Hemp as a Construction Material

BAUHAUS EARTH

Material Guide

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Bauhaus Earth is a Berlin-based research institute aiming to transform the built environment from a carbon source to a carbon sink by leading scientific inquiry into the nexus of climate and the built environment.

Our research agenda encompasses a range of topics, including the entire life cycle of materials, the necessary material transition in construction, global and regional nature-based supply and demand chains – and their socio-spatial, environmental, and political dimensions – regenerative design approaches to buildings, infrastructures, neighbourhoods and urban systems as well as potential solutions that address the challenges and opportunities in specific regional contexts.

We integrate science-based pathways and solutions with real-world application and experimentation. Our interdisciplinary research informs global demonstration projects, which in turn test and refine our scientific findings.

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Abstract

Regnerative building materials for construction purposes like hemp based composites offer a viable alternative to conventional building materials, as they reduce greenhouse gas (GHG) emissions, enhance user comfort, and can support local ecosystem restoration. This report investigates the use of hemp, focusing on its potential as an insulation material for construction purposes. It explores the influence of different binders (lime, earth), shiv sizes, and binder concentration in hemp composites. A literature review that summarizes the current state of research informs the development of six distinct mixture designs. Experimental tests were assessed to compare hemp-earth (HE) and hemp-lime (HL) mixtures by evaluating their properties in terms of raw density, thermal performance, structural integrity, fire resistance, and environmental impact. Findings indicate that all tested materials are generally suitable as insulation material in construction, as all tested materials achieved U-values below 0.24 W/m²·K at a 300 mm wall thickness. Fire resistance tests confirmed compliance with the EN 13501-1 classification, and all mixtures demonstrated a negative CO_2 footprint with significantly lower global warming potentials (GWPs) compared to conventional insulation materials. Mixtures containing lower hemp contents (3:1 hemp to binder ratio) resulted in improved structural performance, whereas higher hemp content (4:1 hemp to binder ratio) enhanced thermal insulation and lowered the GWP. Furthermore, results showed that larger hemp shives contributed to improved thermal insulation and compressive strength, while generally exhibiting lower raw densities. While HE (hemp-earth) samples offered significant environmental advantages compared to HL (hemp-lime) mixtures, HE samples exhibited greater deformation under load. Structural integrity and levels of abraison must be improved for all mixtures if used as self-supporting prefabricated blocks, no additional enhancements are required when used as in-situ infill insulation.

1 Introduction

The building sector is a major contributor to global carbon emissions, responsible for approximately 40% of global carbon emissions and 36% of global final energy consumption.[1] This makes it the largest contributor to energy use and greenhouse gas (GHG) emissions.[2] A decarbonization of the sector is inevitably necessary for effective climate change mitigation and meeting the Paris Agreement's ambitions of limiting global temperature rise to well below 2°C.[3]

Building related carbon emissions result not only from building operations but also from material production, transportation, construction, and disposal, collectively referred to as embodied carbon, which accounts for 11% of global carbon emissions.[4] To align with the Paris Agreement's decarbonization goals, embodied carbon emissions in the built environment must be reduced by 65% by 2030 and eliminated entirely by 2040.[5]

At the same time, with the global population increasing, the demand for new buildings and infrastructure is expected to double by 2060, particually in Asia and Africa. Meanwhile, 97% of existing buildings in Europe will require improvements in energy efficiency to comply with regulatory standards.[6]

Addressing these challenges requires a fundamental shift in resource management to reduce emissions, minimize embodied carbon, and prevent further depletion of natural resources. In this context, nature-based and renewable building materials present a promising solution for reducing the environmental impact while improving the building performance.

Beyond timber, fast-growing, short-rotation plants offer an efficient source of biomass. In comparison to timber, plants like hemp, flax, and kenaf have a shorter growth circles and more rapid carbon sequestration. Hemp in particular stands out due to its high biomass yield, full-plant usability, soil-enhancing properties, and high carbon sequestration potential. It also acts as a natural pesticide, removes heavy metals from soil, and can serve as an effective thermal and acoustic insulation in construction. With its diverse applications across industries and complete plant utilization, hemp plays a key role in advancing sustainable material innovation.[7]

1
"2018 Global Status Report. Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector." 11.

2
"2018 Global Status Report. Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector." 11.

3
'Paris Agreement', Article 2, 1(a).

4
'2030 Challenge for Embodied Carbon – Architecture 2030'.

5
'2030 Challenge for Embodied Carbon – Architecture 2030'.

6
Adams, Burrows, and Richardson, 'Bringing Embodied Carbon Upfront. Coordinated Action for the Building and Construction Sector to Tackle Embodied Carbon.', 22.

7
Ahmed et al., 'Hemp as a Potential Raw Material toward a Sustainable World', 1–2.

2 Hemp as Construction Material

2.1 Industrial Hemp

Definition and Usage

The term industrial hemp refers to varieties of the *Cannabis sativa L.* plant, that have Tetrahydrocannabinol (THC) levels in the flowers and leaves that are below regulated limits set by authorities. The THC levels define the cannabinoid profile of the plant and its usability for the pharmaceutical industry and as a recreational drug.[8]

Cannabis sativa, a member of the *Cannabaceae* family is recognized for its tall, fibrous and unbranched stems, which are well-suited for industrial hemp fiber production and are particularly relevant as resources for the production of building materials. Other than for building materials, Cannabis sativa is used in the production of textiles, clothing, rope, home furnishings, oils, cosmetics, and food. Due to its diverse applications, hemp likely connects with more markets and industries globally than any other crop.[9]

Industrial hemp cultivation allows farmers to produce multiple co-products from a single harvest, e.g. grain (oilseed) and fiber can be obtained from the same crop, whereas hemp fibers can yield different materials like bast fibers and hurds/shives, each suited for distinct uses. The benefits of multi-purpose hemp farming improve its economic viability, as farmers can generate income from the different parts of the plant grown on the same land area with the same input costs. Furthermore, environmental sustainability is improved as water and fertilizer use are optimized. Hemp also offers advantages as a rotational crop, helping to mitigate agricultural risks while supporting local economies with fair employment and environmental benefits, depending on local factors like regulations and market demand.[10]

8
"Commodities at a Glance: Special Issue on Industrial Hemp.," 6.

9
Marquardt and Savage, "Growing Hemp for the Future. A Global Fiber Guide.," 8-9.

10
Marquardt and Savage, "Growing Hemp for the Future. A Global Fiber Guide.," 13.

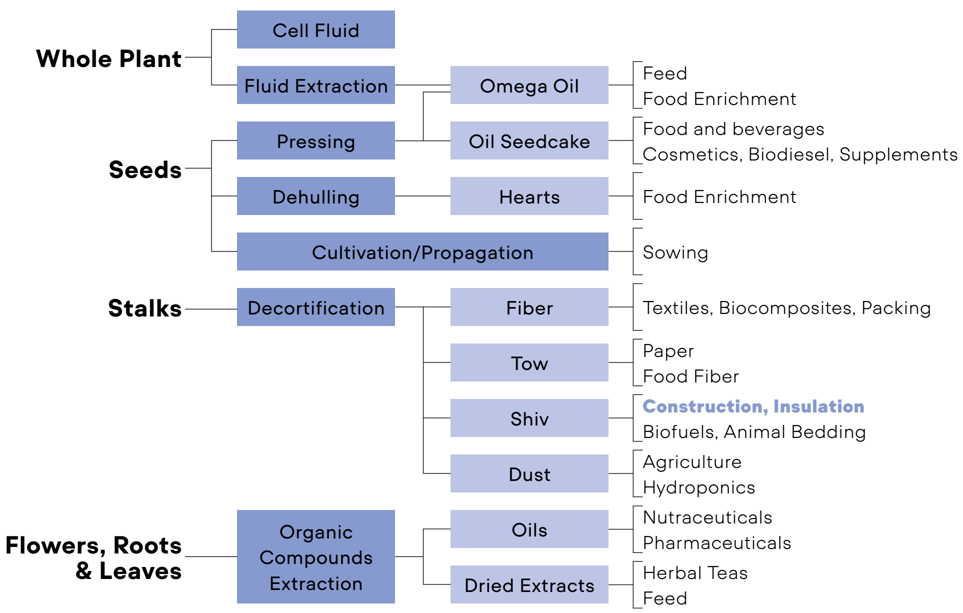

Figure 1. Use of hemp. (Figure from Textile Exchange, "Growing Hemp for the Future. A Global Fiber Guide," 8–9.)

Cultivation

Historically, hemp ranks among the oldest crops cultivated by humans, originating in western Asia before spreading globally. It requires minimal labor and offers high amounts of biomass. One hectar of hemp cultivation can produce up to 12 t of cellulose, 20 t of stem particles, and a total of 57 t of biomass. Compared to cotton, hemp cultivation is significantly more cost-effective, requiring approximately 77% less expenditure on fertilizer, seeds, field operations, and irrigation.[11] Since the 1990s, industrial hemp has seen a resurgence after decades of restricted cultivation in most countries that diminished its genetic diversity and research. Recent studies indicate that incorporating hemp into agricultural systems presents substantial opportunities across various production sectors.[12]

Industrial hemp is gaining recognition as a valuable biomass resource, due to its rapid growth, adaptability, and high energy yield. Capable of reaching heights over 4 m with monthly growth rates of up to 50 cm, hemp thrives particularly well in temperate regions. It requires average temperatures between 13°C and 22°C and 500-700 mm per square meter of water during the growing season, with the highest water need early in its development. Ideal growth conditions include well-drained, loamy soils with near-neutral pH and balanced nutrient management.[13]

Life Cycle and Growth Stages

Hemp's growth and morphology are influenced by planting conditions. The warm-season annual plant flowers when the days begin to shorten after the summer solstice on June 21st (northern hemisphere). Typically, hemp is dioecious, with separate male and female plants, although some commercial cultivars are monoecious, containing both flower types on a single plant. Planting density plays a critical role in its growth form: low-density planting leads to branching, while high-density planting results in tall, straight, unbranched stems suitable for fiber production.[14]

The life cycle of industrial hemp lasts four to six months and is divided into distinct growth stages:

1. *Emergence:* This stage, from sowing to the emergence of the cotyledons, usually takes four to ten days, depending on soil moisture.
2. *Implantation:* Occurs approximately three weeks post-emergence, during which the plant develops a root system and grows to 30-60 cm tall with three pairs of leaves.
3. *Active Growth:* Extends from the end of implantation until the onset of flowering, during which the plant develops significant amounts of hurd and bast fibers.
4. *Flowering:* Marked by the appearance of the first flowers.
5. *Full Flowering:* This stage continues from the initial flower appearance until the last female flowers open, which is consistent regardless of sowing dates.
6. *End of Flowering:* Concludes with the fertilization of the final flowers.
7. (*Senescence:* The plant transitions from physiological maturity to the next growth cycle and prepares for germination.)[15]

11
Ahmed et al., "Hemp as a Potential Raw Material toward a Sustainable World," 2–3.

12
Dudziec, Warmiński, and Stolarski, "Industrial Hemp As a Multi-Purpose Crop," 1.

13
Dudziec, Warmiński, and Stolarski, 2,5,6.

14
Sanjun Gu Ph.D., "All About Hemp - A Manual for Farmers and Other Agricultural Professionals.," 3.

15
Bouloc, Allegret, and Arnaud, "Hemp : Industrial Production and Uses.," 46–47.

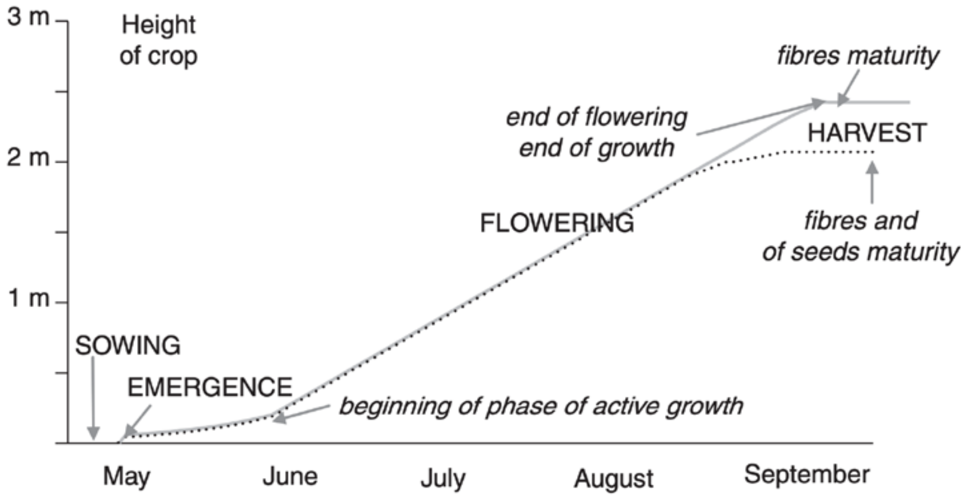

Figure 2. Vegetative cycle of hemp. (Figure from Bouloc, Allegret, and Arnaud, "Hemp: Industrial Production and Uses," 46–47.)

Hemp Fibers

Hemp stems typically range from approximately 1 to 6 meters in height and 0,6 to 1,9 cm diameter, whereas male hemp plants generally grow 10% to 15% taller than female plants. High-density cultivation can promote the growth of taller stems with fewer branches and leaves, which enhances fiber quality and yield.[16] Hemp fiber is one of the most robust and rigid natural fibers available.[17]

Industrial hemp grown for fiber, is an annual broadleaf plant with a deep taproot, producing tall, strong stems with long, strong bast fibers (about 25%) on the outer layer and shorter hurd fibers (approximately 75%). The hemp stem, which is the part of the plant used for fiber production, consists of long strands that extend vertically (bast fiber), encircling the woody core (hurd). These fibers are coated with a thin layer that forms the plant's outer bark. Pectin attaches the fibers to the core, while lignin binds them into bundles along the stalk.[18]

16
Sanjun Gu Ph.D., "All About Hemp - A Manual for Farmers and Other Agricultural Professionals.," 4.

17
Manaia, Manaia, and Rodriges, "Industrial Hemp Fibers," 3.

18
Marquardt and Savage, "Growing Hemp for the Future. A Global Fiber Guide.," 9.

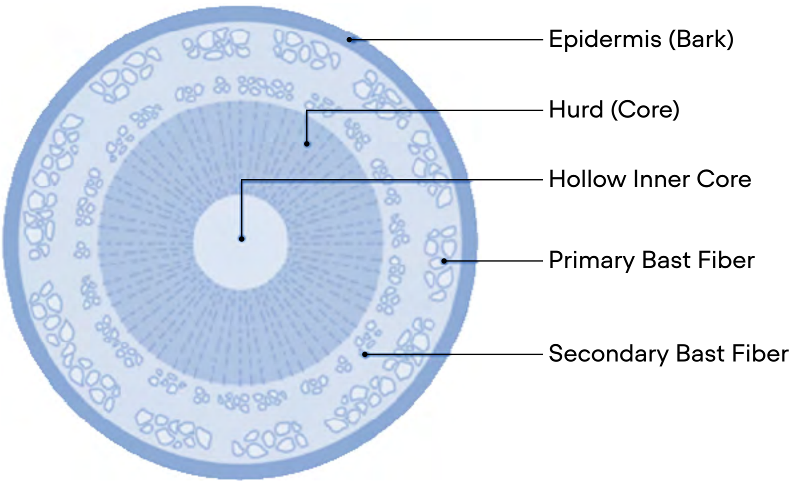

Figure 3: An inside look at a fiber hemp stalk. (Figure from Manaia, Manaia, and Rodriges, "Industrial Hemp Fibers," 3.)

Figure 4. Cannabis sativa L. (Image from Purefarma, "About Us.")

Fiber Production and Processing

For fiber production, late-flowering varieties are often chosen to maximize stem yield, while preferably male plants are chosen.[19] Following steps are required to process the biomass from the field into a usable construction material. Emissions from hemp shiv production range from 0.085 to 0.19 kg CO_2e/kg, compared to 1.5 to 2.1 kg CO_2e/kg sequestered during the growth of hemp.[20]

Harvesting

The timing of hemp harvest is crucial for fiber quality. Delaying harvest leads to increased lignin in the fibers, which complicates the separation process and decreases fiber strength. To avoid this, harvesting is typically done when less than 20% of plants have developed female flowers.[21] While small fields can be harvested manually, with comparable tool used in hay production, large fields require mechanical harvesters. Due to the strong fibers of hemp, the cutting machinery should be equipped with extra strong blades to avoid any damage to the machines.

Retting Process

Field retting is the most common and cost-effective method, where cut stems are left in the field for up to 5 weeks, exposed to dew and rain (or supplemented with irrigation). Stems need to be turned regularly for even retting, which starts the decomposition of the fibers' chemical bonds without degrading fiber quality. Weather conditions and stem diameter influence the duration of this process. Water retting involves the process of submerging stems in water for 7-10 days, sometimes with additional heat applied. This method is more labor-intensive but yields more uniform and higher quality fibers. Once retting is complete, stems are dried to a moisture content below 15% to prevent mold and decay.[22]

Decortification

Traditional fiber extraction techniques, like field and water retting, require significant manual labor and are less commonly used in the Global North due to high labor costs. Instead, large-scale operations typically rely on mechanical decortication, which physically separates the outer bast fibers from the inner, woody hurd. This process involves steps such as beating, scutching and combining. Decortication can be done on either fresh or dried stems, dry decortication yields faster results and greater flexibility outside of the harvest season, though fresh decortication typically produces superior fibers.

While the process to produce hemp hurds is completed after decortification, the production of finer fibers requires chemical and physical methods to break down the sticky substances binding the fibers together. Although these methods can achieve the desired results, they are less economically viable due to the substantial chemical and energy requirements. A more sustainable approach involves using microorganisms in bioreactors to biologically process the fibers. High-quality fibers require consistent raw material, with freshly decorticated green bark being preferred over retted material for better uniformity.[23]

19
Kaiser, Cassady, and Ernst, "Industrial Hemp Production," 4.

20
Asghari and Memari, "State of the Art Review of Attributes and Mechanical Properties of Hempcrete," 79.

21
Visković et al., "Industrial Hemp (Cannabis Sativa L.) Agronomy and Utilization," 10–11.

22
Kaiser, Cassady, and Ernst, "Industrial Hemp Production," 4.

23
"Commodities at a Glance: Special Issue on Industrial Hemp.," 20.

Advantages of Hemp

Carbon Sequestration

The rapid growth cycle of hemp allows for quick biomass production and fast carbon sequestration. It can sequester around 20 tons of CO_2 per hectare, with the carbon primarily stored in the stems. In comparision, forests can sequester up to 11 tons of CO_2 per hectar per year.[24] Cultivating hemp has carbon-negative benefits, as the carbon stored in the stems remains sequestered for the long term, even after application. The biomass produced can be converted into biochar, which enhances soil carbon storage and contributes to mitigating climate change.[25]

Soil Regeneration

Hemp can significantly enhance soil quality, making it ideal as a cover crop or in crop rotation systems. Hemp improves soil quality by suppressing weeds, facilitating phytoremediation, and promoting soil regeneration, all while reducing the need for synthetic pesticides. Its deep and extensive root system improves soil health by enhancing aeration, preventing erosion, and building soil structure. As the roots decay before the next planting season, they naturally fertilize the soil. Additionally, hemp is effective in phytoremediation, helping to remove heavy metals, chemicals, and radiation from contaminated soil. Further research is needed to understand how effectively hemp absorbs these contaminations and whether the plant's fibers can be safely reused afterwards or must be treated as hazardous waste.[26] Notably, hemp maintains soil fertility even under drought conditions by providing consistent organic residues and natural aeration. When used in crop rotation, hemp has been shown to reduce disease incidence in subsequent crops, such as anthracnose in chili peppers.[27]

Wood Substitution

Hemp fibers can substitute conventional wood products and effectively address deforestation, which is a major contributor to greenhouse gas emissions. Hemp fibers can substitute timber in various applications, reducing reliance on deforestation and lowering associated CO_2 emissions. Hemp produces a greater amount of biomass compared to wood, delivering up to twice the amount of usable fibers as forests. Industrial hemp contains up to 77% cellulose, which is roughly three times higher than that found in wood and other agricultural residues.[28] The crop's high biomass yield also makes it a viable source of renewable energy. Hemp biomass can be converted into biogas, ethanol, and heating pellets, with one dry ton of hemp stems producing approximately 310 liters of ethanol. This efficient conversion highlights hemp's potential as a sustainable and versatile energy source.[29]

Potential Negative Externalities of Hemp Cultivation

The benefits of cultivating hemp extend across multiple dimensions, however there are some considerable concerns regarding nitrogen fertilization. Hemp cultivation has significant fertilization needs, requiring up to 224 kg per hectare of nitrogen fertilizer in some regions to optimize yields. This is comparable to or exceeds nitrogen recommendations for crops like cotton, soybeans, and corn. High nitrogen use can lead to environmental pollution through runoff, leaching, and greenhouse gas emissions, particularly nitrous oxide, which is a potent climate-warming gas.

24
Mendelsohn et al., "Fiscal Policy to Mitigate Climate Change. A Guide for Policymakers - Chapter 5, Forest Carbon Sequestration.," 92.

25
Sanjun Gu Ph.D., "All About Hemp - A Manual for Farmers and Other Agricultural Professionals.," 16.

26
Marquardt and Savage, "Growing Hemp for the Future. A Global Fiber Guide.," 12–13.

27
Dudziec, Warmiński, and Stolarski, "Industrial Hemp As a Multi-Purpose Crop," 9–10.

28
Ahmed et al., "Hemp as a Potential Raw Material toward a Sustainable World," 3.

29
Sanjun Gu Ph.D., "All About Hemp - A Manual for Farmers and Other Agricultural Professionals.," 16.

"When nitrogen in its active form, such as in fertilizer, is exposed to soil, microbial reactions take place that release nitrous oxide. This gas is 300 times more potent at warming the atmosphere than carbon dioxide." [30]

Moreso, continuous monoculture of hemp can lead to soil degradation, reducing microbial diversity and overall fertility. Proper management, the choice of hemp variety and cultivation practices also impact environmental outcomes. For example, growing the *Ferimon* variety with moderate nitrogen fertilization (50 kg/ha) and higher plant density (120 plants/m^2) has been identified as a sustainable option with low carbon footprints.[31]

2.2 Hemp-Based Building Materials

For construction purposes the long bast fibers as well as short woody shives from the inner hemp hurd can be used. While commonly used as a component of non-load-bearing composite materials, hemp fibers can also be applied in minimally processed forms. Loose hemp shives are effective insulating materials, filling gaps and spaces under floors. Hemp fibers in composite materials contribute to tensile strength, low density, flexibility, permeability as well as insulating and lightweight properties, which stem from their low mass to volume ratio. These composites often use hemp shives or lower-grade bast fibers, making efficient use of available resources. When incorporated into composites, the material properties can be changed by adjusting the type and ratio of binders added. The composites can be applied in plastering, paving, wall construction, and roof insulation.[32]

Hemp-Lime
Hemp-lime, commonly known as *hempcrete* is a fiber composite, containing a mixture of hemp shives and a lime-based binder. The lime-binder, which is mixed with water, coats the shives and hardens through a chemical reaction, creating a stable matrix. Unlike concrete, the binder in hempcrete does not provide structural support but only binds the hemp particles together. The material features significant void space, which provides its thermal insulation and moisture-regulating properties, making it suitable for wall, roof, and floor insulation.[33]

Applications (see fig. 5)
- In-situ hemp-lime wall systems (non-loadbearing infill)
- Prefabricated non-loadbearing wall panels
- Prefabricated blocks for non-loadbearing walls, ceilings and roofs [34]

Key performance [35]

Raw density:	275 - 500 kg/m^3
Compressive strength:	0.29 - 0.39 Mpa
Water vapor resistance:	$\mu = 4.85 \pm 0.24$ at 400 kg/m^3
Thermal conductivity:	$\lambda = 0.050 - 0.120$ W/(m·K)
Thermal transmittance:	0.39 - 0.46 W/(m^2·K) at 30cm thickness
Fire resistance: [36, 37]	B-s1-d0 / Euroklasse E / F90

30
Marquardt and Savage, "Growing Hemp for the Future. A Global Fiber Guide.," 14.

31
Dudziec, Warmiński, and Stolarski, "Industrial Hemp As a Multi-Purpose Crop," 9–10.

32
Visković et al., "Industrial Hemp (Cannabis Sativa L.) Agronomy and Utilization," 12–13.

33
Asghari and Memari, "State of the Art Review of Attributes and Mechanical Properties of Hempcrete," 67–68.

34
Malloy and Gonzalez, "Hemp and Lime, Examining the Feasibility of Building with Hemp and Lime in USA. Design and Demonstration," 134.

35
Walker and Pavía, "Moisture Transfer and Thermal Properties of Hemp–Lime Concretes," 270–274.

36
"Technisches Merkblatt, Hemplith® Hanfsteine."

37
IsoHemp, "Hanfstein für eine natürlich leistungsfähige Mauerwerkskonstruktion."

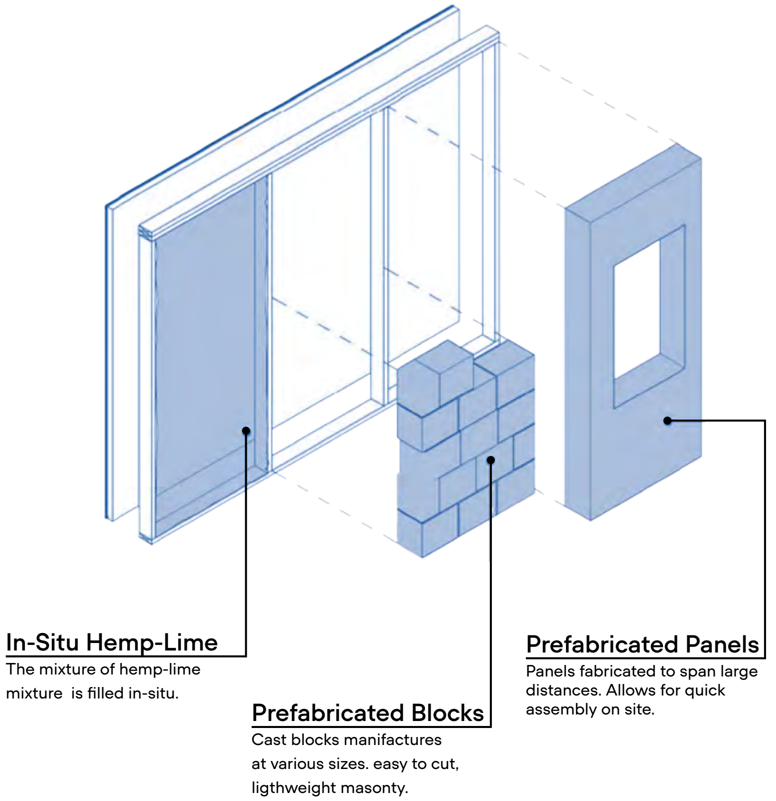

Figure 5. Applications of hemp-lime. (Figure from Malloy and Gonzalez, "Hemp and Lime, Examining the Feasibility of Building with Hemp and Lime in USA. Design and Demonstration," 134.)

Hemp Shives
Hemp shives, composed of cellulose, hemicellulose, and lignin, determine the properties of hempcrete, thereby influencing its overall performance. Cellulose, comprising 44-55 % of hemp shives, provides tensile strength and enhances the insulation properties of hemp-lime due to its porous nature. Hemicellulose, present at 16-18 %, binds fibers and helps regulate moisture. Lignin, ranging from 4-28 %, adds compressive strength, decay resistance, and fire resistance, while extractives influence the material's color, odor, and durability. The strength and longevity of hemp-lime are directly tied to the levels of cellulose and lignin in the hemp shiv, with higher concentrations leading to improved structural integrity.

Binder
Lime is the primary binder used in hemp-lime, for this reason it is also referred to as limecrete. Compared to cement, the primary binder in concrete, lime has lower emissions during production and better compatibility with hemp shives. While lime remains the most commonly used binder in hemp-composites, other binders like cement, gypsum, and magnesium oxide (MgO) are also used, depending on the desired properties and environmental considerations. The mix ratio of hemp shives to binders varies based on the binder type and application is generally around 1:1, measured by weight.[39] The ratio can be adjusted as needed, whereas a higher binder content will produce a stronger material but has hier thermal conductivity.[40]

Sustainability
The lime binder in in-situ infill hemp-lime accounts for 49% of primary energy use, 68% of water consumption, and 47% of air pollution. The carbon footprint of hemp-lime is also affected by factors such as lime type, material

39
Asghari and Memari, "State of the Art Review of Attributes and Mechanical Properties of Hempcrete," 67–80.

40
Asghari, Nima and Memari, Ali M., "Fundamental Properties of Hempcrete."

transportation, and construction methods, with hemp-lime plaster requiring more binder than sand-lime coatings, thus increasing its carbon footprint.[41]

Hemp-Earth

Hemp bast fibers can be incorporated into various earthen materials to significantly enhance the overall performance, particularly in terms of durability and strength. A study examining the mechanical properties of earthen blocks reinforced with hemp bast fibers demonstrated that tensile strength, elastic modulus, and compressive strength improved compared to unreinforced compressed earth blocks.[42]

Applications

- Rammed earth walls
- Compressed earth blocks
- Lightweight earth bricks and building boards
- Timber frame infills

Key performance

Given the diverse applications and varying properties of the materials, it is not possible to present generalized performance metrics.

Hemp-based Insulation Boards

Hemp fibers, bast fibers, and shives can be processed into different types of boards. One category includes rigid hemp lightweight boards used for interior applications. These boards are suitable as wall and ceiling elements, for mold remediation, thermal insulation, as plaster carrier boards, or as non-load-bearing partition walls.[43] In addition, there are hemp fiber insulation boards, comparable to wood fiber insulation. These semi-rigid boards provide effective thermal performance, with performance values similar to fiberglass. Although they are approximately twice as expensive as fiberglass and come in sheets rather than rolls, they can be easily cut and adjusted on-site to fit different wall frames.[44] The performance of these products varies depending on their composition and density, but in general, hemp boards offer good thermal and acoustic insulation.

41
Asghari and Memari, "State of the Art Review of Attributes and Mechanical Properties of Hempcrete," 67–80.

42
Jesudass et al., "Earthen Blocks with Natural Fibres - A Review," 6984.

43
"Technisches Merkblatt, Hemplith® Hanfsteine."

44
Malloy and Gonzalez, "Hemp and Lime, Examining the Feasibility of Building with Hemp and Lime in USA. Design and Demonstration," 141.

2.3 Best Practice Examples from the Built Environment

Hemp and Bamboo - Shah Hemp Inno-Ventures

Projects Location: *Janakpur, Nepal*
Year Completed: *2016 - ongoing*
Builder: *Shah Hemp Inno-Ventures*

Shah Hemp Inno-Ventures, in collaboration with the *International Hemp Building Association (IHBA)*, is dedicated to advancing hemp-lime construction in Nepal. By utilizing local materials like hemp, hydrated lime, and bamboo, and establishing a reliable supply chain, they have not only built the first hemp-lime wall in Asia but also successfully completed multiple hemp-lime projects across a wide range of structures in various climatic and social conditions, including the Langtang region at an altitude of 4000 meters.[45]

45 Shah Hemp Inno-Ventures, “Hempcrete Construction"

Figure 6. In-situ hemp-lime, bamboo structure. (Image from Shah Hemp Inno-Ventures, “Hempcrete Construction.”)

Hemp-Lime Blocks - Pierre Chevet Sports Hall

Project Location:	*Croissy-Beaubourg, France*
Year Completed:	*2021*
Architect:	*Lemoal Lemoal*
Builder:	*Baticible Ventures*

Lemoal Lemoal architecture firm completed France's first public building constructed with hemp-lime blocks, the Pierre Chevet sports hall. The project highlights hemp as a sustainable and high-performance material. The hemp used is locally sourced, supporting short supply chains and reducing emissions. Typically finished with plaster, the hemp-lime blocks in this project are partially exposed to retain their acoustic benefits, while some facades are clad for easier maintenance. [46]

46
Parsons Healthy Materials Lab, "Designing with Hemp and Lime. Open-Source Detailing for Architects and Designers," 38-41.

Figure 7. Interlocking hemp-lime blocks. (Image from, Parsons Healthy Materials Lab, "Designing with Hemp and Lime. Open-Source Detailing for Architects and Designers," 38-41.)

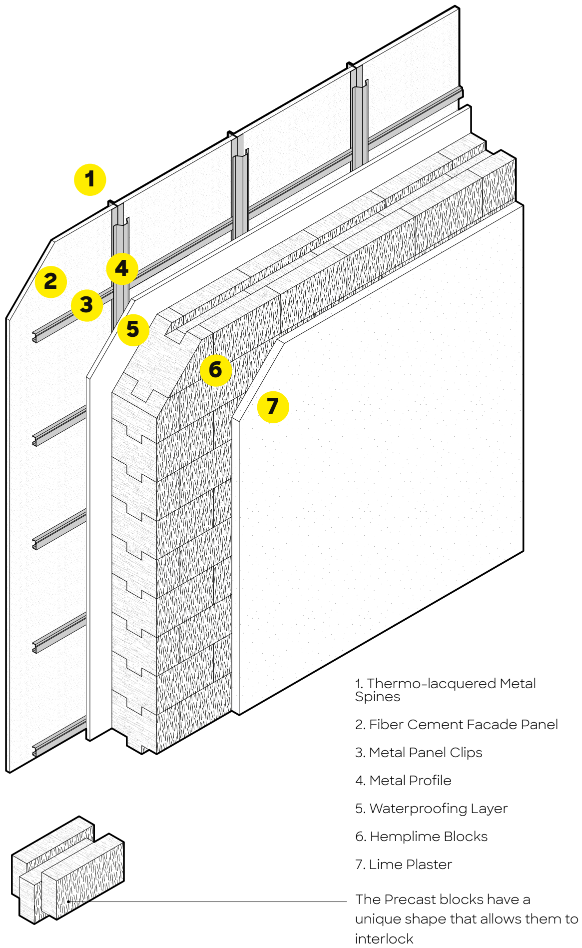

Figure 8. Isometric wall section - hemp-lime blocks. (Figure from, Parsons Healthy Materials Lab, "Designing with Hemp and Lime. Open-Source Detailing for Architects and Designers," 38-41.)

Hemp-Lime Blocks - Woonhuis Balk

Project Location: *Balk, Netherlands*
Year Completed: *2020*
Architect: *TWA Architecten*
Builder: *Agricola Bouw*

The project involved building a future-proof, energy-neutral home that meets passive house standards and is constructed using bio-based materials like hemp and wood. IsoHemp hemp-lime blocks were used on the exterior of a post-and-beam structure. These non-load bearing, prefabricated blocks were laid like traditional masonry. The interior was plastered with a hemp-lime plaster.[47]

47
Parsons Healthy Materials Lab, "Designing with Hemp and Lime. Open-Source Detailing for Architects and Designers," 50-51.

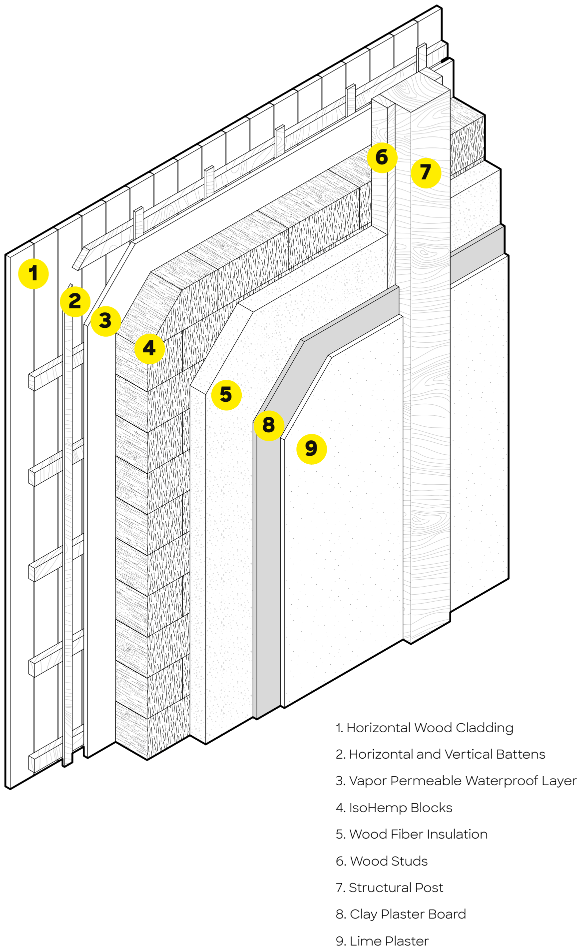

Figure 9. Isometric wall section - hemp-lime blocks. (Figure from, Parsons Healthy Materials Lab, "Designing with Hemp and Lime. Open-Source Detailing for Architects and Designers," 50-51.)

Figure 10. Woonhuis balk - house. (Image from, Parsons Healthy Materials Lab, "Designing with Hemp and Lime. Open-Source Detailing for Architects and Designers," 50-51.)

Prefabricated Hemp-Lime Walls - Flat House

Project Location: *Cambridgeshire, UK*
Year Completed: *2019*
Architect: *Material Cultures*

Flat House is a pioneering low-carbon home designed to showcase the potential of hemp in sustainable construction. The three-bedroom house uses prefabricated panels filled with hemp grown on the farm, with the entire structure assembled in just two days. The project introduced a new hemp fiber cladding, used for the first time in this building. The design demonstrates how hemp-based construction can be scaled up for larger housing projects, offering an eco-friendly alternative to conventional building materials.[48]

48
Architecture Today, "Flat House."

Figure 11. Inside view of Flat House. (Flat House by Material Cultures, photograph by Oskar Proctor. Source: Architecture Today, "Flat House.")

2.4. Material Classifications and International Standards

One of the main challenges for using hemp is the limited industry knowledge about the material. In Europe, hemp-lime has undergone fire testing, showing that it can resist fire for one to two hours depending on the materials thickness. Although hemp-composites have some structural properties, they are not considered structural materials. Their organic composition can lead to inconsistencies, making it difficult to predict performance.

For example, achieving the desired insulation level for a hemp-lime wall typically requires a wall thickness of approximately 300 mm. The insulation properties can vary based on how compacted hemp-lime is; if it is compressed too densely, the R-value reduces, while too little compression can lead to unnecessarily material intensive and costly construction.[49]

The International Residential Code (IRC) now includes specific guidelines for using hemp-lime in construction through the introduction of Appendix BL, titled *Hemp Lime (Hempcrete) Construction* in the 2024 edition. This appendix outlines the standards and requirements for incorporating hemp-lime as a building material in residential construction.

Key aspects include:

1. *Material Composition:* Hemp-lime, a mixture of hemp shives (the woody core of the hemp plant), lime, and water, is recognized as a non-load-bearing material. It is typically used for insulation and wall infill.
2. *Fire Safety:* The material is considered safe as it does not contribute flammable components during a fire.
3. *Insulation Properties:* The insulation value of hemp-lime can vary based on how densely it is packed during construction. Proper application is crucial to achieve the desired thermal performance.
4. *Construction Guidelines:* The appendix provides guidance on the correct application techniques, including wall thickness and compaction standards, to ensure optimal performance.

These updates mark a significant step forward in the acceptance of hemp-lime as a building material, offering a more formalized framework for its use in residential construction.[50]

2.5. Summary of Key Scientific Papers:

Asghari, Nima, and Ali M. Memari. 'State of the Art Review of Attributes and Mechanical Properties of Hempcrete'. Biomass 4, no. 1 (2 February 2024) https://doi.org/10.3390/biomass4010004.
The paper focuses on the potential of hempcrete as a sustainable building material. It examines hempcrete's environmental benefits, particularly its carbon-negative properties, and explores its potential to replace conventional materials like concrete. The paper also delves into hempcrete's compressive strength, discussing strategies to improve this characteristic and envisions hempcrete as a loadbearing material Overall, the paper positions hempcrete as a promising solution for environmentally conscious construction practices.

49
Malloy and Gonzalez, "Hemp and Lime, Examining the Feasibility of Building with Hemp and Lime in USA. Design and Demonstration," 73.

50
"Appendix BL Hemp-Lime (Hempcrete) Construction. 2024 International Resisdential Code (IRC)."

Marquardt, Sandra, and Liz Savage. "Growing Hemp for the Future. A Global Fiber Guide." Textile Exchange, July 2023. https://textileexchange.org/app/uploads/2023/04/Growing-Hemp-for-the-Future-1.pdf.
The paper examines the current state and potential future of hemp fiber production worldwide. It highlights hemp's environmental benefits, and discusses the challenges and opportunities as hemp production expands, including the potential for increased pesticide use and the need for sustainable farming practices. Additionally, it reviews the global production regions, the use of biological pesticides, and the processing of hemp to meet organic standards. The paper emphasizes the need for better traceability, research, and certification to support sustainability claims as the industry grows.

Visković, Jelena, Valtcho D. Zheljazkov, Vladimir Sikora, Jay Noller, Dragana Latković, Cynthia M. Ocamb, and Anamarija Koren. 'Industrial Hemp (Cannabis Sativa L.) Agronomy and Utilization: A Review'. Agronomy 13, no. 3 (21 March 2023): 931. https://doi.org/10.3390/agronomy13030931.
The paper explores the renewed interest in growing grain and fiber hemp, particularly after the legalization under the 2014 and 2018 Farm Bills in the USA. It examines the historical context of hemp cultivation, which was largely abandoned due to strict regulations, competition from synthetic fibers, and the *Green Revolution*. With hemp now legally grown in many countries, research has resumed, focusing on its potential as a sustainable crop. The paper highlights hemp's versatility, ability to absorb heavy metals, suppress weeds, and act as a carbon trap.

Walker, R., and S. Pavía. 'Moisture Transfer and Thermal Properties of Hemp– Lime Concretes'. Construction and Building Materials 64 (August 2014): 270–76. https://doi.org/10.1016/j.conbuildmat.2014.04.081.
The paper investigates the properties of hemp-lime. It focuses on how different types of binders (hydrated lime, pozzolans, hydraulic lime, and cement) affect the material's moisture and thermal behavior. The study concludes that binder type significantly influences capillary action, where hydraulic binders reduce capillary absorption. However, binder type has a lesser impact on permeability, which is more affected by the proportion of spaces between hemp particles. The thermal conductivity and heat capacity are not significantly affected by binder type, although a trend suggests that more hydraulic binders may reduce thermal conductivity and increase heat capacity.

Ahmed, A. T. M. Faiz, Md Zahidul Islam, Md Sultan Mahmud, Md Emdad Sarker, and Md Reajul Islam. 'Hemp as a Potential Raw Material toward a Sustainable World: A Review'. Heliyon 8, no. 1 (1 January 2022). https://doi.org/10.1016/j.heliyon.2022.e08753.
The paper discusses the urgent need to address global warming and climate change, which pose significant threats to biodiversity, human health, food security, and living standards. In response, there is a growing focus on finding sustainable solutions, including the regulation of green production practices, reducing CO_2 emissions, and promoting renewable resources. The paper highlights hemp as a promising renewable resource due to its versatility, short growth cycle, low cultivation costs, carbon-negative potential, and effectiveness in carbon sequestration.

3 Experiment: Materials and Methods

This study aimed to develop recipes for hemp-lime and hemp-earth building composites and was conducted under experimental laboratory conditions using basic equipment and manual procedures. Due to resource limitations, simplified, yet replicable methods were developed to evaluate key material properties. Six mixture designs were deduced, formed, compacted into samples, and allowed to dry. The samples were then tested to determine key performance parameters, including raw density, thermal conductivity, compressive strength, fire resistance, and environmental impact. The objective was to provide comparative insights under consistent conditions, emphasizing performance differences across the tested mixtures.

3.1 Recipe Development

To create recipes applicable in different global contexts and accounting for various external influencing factors, such as value chains and raw material qualities, three key variables were identified. These formed the basis for six distinct mix designs, presented in the form of testing series. The goal of this recipe development was to enable systematic comparisons of key parameters: binder type, hemp shiv size, and binder concentration. By understanding the influence and correlations of these variables, the results can serve as a guideline for further adaptation and refinement based on the specific context of application.

Key Variables

Binder

While lime is a well-established binder for hemp composites, research on alternative binders remains limited. The production of hydraulic lime generates substantial CO_2 emissions, primarily from the high-temperature decomposition of limestone, resulting in a high carbon footprint. Although lime can reabsorb CO_2 over its lifecycle (0.091 - 1.19 kg CO_2/kg) [51], the offset is only up to 38.83% of emissions emitted in production, leaving a significant gap.[52] Furthermore, large-scale mining for limestone depletes finite natural resources, relies on fossil fuels and contributes to biodiversity loss through the destruction of ecosystems.[53] In contrast, earth-based binders are abundant, require minimal processing energy and are infinitively recyclable when not mixed with hydraulic binders. This study proposes the direct comparison of lime- and earth-based binders in hemp composites to understand if earth is equally siutable as binder as lime.

Binder to Hemp Ratio

Recipes and proportions for hemp composites vary significantly across practitioners and manufacturers. Based on a literature review, a commonly used hemp to binder volumetric ratio is 3:1.[54, 55, 56, 57] This research compares the performance of higher hemp content in hemp-lime mixtures to the standard 3:1 ratio, with the goal of reducing the ecological footprint by decreasing the amount on lime. By evaluating the effects of different hemp to binder ratios

51
Arehart, Nelson, and Srubar III, 'On the Theoretical Carbon Storage and Carbon Sequestration Potential of Hempcrete', 2.

52
Bing et al., 'An Investigation of the Global Uptake of CO2 by Lime from 1930 to 2020', 2431.

53
Rhydwen, 'Building with Hemp and Lime', 1.

54
Ruus et al., 'Influence of Production on Hemp Concrete Hygrothermal Properties', 2.

55
Fernea et al., 'Hemp-Clay Building Materials - An Investigation on Acoustic, Thermal and Mechanical Properties', 218.

56
Allin, 'Best Practice Guide. Draft Version of International Standards for Hemp Building Materials and Systems.'

57
Asghari and Memari, 'State of the Art Review of Attributes and Mechanical Properties of Hempcrete', 76.

on material properties, this study assesses the impact of these formulations on both performance and ecological footprint.

Hemp Shiv Size
Hemp shives are a natural material, and its size varies depending on regional cultivation and processing methods. Since the shiv size can influence key material properties, incorporating this factor into this comparative experimental testing is essential for understanding its influence on material performance.

Raw Materials
The hemp shives used in this study were sourced from the French manufacturer Saint-Astier, specifically *Isocanna Hemp Shives* in two size ranges, 0.5–10 mm and 5–25 mm. The hydraulic lime used was NHL 3.5, specifically *Otterbein, Calcidur NHL 3.5* (EN 459-1 NHL 3.5). For the hemp-earth samples, the earth was obtained from a construction excavation site in *Berlin - Marzahn*. The clay content of the soil is 20 % with a well-graduated mix of silt, sand, and gravel.

The raw density of each material was determined during a preliminary assessment of the materials and are presented in table 1:

MATERIAL	RAW DENSITY (kg/m^3)
Earth	1283.0
NHL 3.5	614.8
Hemp Shiv 0.5 - 10	120.0
Hemp Shiv 5 - 25	129.2

Table 1. Raw densities of the materials used. (Table by author.)

Material Ratios
The hemp to binder ratios selected for comparison include 3:1 and 4:1 for hemp-lime mixtures, while for hemp-earth mixtures, only the 3:1 ratio was tested. This is because effective binding in earth mixtures is achieved by compaction, which is only possible if there is sufficient earth to fully coat and bind the hemp shives. A 4:1 ratio would overly dilute the binder, leading to a weaker mix that is prone to fragility and crumbling.

This volumetric proportions were translated into weight-based quantities and calculated according to the sample volume. Volume based ratios are commonly referred to, as they are practical on the construction site for large scale batches, but not suitable for the laboratory environment.

As specified in the mixing guidelines for NHL 3.5 lime and supported by findings from previous research, the amount of water added was in a 1:1 ratio by volume to lime. Based on previous research, the binder to water ratio for hemp-earth mixtures was determined to be at a volumetric ratio of 1:0.4. This ratio was used as the baseline for producing the hemp-earth samples.

3.2 Production Process

Formwork
A cubic form was chosen for the samples to ensure consistent testing conditions across all samples. The samples, each measuring 140 mm × 140 mm × 140 mm, were produced using a formwork as illustrated in fig. 12.

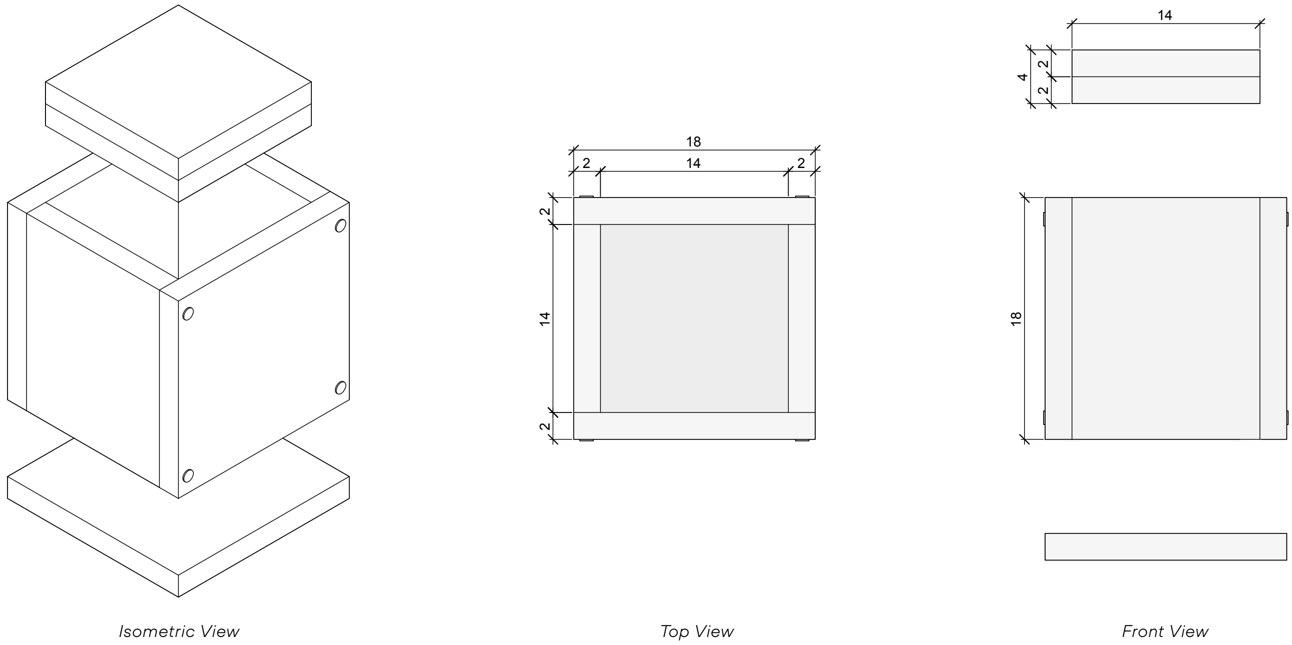

Figure 12. Drawing of formwork (measurements in cm). (Image by author.)

Mixture Preparation

The mixtures were prepared for each testing series, with eight samples per series.

Hemp + Lime

The preparation process followed the same sequence across all series:

1. The hemp shives were combined with half the required amount of water and mixed for approximately two minutes until evenly moistened.
2. A paddle mixer attached to a cordless drill was used for this purpose. The full amount of lime was carefully added to the mixture.
3. The consistency was adjusted by adding the remaining water.
4. The mixture was continuously mixed for three minutes. The total working time depended on the binder; for NHL 3.5, it was limited to a maximum of 30 minutes.

Hemp + Earth

The sequence remained consistent across all mixtures:

1. The soil was moistened 24 hours prior to use to activate its binding properties. Half of the total required water was added to achieve a damp, plastic consistency of the earth. To minimize evaporation and retain moisture, the container was covered with a plastic tarp.
2. The hemp shives were then combined with the remaining half of the water and manually mixed for two minutes until evenly moistened.
3. A paddle mixer attached to a cordless drill was used for mechanical mixing of the shives.
4. The full amount of hemp shives was gradually added to the previously moistened soil, mixing continued until the hemp shives were uniformly coated with the soil mixture.

Forming and Compacting

To determine the compression rate, an initial wet weight analysis was performed on both the hemp-lime and hemp-earth mixtures. The analysis involved applying a specific weight to the mixture to achieve a controlled compression. A cylindrical measurement tool with a surface diameter of 6 cm was used for this purpose. Preliminary samples were prepared with varying compaction levels, and the most suitable compaction levels were selected based on visual assessment and handling characteristics, which served as the basis for the mix design.

The mixtures were subsequently placed and compacted in layers into formwork, with each layer reaching an approximate height of 3-4 cm after compression. For the hemp-lime mixtures, a total weight of 16 kg was applied during the wet weight analysis, corresponding to a pressure of 0.57 kg/cm². This level of compression reflects manual techniques, such as tamping or pressing with moderate effort. This weight application resulted in varying volume reductions across the series (see results section, table 4).

In contrast, the hemp-earth mixtures required higher pressure to ensure a uniform binding of the components. Due to equipment limitations, the hemp-earth mixtures could not be analyzed in the same way. Instead of using weights, manual pressure was applied until a cohesive binding was achieved.

Figure 13. Wet weight analysis. (Image by author.)

Removing Formwork
When the required height of 14 cm was reached, the formwork was carefully removed by pressing the lid downward while simultaneously lifting the formwork. Due to the material's fragility in its wet state, the samples were not touched or handled until they were fully dried.

Drying Process
The samples were left to dry for 28 days to ensure adequate mechanical strength of the hemp composite materials. This duration ensures the carbonation of lime, which is essential for achieving structural integrity. This specific curing period has been identified as a critical threshold in a previous study on the physico-mechanical properties of hempcrete materials.[58] Additionally, the technical sheet for NHL 3.5 lime, provided by the manufacturer, recommends a minimum setting time of 28 days.[59]

The drying area was maintained at a temperature of 18 °C, with adequate air circulation ensured throughout the process.

3.3 Experimental Testing

To analyze the material's properties and its suitability for construction applications, an experimental testing procedure was designed. Five key testing parameters were defined to evaluate the material's overall performance.

Raw Density
Determining the raw density of the material is essential for quality control, structural integrity, and compliance with industry standards. It influences key properties such as compressive strength, thermal insulation, and overall durability. Raw density also provides insights into the material's porosity, which affects moisture resistance and long-term performance, while being crucial for optimizing formulations and balancing the strength to weight ratio.

Method
The raw density was determined by measuring and weighing the samples with nominal dimensions of 140 mm × 140 mm × 140 mm. The values were taken after a drying period of 28 days. The mass was determined using a scale, with an accuracy of 0.5 g. The dimensions were measured with a caliper, and the height of all four sides of each sample was averaged to account for surface inconsistencies.

Testing Procedure
For each test series, the average dry weight, dry weight standard deviation, and average raw density were analyzed to assess material consistency.

Thermal Conductivity
Evaluating the thermal conductivity of the material is essential to determine its thermal insulation properties and assess its suitability for insulation applications. Thermal conductivity, along with the resulting thermal transmittance (U-value), are key performance indicators that directly influence energy efficiency and thermal comfort.

58
Adam and Isopescu, 'Physico-Mechanical Properties Investigation of Hempcrete', 80.

59
'Technisches Merkblatt CALCIDUR® NHL 3,5 Natürlich Hydraulischer Kalk EN 459-1 NHL 3,5'.

Method
The material samples were tested using the *Meter Tempos Thermal Properties Analyzer* with a *KS-3 sensor*, with measurements conducted at a depth of 60 mm within the sample. Thermal conductivity was measured in W/m·K. For each sample, three valid measurements were taken at different points of the sample to ensure accuracy, while two samples per series were tested. Based on the average of these values, the U-value (thermal transmittance) for a 300 mm wall thickness was determined. The calibration of the thermal analyzer was conducted using glycerin with a known thermal conductivity of 0.285 W/m·K.

To ensure compliance with regulatory standards, the thermal transmittance (U-value) of the materials was evaluated with reference to the maximum allowable limits for exterior walls in new buildings as specified by German building regulations. The *Gebäudeenergiegesetz (GEG)*, establishes a maximum U-value of 0.24 W/(m²·K), which was used as a benchmark for the results. [60]

Testing Procedure and Calculation
The testing was carried out at an ambient temperature of 18 °C. The thermal conductivity (λ) of each sample was measured in W/m·K. The U-value (thermal transmittance) was then calculated using the following formulas:

λ = thermal conductivity (W/m·K)
d = material thickness (mm)
U = thermal transmittance (W/m²·K)

$R = d/\lambda/1000$
$U = 1/R$

Compressive Strength
The composites' compressive strength was determined to ensure its ability to support its own weight and maintain structural stability as part of a standard masonry assembly under realistic conditions. Since the material is intended for non-load-bearing walls, a minimum required compressive strength was defined, considering the material's density. The material was hence not tested for its breaking load.

Method
The compressive load of a wall with dimensions of 300 cm × 300 cm × 30 cm served as the basis for determining the minimum required compressive strength of the material. The calculations were based on the maximum raw density observed in the HE3L series, with a value of 516.7 kg/m³. The required compressive strength was calculated by translating the wall load and scaling it to match the sample size.

A maximum deformation of 3 mm was defined to ensure the structural integrity of the samples during testing, this limit applied under the condition that no cracking or structural failure occurred. Both structural failure and deformation were documented in the layering and rotated directions.

60
'Anlage 7 (zu § 48) Höchstwerte der Wärmedurchgangskoeffizienten von Außenbauteilen bei Änderung an bestehenden Gebäuden'.

To account for material variability and ensure reliability, a safety factor of 2.5 was applied. As general recommendations for the appliance safety factors are outlined, *"for use with less tried and for brittle materials where loading and environmental conditions are not severe"* a value of 2.5-3 is suggested.[61]

Calculation

H = height of wall (m)
W = width of wall (m)
T = thickness of wall (m)
V = volume of the wall (m^3)
ρ = raw density (kg/m^3)
g = gravitational acceleration (m/s^2)
F_g = weight force (N)
σ = compressive load (N/mm^2)

$V = H \cdot W \cdot T$
$V = 3 \cdot 3 \cdot 0.3 = 2.7\ m^3$
$F_g = V \cdot \rho \cdot g$
$F_g = 2.7 \cdot 516.7 \cdot 9.81 = 13685.8\ N$
$\sigma = F_g / (L \cdot T)$
$\sigma = 13685.8 / (3 \cdot 0.3) = 15206.4\ N/m^2$
$\sigma_{min} = \sigma \cdot 2.5 = 38016.1\ N/m^2 = 0.038\ N/mm^2$

Required load application derived from minimum compressive strength:

F = force (N)
A = area of sample (m^2)
m = mass (kg)

$F = \sigma_{min} \cdot A$
$F = 38016.1 \cdot 0.0196 = 745.5\ N$
$m = F / g$
$m = 745.5 / 9.81 = 76\ kg$

Testing Procedure

The samples were tested along the direction of production, where the load was applied in the same direction as during layering, as well as in the rotated orientation, where the material was loaded on surfaces that were not directly compacted during production (layering direction - rotated direction).

To ensure uniform load distribution, a stiff plate was placed on both the bottom and top of the sample. For each of the six test series, three samples were tested to vertical compression loads using weights, the loading was done with bricks of an average weight of 4820g. The load was applied until the required weight was reached or failure occurred.

A series was considered to have passed the test only if all three specimens exhibited no structural failure and maintained deformation ≤ 3 mm, specifically in the layering direction. Deformation or failure in rotated directions was not considered in the evaluation.

61
Engineering ToolBox, 'Factors of Safety - FOS'.

Figure 14. Load application. (Image by author.)

Figure 15. Monitoring deformation. (Image by author.)

Fire Resistance

The evaluation of the material's fire resistance ensures its safety performance and compliance with building regulations. Understanding the material's reaction to prolonged flame exposure is crucial for determining its suitability for construction applications and required fire safety criteria. Fire safety requirements for insulation materials depend on building type, use, and local regulations. A high fire classification is pursued to ensure the material's versatility for different applications.

Method

The fire resistance of the material was assessed in reference to the fire resistance classification outlined in EN 13501-1 [62], the European standard for the fire classification of construction products. This standard defines the testing methodology for evaluating the fire performance of materials by considering their combustibility, smoke production, and the occurrence of flaming droplets. The EN 13501-1 standard divides materials into different classes based on their fire resistance characteristics, as shown in table 2. For non-combustible materials or those with limited combustibility, classes A1, A2, and B are used.[63]

62
Distributor of Tristone™ Solid Surface - Tristone UK Limited, 'Fire Ratings Explained'.

63
Kaukanen, "EN 13501-1 Fire Classification | Performance Classes & Criteria | Measurlabs."

Definition	Grade	Smoke Propagation	Flaming Droplets
Non-Combustible Materials	A1	-	
	A2	s1	d0
		and all variations	
Combustible materials: Very limited contribution to fire	B	s1	d0
		and all variations	
Combustible materials: Limited contribution to fire	C	s1	d0
		and all variations	
Combustible materials: Medium contribution to fire	D	s1	d0
		and all variations	
Combustible materials: High contribution to fire	E	E-d2	
Combustible materials: Easily flammable	F		

Table 2. Fire resistance rating according to EN 13501-1. (Source: Tristone UK Limited, "Fire Ratings Explained.")

Testing Procedure
The fire resistance of the samples was tested using a jet flame *(CFH, Lötmeister LM 1000)*, exposing the material to a direct flame for 30 minutes. Throughout the test, the temperature of the surfaces of the samples were observed and documented. The analysis focused on combustibility, smoke production, and flaming droplets, with the evaluation conducted in reference to the fire resistance classification outlined in EN 13501-1. The flame reached temperatures of approximately 650 °C, while the tests were performed outdoors under an average ambient temperature of 5 °C. For this assessment, one test sample from each of the six series was tested.

Life Cycle Assessment (LCA)
The LCA was conducted to evaluate the environmental footprint of each series, focusing on variations in ecological impact between different formulations.

Method
Since the scope of the research focuses on the material development, only the Global Warming Potential (GWP) of the raw materials within stages A1-A3 (raw material extraction, transport, and manufacturing) was considered and proportionally assigned to the respective composite mixtures. However, it is important to note that the calculation does not account for the transportation of materials to the experimental site or the production process of the samples themselves, as this study is based on an experimental setup and does not represent a realistic construction context. In this experiment the production of the samples caused no additional CO_2 emissions.

Analysis
Data for each material was sourced from literature and open databases, with the environmental impact calculated in kg CO_2-equivalent per m^3 for each series.[64] The GWP of each material was proportionally scaled based on the ratio within the mixture of each series.

For comparison, GWP data (A1–A3) for conventional insulation materials was sourced from the german *Ökobaudat* database.[65]

64
Earth: Ökobaudat 2018, Stampflehmwand
Lime: EPD Danmark 2023, Lime NHL 3.5
Hemp shives: Arehart, Nelson, and Srubar III, 'On the Theoretical Carbon Storage and Carbon Sequestration Potential of Hempcrete', 7.

65
EPS: Ökobaudat 2023, Blaugelb Dämmplatten EPS
XPS: Ökobaudat 2018, XPS-Dämmstoff
Mineral Wool: Ökobaudat 2023, Mineralwolle (Fassaden-Dämmung)
Wood Fiber: Ökobaudat 2023, Holzfaser-Einblasdämmstoff (Durchschnitt DE)

66
One Click LCA Help Centre. 'Life Cycle Stages'.

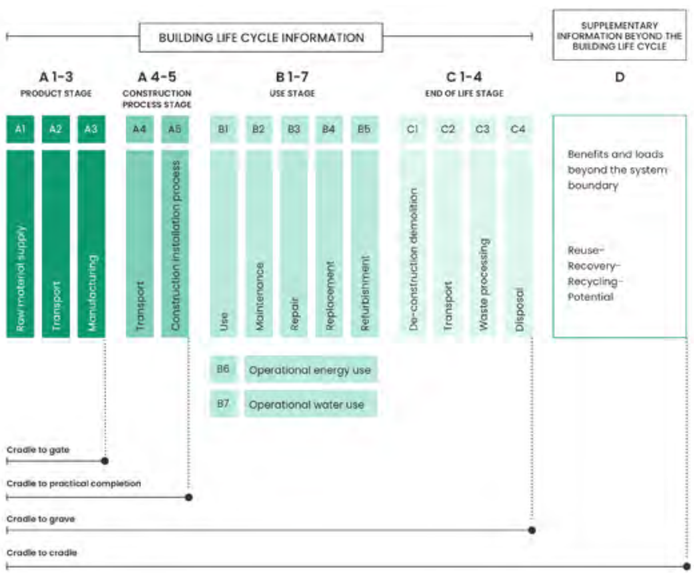

Figure 16. Life Cycle Assessment overview. (Image from One Click LCA Help Centre, "Life Cycle Stages.")

4 Results and Discussion

4.1 Recipe Development

Based on the key parameters the mix design was conducted, yielding six series to control for each variable, as shown in table 3. Each series includes eight samples, resulting in a total of 48 samples (see fig. 17).

SERIES* (mm)	RATIO (hemp : binder : water)	SHIV SIZE (mm)	BINDER (lime | earth)
HL3S	3 : 1 : 1	0.5 - 10	Lime
HL4S	4 : 1 : 1	0.5 - 10	Lime
HL3L	3 : 1 : 1	5 - 25	Lime
HL4L	4 : 1 : 1	5 - 25	Lime
HE3S	3 : 1 : 0.4	0.5 - 10	Earth
HE3L	3 : 1 : 0.4	5 - 25	Earth

**HL: Hemp-Lime, HE: Hemp-Earth, 3: 3:1 Hemp to Binder, 4: 4:1 Hemp to Binder, S: Small Shives, L: Large Shives*

Table 3. Mix design. (Table by author.)

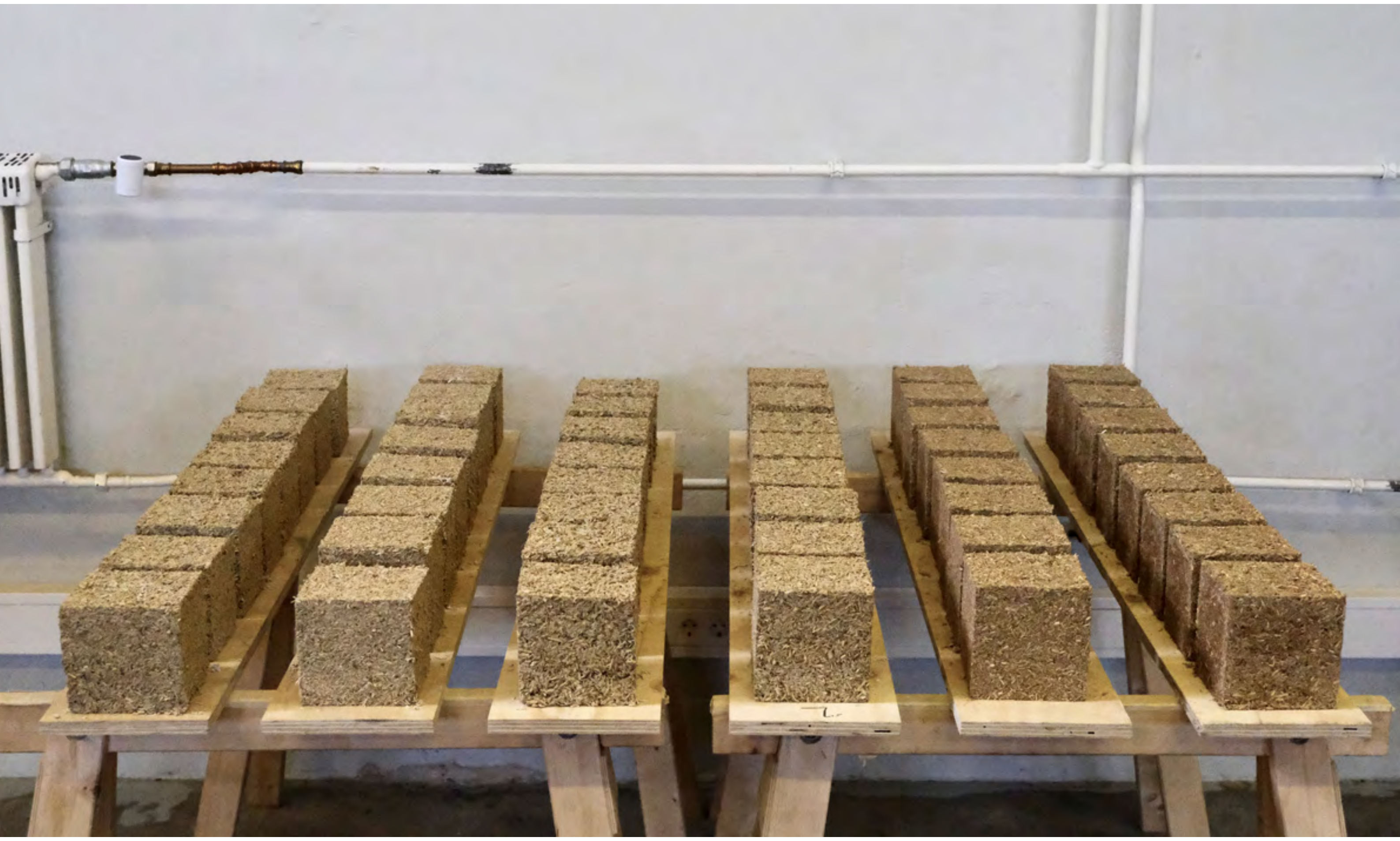

Figure 17. Mix design - HL3S, HL4S, HL3L, HL4L, HE3S, HE3L (from left to right). (Image by author.)

Figure 18. Hemp shives 0.5 -10 mm (HL4S). (Image by author.)

Figure 19. Hemp shives 5 -25 mm (HL4L). (Image by author.)

Figure 20. Hemp-lime samples - close up. (Image by author.)

Figure 21. Hemp-earth samples - close up. (Image by author.)

The quantities for each test series were converted into mass ratios (see table 4) and based on the dry density of each material, a weight based recipe was deduced. The predetermined weight load was applied during the production of the samples and the resulting compression was expressed as percentage of volume reduction for each series. This applied load resulted in varying degrees of volume reduction across the mix designs, with the hemp-lime mixtures showing an average reduction of 9.3 % from their uncompressed to compressed states. However, the HL3L mix exhibited a significantly lower compression ratio of just 3%, while the mixtures HL3S, HL4S and HL4L exhibited compression rates between 12% and 14%. The hemp-earth mixtures, required higher compression to achieve cohesive binding, resulting in a volume reduction of 29% in both series.

SERIES	HEMP (g)	LIME (g)	EARTH (g)	WATER (g)	TOTAL WET WEIGHT (g)	COMPRESSION RATE (%)
HL3S	271.0	463.0	-	753.0	1487.0	12
HL4S	291.5	373.5	-	608.0	1273.0	13
HL3L	286.5	454.5	-	739.0	1480.0	3
HL4L	313.5	373.0	-	606.5	1293.0	14
HE3S	319.5	-	1138.0	355.0	1812.0	29
HE3L	345.0	-	1143.5	356.5	1845.0	29

Table 4. Weight and compression per sample. (Table by author.)

The ratio of water to earth appears to be a critical factor. Samples with a 1:1 water to binder ratio began developing white mold on their surfaces within one day, which continued to spread (see fig 22). Conversely, if the water content is too low (<0.4), the clay is insufficiently activated to bind the hemp shives effectively. The goal is to use the minimum amount of water necessary to achieve proper binding without promoting mold growth or compromising the integrity of the earthen material.

The compression rate results for the HL3L series exhibited inconsistencies, likely due to the delayed water absorption of the large hemp shives, combined with the 3:1 hemp to water ratio, which resulted in a more liquid lime-water mixture. This increased fluidity affected the consistency of the mixture during compression and influenced the calculation of volume reduction from the uncompressed to the compressed state. These factors contributed to variations in the observed results (see table 4).

Figure 22. Mold on hemp-earth specimen with water to earth ratio 1:1. (Figure by author.)

4.2 Production Process

To prevent premature setting, the mixing process was conducted in batches not exceeding four samples at a time. The required quantities were scaled accordingly while mantaining the proportions across all samples.

Mixtures containing larger hemp shives (5–25 mm) appear to have higher moisture levels than mixtures with smaller shives, often exhibiting visible bubbles and a fizzing sound. This indicates reduced water absorption capacity in larger shives, likely due to their lower specific surface area and reduced ability for capillary transport. These findings are supported by previous studies, suggesting that smaller or finer hemp shives absorb and retain water more effectively.[67]

The hemp-earth mixtures required an extended mixing time due to the damp nature of the earth. Initially, the earth formed clumps and did not bond well with the hemp shives, requiring multiple mixing cycles to achieve uniform coating. (see fig 23-25)

67
Ruus et al., 'Influence of Production on Hemp Concrete Hygrothermal Properties', 5.

Figure 23. Mixing hemp-earth composite. (Image by author.)

Figure 24. Unevenly mixed hemp-earth. (Image by author.)

Figure 25. Well mixed hemp-earth. (Image by author.)

The weight application method for the wet weight analysis was ineffective for hemp-earth mixtures, as the required weights exceeded the capacity of the testing equipment. Placing weights directly on the top surface led to inaccurate results, as compaction only occurred at the uppermost layer. The narrow cylindrical shape caused the hemp-earth mixture to become stuck, resulting in uneven compaction.

For the hemp-lime mixture with a low compression rate, the pressure applied when pressing the lid through the formwork was somewhat uncontrollable, leading to variations in height and uneven top surfaces. In the case of the hemp-earth samples, the mixtures were relatively damp and compressed to a higher level, making it challenging to press the sample through the formwork. The formwork needed to be cleaned and moistened before filling it with the hemp-earth mixture.

Figure 26. Compacting process. (Image by author.)

Figure 27. Removing formwork. (Image by author.)

4.3 Performance Evaluation

Raw Density

SERIES	DRY WEIGHT RANGE (g)	AV. DRY WEIGHT (g)	ST. DEVIATION (dry weight)	AV. RAW DENSITY (kg/m³)	WATER LOSS (g)
HL3S	795 - 810.5	803.3	6.6	301.5	683.7
HL4S	740 - 757	747.3	5.8	268.5	525.8
HL3L	791 - 810	803.1	6.5	299.6	676.9
HL4L	751.5 - 765.5	756.3	5.0	267.6	536.7
HE3S	1430.5 - 1435	1432.8	1.8	501.2	379.2
HE3L	1479 - 1492	1485.5	1.6	509.6	359.5

Table 5. Raw density, dry weigth, standard deviation, water loss. (Table by author.)

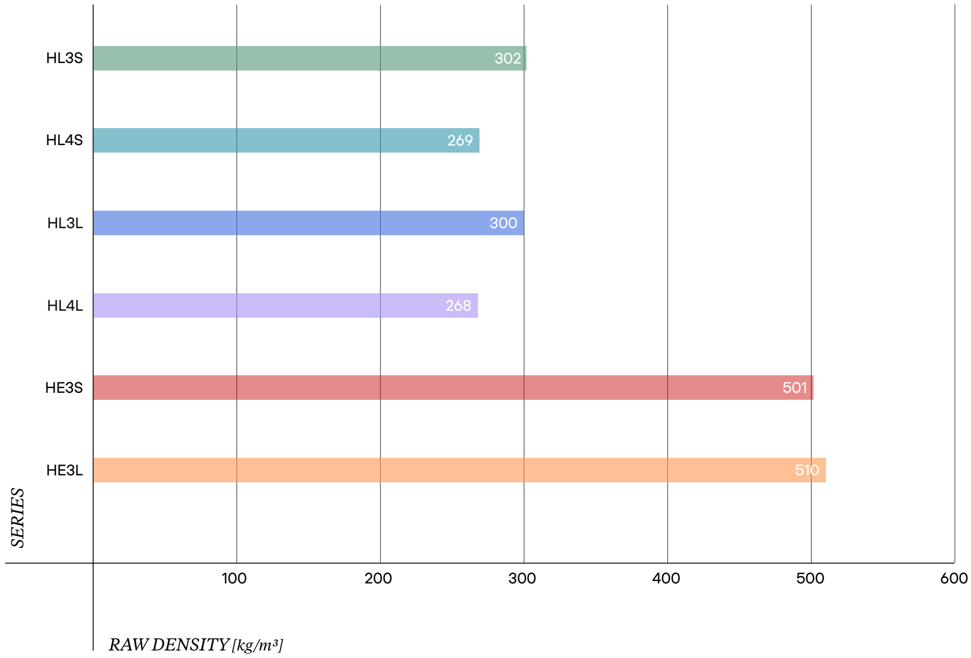

Figure 28. Comparison of raw densities . (Image by author.)

As shown in table 5 and fig. 28, hemp-earth mixtures (HE) display higher average densities than hemp-lime mixtures (HL). Hemp-earth samples (HE3S and HE3L) exhibited significantly higher dry weights (1430.5 - 1492 g) and average densities (509.6 / 501.2 kg/m³) compared to hemp-lime samples (267.6 – 301.5 kg/m³), reflecting the denser structure and higher compaction level of earth-based mixtures.

Furthermore, it can be noted that the mixture ratio of 4:1 hemp to lime (HL4S, HL4L) results in a lower density compared to the 3:1 hemp to binder, due to the higher hemp content, which has a lower density compared to lime.

Additionally, mixes containing larger hemp shiv sizes (HL3L, HL4L) exhibited slightly lower densities compared to those with smaller shiv sizes. Previous studies support this finding, suggesting that larger hemp shives create larger air pockets, reducing compaction and density. However, this trend does not apply to hemp-earth mixtures. In the case of hemp-earth samples, the mixture with larger hemp shives (HE3L) exhibited a higher average density than the one with smaller shives (HE3S). The initial wet weight was higher for the smaller shives (HE3S: 1892g - HE3L: 1845.1g), but the average dry weight was lower than that of the mixture with larger shives (HE3S: 1432.8g - HE3L: 1485.5g). This discrepancy could be attributed to differences in water absorption properties based on shiv size or a higher compaction level in mixtures with larger shives. As suggested in previous studies, smaller particles may achieve better binder coating, thus requiring less compaction.[68] Further research is necessary to confirm this conclusion.

HL3S showed the highest standard deviation of the dry weights (6.6 %), indicating inconsistencies in compaction or material distribution. In contrast, HE3S had the lowest standard deviation (1.8 %), suggesting a more uniform mixture with better cohesion. The higher variance could be attributed to fluctuations in compaction methods during production, influenced by the experimental setting.

Thermal Conductivity

SERIES	THERMAL CONDUCTIVITY (W/m·K)	MATERIAL THICKNESS (mm)	R -VALUE (m^2·K/W)	U -VALUE (W/m^2·K)
HL3S	0.044	300	6.869	0.146
HL4S	0.033	300	8.983	0.111
HL3L	0.037	300	8.125	0.123
HL4L	0.020	300	15.084	0.066
HE3S	0.057	300	5.251	0.190
HE3L	0.051	300	5.937	0.168

Table 6. Thermal conductivity, thermal transmittance (U-value). (Table by author.)

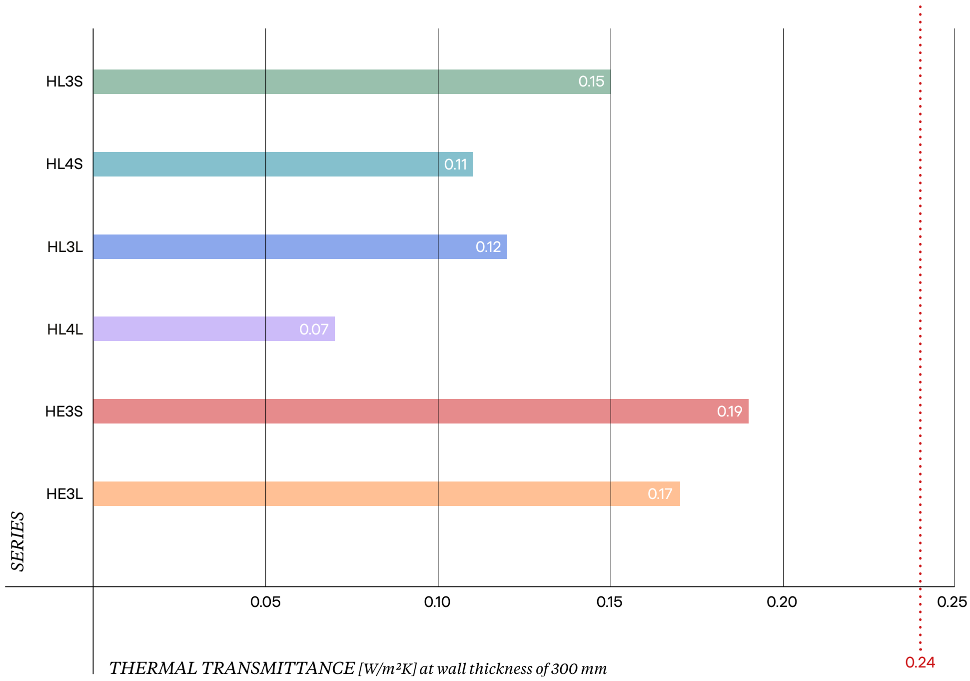

Figure 29. U-values for 300mm wall thickness . (Image by author.)

The results presented in table 6 indicate that hemp-lime mixtures (HL series) exhibit lower thermal conductivity compared to hemp-earth mixtures (HE series), therefore showing better insulation properties. HL4L has the lowest thermal conductivity at 0.020 W/m·K, whereas HE3S has the highest at 0.057 W/m·K. The R-value (thermal resistance) and U-value (thermal transmittance) further support these findings. HL4L, which has the lowest thermal conductivity, also achieves the highest R-value (15.09 m^2·K/W) and the lowest U-value (0.066 W/m^2·K). In contrast, HE3S has the lowest R-value (5.25 m^2·K/W) and the highest U-value (0.19 W/m^2·K), making it the least effective insulator of the series.

68
Ahmed et al., 'Hemp as a Potential Raw Material toward a Sustainable World', 11.

It can be noted that all tested samples remain below the target U-value of 0.24 W/m²·K if adjusted to a wall thickness of 300 mm, as illustrated in fig. 29. All mixtures except for HE3S could even be applied at a thickness of 200mm and still meet the 0.24 W/m²·K target. The verification measurements showed a deviation of around 8.7% (0.250 W/m·K), which must be considered in the results of the series.

Correlation Shiv Size - Thermal Transmittance
Mixtures containing larger hemp shives (HL3L, HL4L, HE3L) exhibit lower U-values compared to those with smaller hemp shives (HL3S, HL4S, HE3S), as illustrated in fig. 30. This suggests that larger shives generate more air pockets, thereby enhancing insulation properties. These findings align with previous studies, which indicate that smaller shives tend to form a more homogeneous and compact structure due to their arrangement.[69, 70] Compared to mixtures with small hemp shives, those containing large hemp shives exhibit an average U-value that is 0.03 W/m²·K lower. Specifically, the average U-value for mixtures with large shives is 0.12 W/m²·K, compared to 0.15 W/m²·K for mixtures with small shives.

Correlation Raw Density – Thermal Transmittance

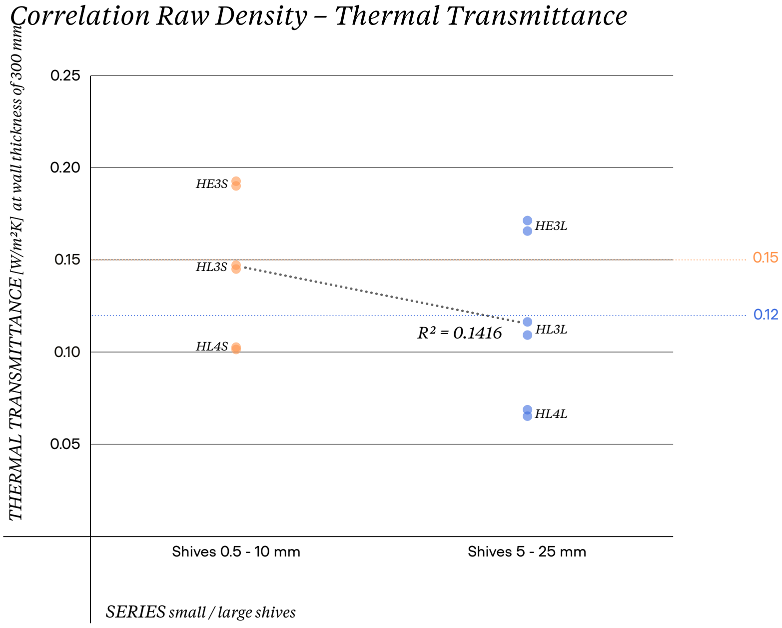

Figure 30. Correlation shiv sizes and U-value. (Image by author.)

A direct correlation between raw density and thermal transmittance is observed, as illustrated in fig. 31. Lower raw density is associated with enhanced thermal performance. Among the samples, HL4L exhibits the lowest raw density and the lowest thermal transmittance value. These findings align with previous studies, which have demonstrated a linear relationship between raw density and thermal conductivity.[71, 72]

A lower raw density indicates a greater presence of air pockets within the material, which enhances its insulating properties. The results suggest that reduced compaction rates facilitate increased air entrapment, thereby improving insulation efficiency. Furthermore, the presence of larger hemp shives contributes to lower compaction, exhibiting lower densities and therefore further enhancing thermal properties.

As previously discussed, larger hemp shives do not necessarily lead

69
Brzyski et al., 'Influence of Hemp Shives Size on Hygro-Thermal and Mechanical Properties of a Hemp-Lime Compo-site', 9.

70
Adam and Isopescu, 'Physico-Mechanical Properties Investigation of Hempcrete', 82.

71
Adam and Isopescu, 81.

72
Abdellatef et al., 'Mechanical, Thermal, and Moisture Buffering Properties of Novel Insulating Hemp-Lime Composite Building Materials', 10.

to lower density in earth-hemp mixtures. However, the HE3L series, which incorporates larger hemp shives, exhibits a lower U-value compared to HE3S. This observation indicates that the typical correlation between low raw density and low thermal transmittance does not apply in this case.

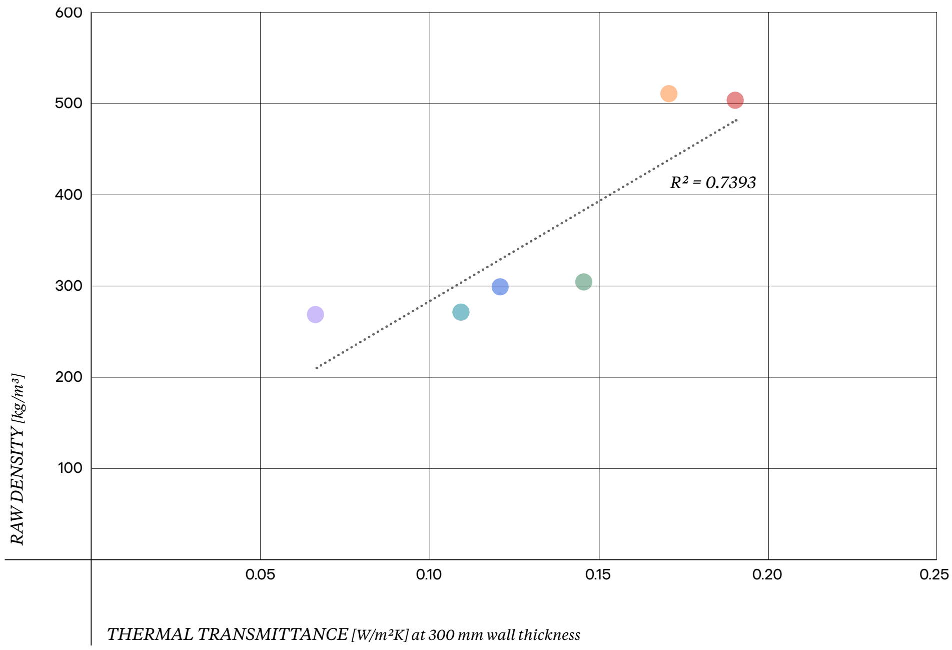

Figure 31. Correlation raw density and thermal transmittance (U-value). (Image by author.)

Compressive Strength

SERIES	DEFORMATION L.D. (mm)	DEFORMATION R.D. (mm)	STRUCTURAL FAILURE L.D. (out of 3 samples)	STRUCTURAL FAILURE R.D. (out of 3 samples)	RESULT (pass | fail)
HL3S	1.5	1.6	0	1	pass
HL4S	1.9	-	0	3	pass
HL3L	1.2	2.3	0	0	pass
HL4L	2.4	1.8	0	1	pass
HE3S	3.2	2.4	1	1	fail
HE3L	4.0	4.0	0	1	fail

** L.D.= Layering Direction, R.D.= Rotated Direction*

Table 7. Compressive strength. (Table by author.)

The analysis of the compressive strength testing (see table 7) shows inconsistency in the results. However, certain correlations of parameters were observed.

The HL4S series exhibits notable differences in structural behavior between the layering and rotated direction. While all samples within the series passed the test in the layering direction, none withstood the load when tested in the rotated direction. This suggests that mixtures with the combination of small shives and high hemp content have weaker binding properties between compacted layers.

Furthermore, samples from the HE (hemp-earth) series were generally more fragile and showed greater deformation in height (2.4-4.0 mm) during load application. This increased deformation occurred only during load application, with the material partially recovering its height after the load was released. The only sample that failed the compressive strength test in the layering direction is from the HE3S series, emphasizing the material's fragility of HE mixtures. The presence of loose shives and structural weakness suggests that earth-based binders may require improved processing methods or improved compositions to enhance its performance. Overall, hemp-lime mixtures (HL) show better structural integrity than hemp-earth mixtures (HE).

Correlation Compressive Strength - Shiv Size
Fig. 32 further supports the finding that mixtures containing smaller hemp shives exhibit weaker structural properties, underscoring the correlation between shiv size and compressive strength. This indicates that larger hemp shives contribute to stronger, more cohesive structures.It must be noted, that in fig. 32 deformation of the samples was not considered. The graph shows structural failure in either layering or rotated direction (<0.035 N/mm² / >0.035 N/mm²), in both directions (<0.035 N/mm²) or no structural failure (>0.035 N/mm²).

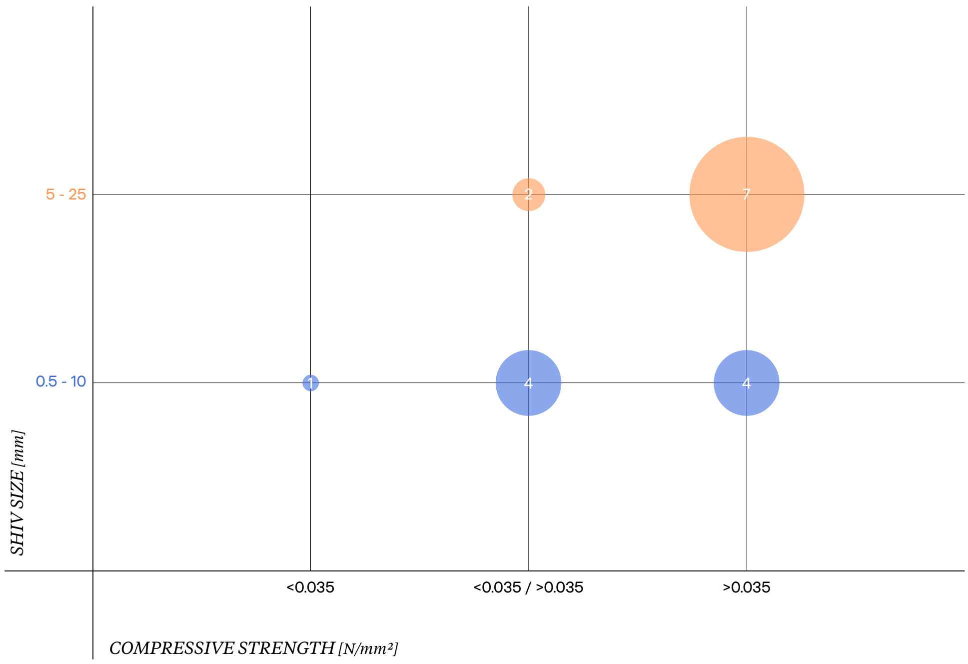

Figure 32. Correlation compressive strength and shiv size. (Image by author.)

Fire Resistance
All series demonstrated adequate fire resistance, making them suitable as an insulation material. The results of the fire restistance tests showed, that all series exhibited low flammability and withstood 30 minutes without fire ignition. These findings are consistent with previous studies, which involved longer duration flame resistance tests.[73]

In reference to the fire resistance rating outlined in EN 13501-1 following results were achieved:

Hemp-Lime (HL3S, HL4S, HL3L, HL4L)
The material exhibits properties that align with the requirements for B-s1, d0 fire resistance classification under EN 13501-1, showing very limited combustibility, minimal smoke production, and no flaming droplets or particles.

73
Shewalul et al., 'Fire Behavior of Hemp Blocks', 8,7,15.

These results align with the performance of various hemp-lime composite products currently on the market, such as Hempcrete blocks from IsoHemp or Hemlith, which are certified with a B-s1, d0 fire classification.[74, 75]

Figure 33. Fire resistance test - hemp lime (HL). (Image by author.)

Figure 34. Fire resistance result - hemp lime (HL). (Image by author.)

Hemp-Earth (HE3S, HE3L)

In the case of the hemp-earth series, the materials exhibited slightly better fire resistance compared to the hemp-lime series. The observed properties align with the requirements for an A2-s1, d0 fire classification, indicating that the material is virtually non-combustible, produces minimal smoke, and generates no flaming droplets or particles.

These results are further supported by a previous study, which found that hemp-earth composites did not ignite under testing conditions and remaied non-flammable.[76]

Figure 35. Fire resistance test - hemp lime (HL). (Image by author.)

Figure 36. Fire resistance result - hemp lime (HL). (Image by author.)

74
"Technisches Merkblatt, Hemplith® Hanfsteine."

75
IsoHemp, "Hanfstein für eine natürlich leistungsfähige Mauerwerkskonstruktion."

76
Laborel-Préneron et al., 'Fire Behavior of Bio-Based Earth Products for Sustainable Buildings', 164.

Life Cycle Assessment, GWP (A1-A3)

SERIES	HEMP (kg CO_2 e/m³)	BINDER (kg CO_2 e/m³)	TOTAL (kg CO_2 e/m³)
HL3S	-171.4	35.6	-135.8
HL4S	-184.4	28.7	-155.7
HL3L	-181.3	34.9	-146.3
HL4L	-198.3	28.7	-169.7
HE3S	-202.1	2.1	-200.1
HE3L	-218.3	2.1	-216.2

Table 8. LCA, GWP total of raw materials (kg CO_2e/m³). (Table by author.)

The analysis of the GWP of the raw materials for modules A1-A3 indicates a negative CO_2e per cubic meter for all series, ranging from -135.8 to -216.2 kg CO_2e/m³, as shown in table 8. The lowest value was achieved in the HE series, with HE3L showing a GWP of -216.2 kg CO_2e/m³. The highest ecological impact, disregarding the biogenic storage of hemp, was observed in the HL3S series, where the lime component contributed 35.6 kg CO_2e/m³, while the HE3L series showed the lowest impact with 2.1 kg CO_2e/m³.

In general, earth has a significantly lower environmental impact (9.96 kg CO_2e/m³) compared to lime (127.66 kg CO_2e/m³) when considering the GWP for modules A1-A3. The hemp-earth mixtures consistently exhibit lower CO_2e/m³ values, emphasizing their environmental advantages.

The high carbon sequestration potential (GWP-biogenic) of hemp enhances the overall environmental performance of mixtures with greater hemp content. This effect is particularly evident in series with elevated hemp to binder ratios, such as HL4S and HL4L. Table 9 compares the GWP of the test series with conventional insulation materials. [77]

MATERIAL	TOTAL (kg CO_2 e/m³)
HL3S	-135.8
HL4S	-155.7
HL3L	-146.3
HL4L	-169.7
HE3S	-200.1
HE3L	-216.2
Wood Fiber	-84.1
Mineral Wool	68.7
XPS	96.3
EPS	604.1

Table 9. LCA comparison of conventional insulation materials. (Table by author. Data from Ökobaudat 2018 and 2023.)

The results indicate a significant reduction in CO_2 emissions compared to other comparable materials. Even when compared to ecological alternatives like wood fiber insulation (-84.1 CO_2e/m³), which have a negative CO_2 footprint, hemp composites still demonstrate substantially lower emissions (-135.8 to -216.2 kg CO_2e/m³).

77
EPS: Ökobaudat 2023, Blaugelb Dämmplatten EPS
XPS: Ökobaudat 2018, XPS-Dämmstoff
Mineral Wool: Ökobaudat 2023, Mineralwolle (Fassaden-Dämmung)
Wood Fiber: Ökobaudat 2023, Holzfaser-Einblasdämmstoff (Durchschnitt DE)

5 Conclusion and Outlook

While earth as a binder showed a weaker performance in certain aspects, such as thermal transmittance and structural integrity, compared to lime, it offers notable environmental advantages, including a lower CO_2 footprint, resource efficiency, and reduced pollution.

The structural integrity of all mixtures suggests potential for improvement and further investigation. Future research should focus on optimizing the structural performance of these mixtures, particularly hemp-earth mixtures. HE mixtures exhibit greater overall fragility and deformation under load compared to HL mixtures, highlighting the need for enhanced formulations, in particular earth to water ratio.

The size of the hemp shives also influenced the results. Larger hemp shives led to lower raw density and improved thermal properties. However, in the hemp-earth series containing larger hemp shives, the expected reduction in raw density was not observed. This suggests that further research is needed to better understand the correlation between larger hemp shives and raw density in hemp-earth mixtures. Additionally, mixtures containing larger hemp shives appeared to enhance compressive strength and overall structural integrity.

Regarding the hemp to binder ratio, the 3:1 mixtures exhibited better compressive strength, while higher hemp content (ratio 4:1) improved thermal insulation and life cycle performance. Achieving a balance between structural integrity and sustainability remains key aspect to material optimization.

Thermal analysis confirmed that all mixtures achieved U-values below the 0.24 $W/m^2 \cdot K$ at 300 mm wall thickness, with hemp-lime (HL) mixtures showing slightly better results. Fire resistance tests demonstrated compliance with construction standards, supporting the material's versatile application potential.

From an environmental perspective, hemp-earth mixtures performed best because of the low environmental impact of earth as a binder. However, all tested mixtures achieved a negative CO_2 footprint, due to hemp's high CO_2 sequestration potential.

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