thermal mass and aids in moisture regulation, lowering the likelihood of mold growth inside. The thermal mass improves comfort and energy efficiency by allowing for greater control over interior temperature swings. Despite all of hempcrete's advantages, there are still barriers keeping its widespread use. Longer build times and the requirement for specialized training may arise from the fact that it is a more recent building material, which also means that there is a smaller pool of tradespeople who have received training to work with it and a smaller body of public knowledge. While the porosity of the material aids in moisture reduction, prolonged exposure to standing water or other persistent moisture can also significantly reduce the material's performance. Furthermore, because hempcrete has a limited structural capacity and cannot support objects like floors or roofs, it is only used for wall cavities and insulation applications.

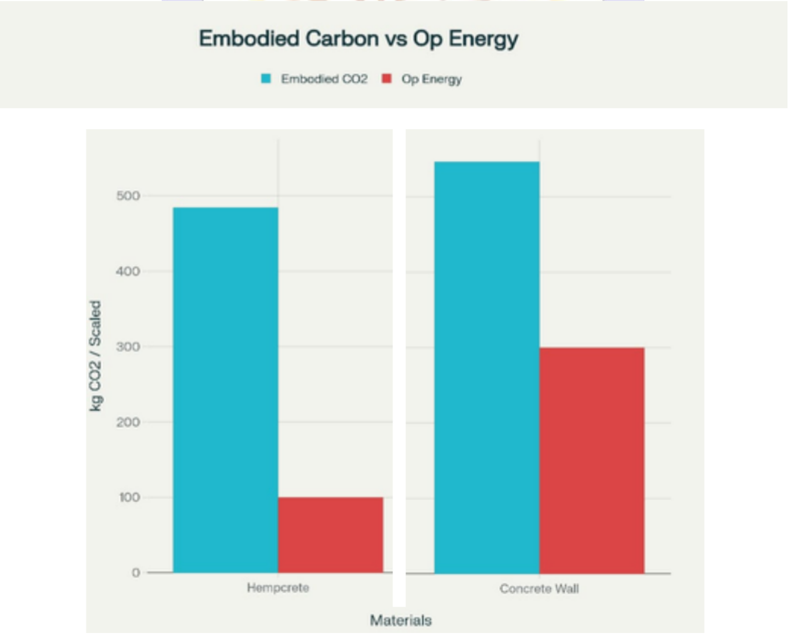

Fig2. Comparison of embodied energy and operational energy between hempcrete and conventional concrete wall assemblies.

4.Methodology

While several research papers discuss the performance of hempcrete, the main focus is on mechanical, thermal, and carbon absorption aspects. The details about built infrastructure, including both building components and transportation are not held with elaborately. In addition, these reviews usually lack the complete sustainability view. The research papers should integrate economic, social, and environmental factors along with the challenges of hemp production and supply chains. To fill these gaps, we need to pursue specific research objectives. These should address the full life cycle of hempcrete structures, the wider infrastructural context, and the varied sustainability challenges in the hemp industry.

The research looks at how well hempcrete performs environmentally and its feasibility for small-scale buildings. It compares three different wall construction methods: a) cast-in-place hempcrete,
b) prefabricated hemp panels, and c) developing 3D printed hempcrete. The evaluation used two life-cycle assessment (LCA) scopes. The first was cradle-to-gate, which covers raw material extraction, growing, binder production, initial processing of hemp, and transportation to the factory. This scope helped compare prefabricated panels with in situ mixing. The second scope studied cradle-to-grave, which includes on-site construction, energy performance in use, maintenance, and end-of-life scenarios like deconstruction, recycling, and composting. The study will model the energy performance in use through a detailed simulation of building physics. It will also convert simulation data into annual greenhouse gas (GHG) emissions based on the local electricity grid factors. The research defined a functional unit of one square meter of external wall, with a target thermal transmittance (U-value) of 0.35 $W \cdot m^{-2}$.

System boundaries follow ISO standards with cradle-to-gate covering stages A1 to A3. These stages include raw hemp cultivation, binder production (lime or cement where applicable), hemp decortication and hurd processing, and transport to the production or building site.
Cradle-to-grave extends these stages to cover on-site construction (A4 to A5), operational use, which involves heating and cooling energy demand and maintenance (B1 to B7), and end-of-life treatment and disposal (C1 to C4). We calculate the material quantities (kg/m^2) needed to achieve thermal equivalence for each method. These quantities are then multiplied by life-cycle inventory (LCI) impact factors to find the embodied GHG emissions. If there are differences in wall thickness, we report both mass and emissions per functional unit for transparency.

Construction logistics and site conditions are modeled with in-situ casting. This process requires extra energy, labor, and curing delays that are sensitive to the surrounding humidity and temperature. The data comes from small-scale projects that provide information on labor hours per square meter. Prefabricated panels account for off-site curing energy, transport emissions measured in kilogram-kilometers, and site installation labor. They also help reduce waste on site and offer faster schedule benefits. For 3D-printed hempcrete, recent assessments look at printer energy use, the ingredients needed for printability, the higher binder content common in printable mixes, and the limitations of layer-by-layer deposition. Logistics, like equipment transport, are also considered, using parameters from rheology and 3D concrete printing research.

Fig.3.In-situ layered hempcrete wall construction.

(image source: natural-building-alliance.org)

Fig.4.Precast hempcrete masonry blocks for construction.

(image source: hempbuildmag.com)

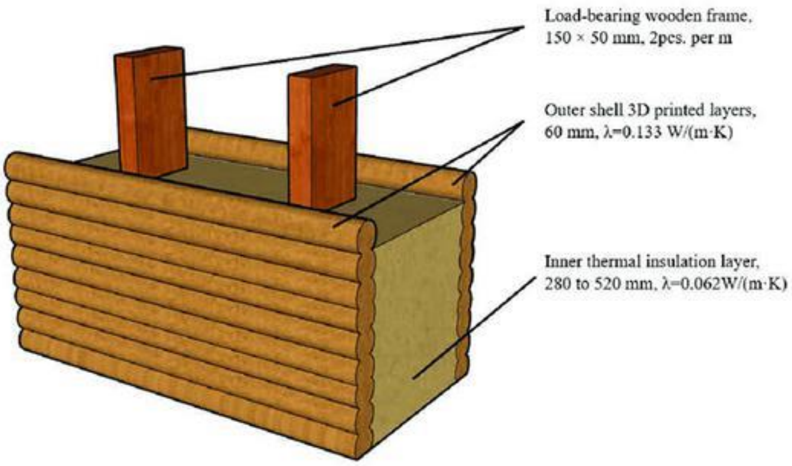

Fig.5.Precast hempcrete masonry blocks for construction.

(image source: Schematic 3D printed hempcrete wall fragment, Researchgate.com)

The in-situ measurement and assessment of hempcrete walls in a retrofitted single-family home in New Castle, Pennsylvania, USA, by Memari et al. (2025) is an example of a pertinent case study that is currently available. In order to ascertain the true thermal resistance (R-value) of hempcrete applied to wood-framed walls in a house that was first constructed in 1900, this study required practical instrumentation using the Heat Flow Meter Method. A 10-inch-thick hempcrete insulation layer and hemp-rich plaster were two of the several layers that made up the hempcrete wall system. Measurements of thermal resistance revealed an average R-value of roughly 16.93 (R-1.45 per inch), which is roughly 5.6 times higher than the R-value of the building's original uninsulated wood stud walls and more than ten times higher than that of a typical concrete wall of the same thickness. The study highlighted that hempcrete's porous structure offers excellent vapor permeability. This helps regulate moisture and prevents mold growth, while the lime binder coating on the hemp fibers adds antimicrobial properties. The study also showed that hempcrete improves thermal performance and energy efficiency. It has potential for carbon sequestration as well. Compared to traditional wall materials like cement or clay bricks, which emit much higher greenhouse gases per square meter, hempcrete walls have significantly lower embodied emissions. In some cases, they even showed net negative emissions due to biogenic carbon storage during the growth of hemp.

This real-life evaluation assesses thermal and environmental performance of hempcrete and showcases a successful small technology retro-fit that utilizes sustainable materials, supported by empirical testing and life cycle assessment. Ultimately, the output provided indispensable information illustrating the building potential of hempcrete, and the environmental merits of its use in residential contexts.

5.Result

The current study provides a thorough look at hemp fiber and hempcrete as sustainable construction materials. It examines their mechanical properties, energy performance, and suitability for building and highway applications. The study reviews recent developments in the UK construction industry, backed by case studies that show practical uses of hempcrete. The evaluation of hemp fiber-based materials considers environmental, economic, and social impacts. It emphasizes their eco-friendly production processes and possible benefits to society while recognizing the challenges that still exist.

The production of hempcrete uses little energy, which makes it a good choice for the environment. The methods of compaction greatly affect energy use during manufacturing, as well as thermal performance, density, and mechanical strengths like compressive and flexural strength. The binder, mainly lime-based because of its low emissions and compatibility with hemp shives, is crucial for structural stability; however, it contributes to over 75% of the total greenhouse gas emissions linked to hempcrete production. Important factors that determine whether hempcrete is suitable for a project include its density and binder content. Yet, one main challenge is the natural breakdown of plant materials like hemp fibers. This calls for more research on durability and factors like resistance to termites.Based on these conclusions, future research should focus on developing self-compacting hempcrete to lower carbon footprint and ensure material consistency.

It should explore different binder formulations for environmental benefits and study the effects of curing conditions and hemp shives gradation. Durability issues, such as termite resistance, need thorough investigation. For asphalt applications, research should improve our understanding of hemp fiber reinforcement mechanisms, failure modes, moisture interactions, and aging effects to enhance pavement design and lifespan. Additionally, from a consumer viewpoint, accurately measuring insulation benefits and energy savings in hempcrete buildings is vital to justify the initial costs. Creating sustainable business models will help the material gain market acceptance and economic viability.

In conclusion, hempcrete shows a lot of potential as a sustainable construction material with various environmental and socio-economic advantages. However, focused research on material performance, supply chain issues, and broader sustainability challenges is essential for its wider use and incorporation into greener building practices.

Hempcrete has far less embodied carbon than traditional building materials such as double hollow brick and concrete walls. Life cycle assessments have estimated that hempcrete walls emit approximately 484.42 kg CO2 per functional unit while double hollow brick and concrete walls emit roughly 546.0-546.55 kg CO2 throughout their life cycles. These carbon-negative characteristics of hempcrete are due to its ability to sequester carbon as part of lime carbonation as well as the usage of quickly renewable hemp biomass. Hempcrete also aids in better indoor climate regulation due to its thermal mass and vapor permeability.

Conclusion

Hempcrete has emerged as a forward-thinking material capable of redefining sustainability in small-scale architecture. Its distinctive combination of low embodied carbon, effective thermal insulation, and natural vapor permeability provides a practical response to one of the biggest challenges in the construction sector—reducing environmental impact without sacrificing comfort or functionality. Through the dual processes of hemp cultivation and lime carbonation, hempcrete actively sequesters carbon dioxide, often achieving a carbon-negative balance over its life cycle. This means it does more than simply minimize emissions; it contributes positively to environmental regeneration.

From a performance perspective, hempcrete enhances indoor comfort by regulating temperature and humidity, supporting healthier and more stable living environments. However, its broader adoption still faces challenges, including limited load-bearing capacity, longer curing periods, and a shortage of skilled labor familiar with hemp-based construction techniques. Future innovation should focus on improving binder compositions, experimenting with hybrid structural systems, and expanding the use of prefabricated panels to increase consistency and reduce on-site labor.

Equally important are government incentives, building code integration, and public awareness campaigns that can help establish hempcrete as a mainstream, trusted construction option. Ultimately, this study reinforces hempcrete's potential as a regenerative, low-carbon material—one that bridges environmental responsibility with practical, modern architecture and offers a clear path toward a greener built future.

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