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Serhat Fidan[1], Miroslava Kavgić[2], Jelena Carević[3]

PARTICLE SIZE AND DENSITY EFFECTS ON HEMP–LIME REINFORCEMENT EFFICIENCY

Summary: Hemp–lime composites are sustainable bio-based materials with excellent hygrothermal performance and carbon sequestration potential, but their high porosity limits mechanical strength and broader use. This study examines the influence of fiberglass mesh reinforcement on the compressive behavior of hemp–lime composites with different particle sizes and densities. Test specimens were produced with a slag–hydrated lime binder (50:50 by mass), a binder-to-hemp ratio of 1.0, two hemp particle sizes (mean lengths 1.20 mm and 2.88 mm), and two density ranges. Four layers of fiberglass mesh were embedded at regular intervals, and compressive tests were conducted. The results showed that reinforcement efficiency depended strongly on particle size and density: it increased compressive strength by up to 118.7% in fine-particle composites, changing quasi-brittle to quasi-ductile behavior, but had only minor effects in coarse-particle composites.

Keywords: hemp-lime composites, fiberglass mesh reinforcement, compressive strength, failure behavior, sustainable construction

KOMPOZITI SA KONOPLJOM I KREČOM ARMIRANI MREŽOM OD STAKLENIH VLAKANA

Rezime: Kompozitni materijali napravljeni od konoplje i kreča predstavljaju održive biomaterijale sa odličnim higrotermalnim performansama i potencijalom za vezivanje ugljenika, ali su mehaničke karakteristike i šira primena ograničeni velikom poroznošću. U ovom radu je analiziran uticaj armiranja mrežom od staklenih vlakana na ponašanje kompozita od konoplje i kreča sa različitim veličinama čestica i gustinama na čvrstoću i ponašanje pri pritisku. Uzorci koji su ispitani su proizvedeni sa vezivom od zgure i hidratisanog kreča (50:50 maseni odnos), sa odnosom veziva i konoplje od 1.0, sa dve veličine čestica konoplje (srednje dužine 1.20 mm i 2.88 mm) i sa dve različite gustine. Četiri sloja mreže od staklenih vlakana su ugrađena u pravilnim razmacima u uzorke. Rezultati su pokazali da efikasnost armiranja značajno zavisi od veličine čestica i gustine matrice. Armiranje je povećalo čvrstoću pri pritisku za 118.7% kod kompozita sa sitnim česticama, menjajući pritom i ponašanje kompozita od kvazi krtog do kvazi duktilnog. Kod kompozita sa krupnim česticama uticaj armiranja je bio zanemarljiv.

Ključne reči: kompoyiti sa konopljom i krečom, mreža sa staklenim vlaknima, čvrstoća pri pritisku, ponašanje pri lomu, održivo građevinarstvo

[1] University of Ottawa, Ottawa, Ontario, K1N 6N5, Canada
[2] University of Ottawa, Ottawa, Ontario, K1N 6N5, Canada, mkavgic@uottawa.ca
[3] University of Belgrade, Faculty of Civil Engineering, Serbia

1. INTRODUCTION

Hemp-lime composites (HLC), also known as hempcrete, produced by mixing hemp shiv, a lime-based binder, and water, have emerged as a promising candidate for reducing the carbon footprint of building materials [1]. The CO_2 sequestered during hemp growth and the carbonation of the lime collectively result in a negative carbon balance for HLC [2,3]. Beyond its environmental benefits, HLC offers superior thermal insulation and moisture-buffering capacity [4]. Despite these advantages, HLC's limited mechanical strength, particularly in low-density mixes, raises concerns about handling, installation, and in-service performance. Reported compressive strengths for low-density HLC range as low as 0.05–0.10 MPa at densities of 197–236 kg/m³ [5] and 0.03–0.11 MPa at 140–200 kg/m³ [6].

To address this limitation, reinforcement strategies have recently been explored for bio-based composites. Most efforts to date have focused on externally applied Fabric Reinforced Cementitious Matrix (FRCM) systems. In one approach, cement-based hempcrete cylindrical specimens were externally reinforced with a flax-FRCM confining wrap, resulting in improvements of 258% in compressive strength and 531% in rigidity compared to unreinforced reference specimens [7]. More recently, a flax-FRCM system applied to two opposite faces of hempcrete specimens increased compressive strength and rigidity by up to 125% and 515%, respectively, when oriented parallel to the loading direction [8]. These gains were more limited when the reinforcement was applied to the transverse faces, reaching only 24% and 90%, respectively. In both cases, the FRCM reinforcement was bonded externally to the specimen surface, and the binders were cement-based. A different approach involved embedding jute fabric internally within flax-lime concrete beams [9]. Under three-point bending, moving the fabric layer from mid-height to the bottom quarter doubled the yielding load, whereas additional fabric layers increased the average displacement rather than the yielding load. However, compression tests in that study were conducted only on unreinforced samples, leaving the combined effect of internally embedded reinforcement and compressive loading unexamined.

This study examines HLC specimens with hemp shiv of varying particle size (coarse and fine) and target dry density (200 and 300 kg/m³), reinforced with horizontally embedded fiberglass mesh layers. Specifically, the objectives of this study are to: (i) evaluate the effect of embedded mesh reinforcement on the compressive strength of HLC across different particle sizes and densities, (ii) characterize the resulting changes in failure mode and crack pattern between unreinforced and reinforced specimens, and (iii) examine the corresponding stress-strain response to identify the conditions under which mesh reinforcement provides the greatest mechanical benefit.

2. MATERIALS AND METHODS

Hemp shivs supplied by Terrafibre were ground into two grading levels (coarse and fine) using an industrial grinder. ImageJ analysis was conducted to determine the mean length of the shivs [10]. Approximately 3 g of coarse shivs and 1 g of fine shivs were used for the analysis. Mean length was determined as 2.88 mm and 1.20 mm for coarse and fine shivs, respectively. Bulk density was determined following the RILEM TC 236-BBM recommendation [11]. Oven-dried shivs were placed in a cylindrical mold, upended ten times, and gently shaken to level the surface, which was then marked. The occupied volume was measured by filling the mold with water to this level. Measured values were 118 kg/m³ for fine shivs and 102 kg/m³ for coarse shivs.

Hydrated lime conforming to ASTM C207–24 [12] and slag conforming to ASTM C989/C989M-25 [13] were employed as binders in a 1:1 mass ratio. Slag was incorporated to enhance early strength development through latent hydraulic reactions [14] while also reducing the binder system's embodied carbon, given its industrial by-product nature [15]. Sample preparation was carried out as follows. The binder components were dry-mixed, then hemp shivs were added, followed by water to produce a homogeneous mixture. The workability of the fresh mixture was assessed using the ball-and-finger test, a qualitative method for evaluating the consistency of hemp-lime composites [6,16].

All samples were prepared with a fixed binder-to-hemp ratio of 1, with two target dry densities of 200 and 300 kg/m³, suitable for attic and wall insulation applications [17], respectively. Samples were cast into 100 × 100 × 100 mm³ molds in five layers. For reinforced samples, four fiberglass mesh layers, each measuring 100 mm × 100 mm with an opening size of 1 mm × 1 mm, were horizontally placed between layers (Figure 1). Fiberglass mesh was selected as reinforcement due to its low cost and wide availability in construction applications. In addition, fiberglass is considered hydrophobic [18], which is expected to minimize disturbances to the composite's hygrothermal properties.

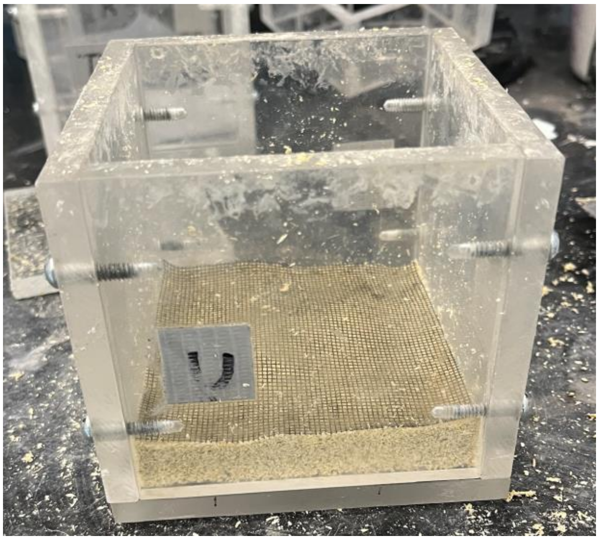

Figure 1: Preparation of reinforced hemp-lime composite specimens

Samples were cured at 21 ± 1 °C and 70 ± 2% relative humidity (RH) for 28 days before testing. After the curing period, samples were placed in a convection oven at 60 °C for three days to remove residual moisture. Compressive strength tests were then conducted on six samples per specimen designation in accordance with BS EN 826:2013 [19]. A displacement rate of 3 mm/min was applied using a universal testing machine with a 10 kN load cell. The peak stress was reported as compressive strength for samples exhibiting a distinct failure point. For samples without a clear peak, the stress at 10% strain was adopted as the compressive strength.

3. RESULTS AND DISCUSSIONS

Table 1 summarizes measured dry densities ranging from 191.2 to 325.0 kg/m³, with low coefficients of variation (CoV) ranging from 0.67% to 3.51%, indicating high repeatability in sample preparation. Specimen designations follow the format [Particle Size]-[Target Density]-[Reinforcement]. F and C refer to fine and coarse shivs, 200 and 300 denote target dry density in kg/m³, and UR and R represent unreinforced and reinforced specimens, respectively. Reinforced specimens consistently showed densities approximately 10 kg/m³ higher than those of their unreinforced counterparts, due to the added mass of the fiberglass mesh layers embedded in the matrix.

Table 1: Density and variability of hemp-lime composite specimens

Specimen Designation	F200-UR	F200-R	C200-UR	C200-R	F300-UR	F300-R	C300-UR	C300-R
Mean Density (kg/m³)	193.2	203.1	191.2	203.7	290.5	302.7	316.5	325.0
CoV (%)	1.61	1.98	2.22	3.51	0.78	0.70	0.67	1.74

Figure 2 presents the compressive strength results of unreinforced and reinforced hemp-lime composites for all specimens. For the 200 kg/m³ group, both F200-UR and C200-UR recorded a compressive strength of 0.040 MPa. Upon incorporating fiberglass mesh reinforcement, F200-R exhibited a compressive strength of 0.089 MPa, representing a 118.7% increase. In contrast, C200-R showed no meaningful improvement with only a 1.6% increase. This pronounced difference suggests that fine-particle shivs improve stress transfer between the HLC matrix and the mesh reinforcement, thereby more effectively preventing crack propagation.

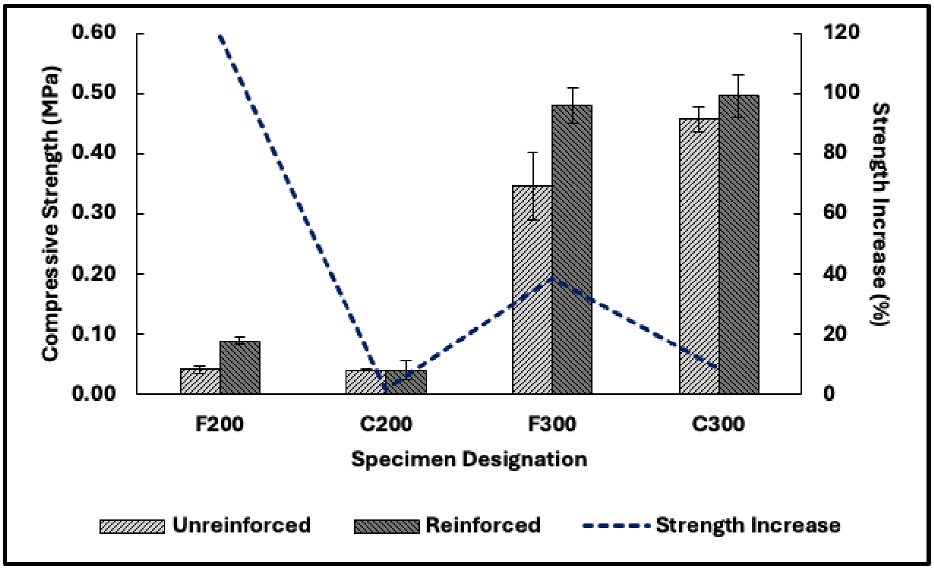

Figure 2: Compressive strength of unreinforced and reinforced hemp-lime composites

The 300 kg/m³ group demonstrated substantially higher compressive strengths than the 200 kg/m³ group, with values approximately 8-12 times higher, confirming the strong influence of density on the mechanical performance of HLC, as previously reported in the literature [5,20]. Following reinforcement, F300-R achieved 0.48 MPa, a 38.7% increase over F300-UR. C300-R recorded 0.50 MPa, corresponding to a modest 8.5% increase over C300-UR. The lower reinforcement effect observed in the F300-R compared to the F200-R can be attributed to the denser, inherently more crack-resistant HLC matrix, which reduces the reinforcement's relative contribution.

As illustrated in Figure 3-a, the unreinforced fine particle specimens (F200-UR and F300-UR) developed vertical cracks that propagated through the full height of the sample, ultimately splitting the matrix into several discrete fragments. This brittle fracture pattern reflects the limited tensile and shear capacity of the unreinforced hemp-lime matrix, which offers minimal crack resistance. In contrast, the reinforced fine-particle specimens (F200-R and F300-R), shown in Figure 3-b, exhibited a markedly different crack pattern, with damage concentrated along horizontal planes that coincide with the embedded fiberglass mesh layers. Rather than splitting apart, the specimen remained structurally coherent, with the mesh layers appearing to confine the fractured matrix and restrict crack propagation across layer boundaries. This delamination-like failure mode reflects the mesh's role in redistributing stress away from the cracked matrix, consistent with the enhanced load-bearing capacity discussed below in relation to the stress–strain response.

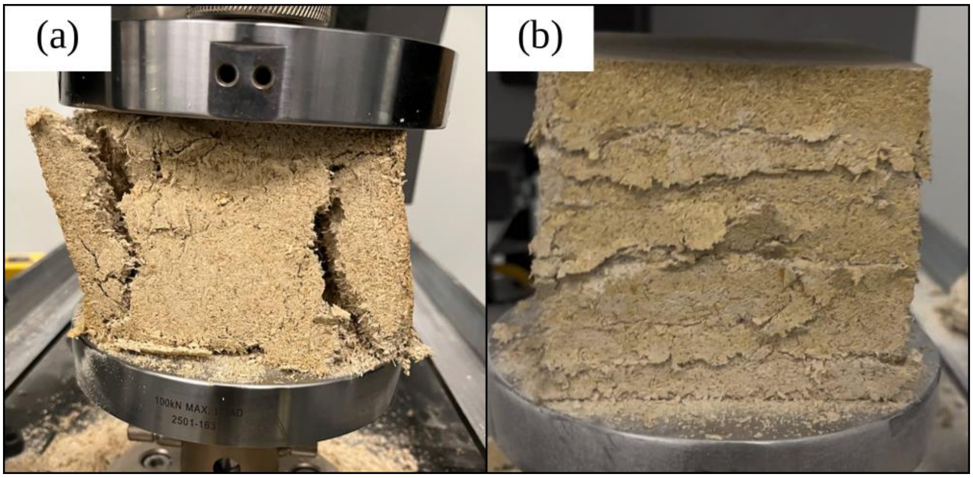

Figure 3: Typical crack behavior of (a) unreinforced and (b) reinforced fine particle HLC samples under axial compressive loading

Figure 4 presents the typical stress-strain curves of unreinforced and reinforced specimens. Unreinforced fine shiv specimens (F200-UR and F300-UR) exhibited quasi-brittle behavior, characterized by a distinct peak stress followed by a rapid load drop. In contrast, reinforced fine shiv specimens (F200-R and F300-R) exhibited a markedly different response, with no distinct failure point observed within the tested strain range, indicative of quasi-ductile behavior. This shift in mechanical response suggests that fiberglass mesh reinforcement effectively suppresses crack propagation by transferring stresses from the cracked HLC matrix to the mesh layers, enabling continued load-bearing capacity.

Unreinforced coarse shiv specimens (C200-UR and C300-UR) continued to bear load throughout the tested strain range without exhibiting a distinct peak stress, consistent with the strain-densifying behavior previously reported [21,22]. Reinforced specimens (C200-R and C300-R) exhibited a similar stress–strain response to their unreinforced counterparts up to 10% strain, in agreement with the marginal increase in compressive strength shown in Figure 2. The discontinuous microstructure of the coarse HLC matrix likely impedes efficient stress transfer to the embedded fiberglass mesh, thereby limiting its contribution to overall load-bearing behavior.

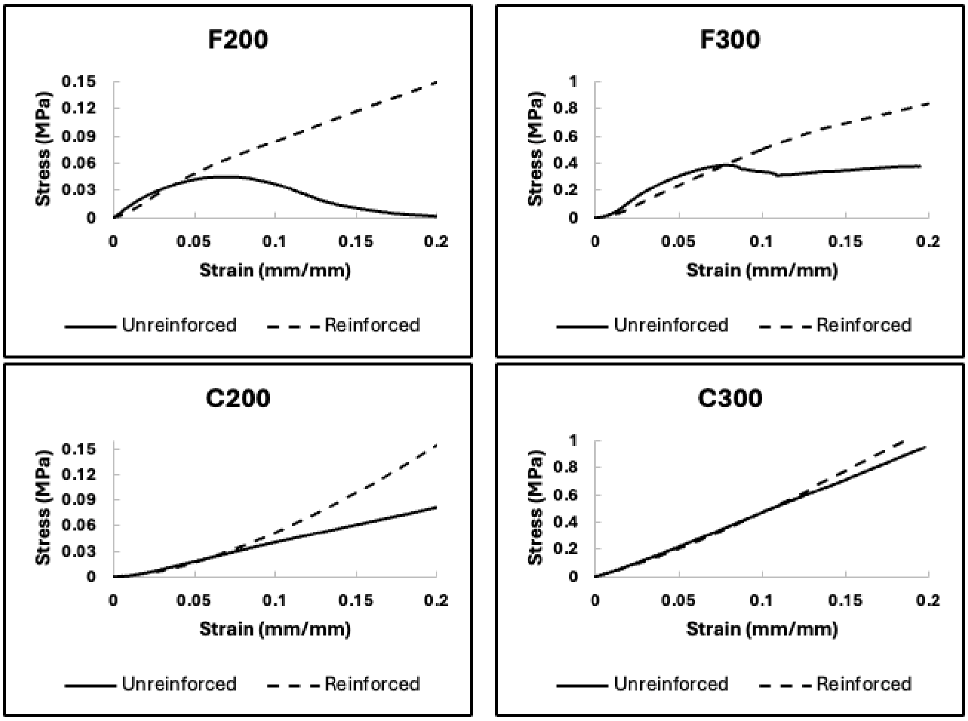

Figure 4: Typical stress-strain behavior of unreinforced and reinforced hemp-lime composites

4. CONCLUSION

This study investigated the compressive behaviour of unreinforced and fiberglass-mesh-reinforced hemp–lime composites by examining the combined effects of hemp shiv particle size and dry density.

The results demonstrate that the interaction between particle size and density governs the effectiveness of fiberglass mesh reinforcement. Fine shiv composites, which form a more homogeneous, continuous matrix, enable efficient stress transfer to the embedded mesh and increase compressive strength by up to 118.7% at a dry density of 200 kg/m³. In contrast, coarse shiv composites showed only marginal improvements, as their discontinuous matrix limited interfacial stress transfer. At the higher density of 300 kg/m³, the inherently stronger, more crack-resistant matrix reduced the relative contribution of the reinforcement, indicating that reinforcement efficiency depends on the combined effects of matrix continuity and density rather than on either parameter alone.

The influence of matrix continuity was also evident in the failure mechanisms. Reinforced fine shiv specimens transitioned from brittle vertical splitting into discrete fragments to a delamination-like failure mode confined to the mesh layers, allowing the specimens to remain structurally coherent throughout loading. This change was accompanied by a transition from quasi-brittle to quasi-ductile stress–strain behaviour, demonstrating that the embedded mesh effectively restrained crack propagation and sustained load-bearing capacity after initial cracking. In contrast, reinforced coarse shiv specimens exhibited behaviour comparable to that of their unreinforced counterparts, confirming the limited contribution of the mesh in a discontinuous matrix.

These findings demonstrate that reinforcement should be applied selectively rather than uniformly in hemp–lime composites. Fine-shiv, low-density mixtures, which are particularly susceptible to brittle failure, derive the greatest benefit from embedded fiberglass mesh, making them attractive for applications such as attic insulation where improved handling and mechanical robustness are desirable. Overall, the study provides practical design guidance by demonstrating that tailoring reinforcement to the internal structure of hemp–lime composites can maximize mechanical performance while minimizing unnecessary material use, cost, and embodied carbon.

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REFERENCES

[1] Y. Florentin, D. Pearlmutter, B. Givoni, E. Gal, A life-cycle energy and carbon analysis of hemp-lime bio-composite building materials, Energy Build. 156 (2017) 293–305. https://doi.org/10.1016/j.enbuild.2017.09.097.

[2] S. Pretot, F. Collet, C. Garnier, Life cycle assessment of a hemp concrete wall: Impact of thickness and coating, Build. Environ. 72 (2014) 223–231. https://doi.org/10.1016/j.buildenv.2013.11.010.

[3] A. Arrigoni, R. Pelosato, P. Melià, G. Ruggieri, S. Sabbadini, G. Dotelli, Life cycle assessment of natural building materials: the role of carbonation, mixture components and transport in the environmental impacts of hempcrete blocks, J. Clean. Prod. 149 (2017) 1051–1061. https://doi.org/10.1016/j.jclepro.2017.02.161.

[4] Y. Abdellatef, M.A. Khan, A. Khan, M.I. Alam, M. Kavgic, Mechanical, Thermal, and Moisture Buffering Properties of Novel Insulating Hemp-Lime Composite Building Materials, Materials 13 (2020) 5000. https://doi.org/10.3390/ma13215000.

[5] M. Gołębiewski, B. Pietruszka, W. Piątkiewicz, M. Kubiś, O. Oleksiienko, Compressive Strength, Thermal Conductivity, Vapor Permeability and Specific Heat of Hemp-Lime Composites Varying in Density for Wall, Roof and Floor Applications, Materials 18 (2025) 4958. https://doi.org/10.3390/ma18214958.

[6] O. Mahmood, M. Kavgic, M. Noel, Hygrothermal and mechanical characterization of novel hemp-lime composites with enhanced consistency, Constr. Build. Mater. 450 (2024) 138720. https://doi.org/10.1016/j.conbuildmat.2024.138720.

[7] R. Bardouh, O. Homoro, N. Reboul, M. Saidi, S. Amziane, Enhancing bio-based concrete mechanical properties: a novel approach with composite sandwiches and confined cylinders, Mater. Struct. 57 (2024) 139. https://doi.org/10.1617/s11527-024-02400-3.

[8] O.G. Agossou, O. Homoro, S. Amziane, Strengthening of hemp concrete with vegetal fabric reinforced cementitious matrix: experimental study on compression and shear behaviour, J. Build. Eng. 127 (2026) 116443. https://doi.org/10.1016/j.jobe.2026.116443.

[9] K.P. Garikapati, P. Sadeghian, Mechanical behavior of flax-lime concrete blocks made of waste flax shives and lime binder reinforced with jute fabric, J. Build. Eng. 29 (2020) 101187. https://doi.org/10.1016/j.jobe.2020.101187.

[10] J. Williams, M. Lawrence, P. Walker, The influence of constituents on the properties of the bio-aggregate composite hemp-lime, Constr. Build. Mater. 159 (2018) 9–17. https://doi.org/10.1016/j.conbuildmat.2017.10.109.

[11] S. Amziane, F. Collet, M. Lawrence, C. Magniont, V. Picandet, M. Sonebi, Recommendation of the RILEM TC 236-BBM: characterisation testing of hemp shiv to determine the initial water content, water absorption, dry density, particle size distribution and thermal conductivity, Mater. Struct. 50 (2017) 167. https://doi.org/10.1617/s11527-017-1029-3.

[12]ASTM, Standard Specification for Hydrated Lime for Masonry Purposes, (2024). https://doi.org/10.1520/C0207-24.

[13]ASTM, Standard Specification for Slag Cement for Use in Concrete and Mortars, (2025). https://doi.org/10.1520/C0989_C0989M-25.

[14]R. Walker, S. Pavia, R. Mitchell, Mechanical properties and durability of hemp-lime concretes, Constr. Build. Mater. 61 (2014) 340–348. https://doi.org/10.1016/j.conbuildmat.2014.02.065.

[15]J.R. Prusinski, M.L. Marceau, M.G. VanGeem, LIFE CYCLE INVENTORY OF SLAG CEMENT CONCRETE, in: Eighth CANMETACI Int. Conf. Fly Ash Silica Fume Slag Nat. Pozzolans Concr., American Concrete Institute, Farmington Hills, MI, 2004.

[16]W. Stanwix, A. Sparrow, The hempcrete book: designing and building with hemp-lime, Green Books, London, 2014.

[17]I.B. Muhit, E.L. Omairey, V.G. Pashakolaie, A holistic sustainability overview of hemp as building and highway construction materials, Build. Environ. 256 (2024) 111470. https://doi.org/10.1016/j.buildenv.2024.111470.

[18]A. Célino, S. Fréour, F. Jacquemin, P. Casari, The hygroscopic behavior of plant fibers: a review, Front. Chem. 1 (2014). https://doi.org/10.3389/fchem.2013.00043.

[19]British Standards, Thermal insulating products for building applications. Determination of compression behaviour, (2013).

[20]J. Williams, M. Lawrence, P. Walker, The influence of the casting process on the internal structure and physical properties of hemp-lime, Mater. Struct. 50 (2017) 108. https://doi.org/10.1617/s11527-016-0976-4.

[21]W. Piątkiewicz, A. Piotrowski, P. Narloch, Determination of Compressive Strength in Hemp–Lime Composites: Comparative Study of Testing Methodologies and Proposal of Improved Approach, Appl. Sci. 16 (2025) 306. https://doi.org/10.3390/app16010306.

[22]S. Elfordy, F. Lucas, F. Tancret, Y. Scudeller, L. Goudet, Mechanical and thermal properties of lime and hemp concrete (“hempcrete”) manufactured by a projection process, Constr. Build. Mater. 22 (2008) 2116–2123. https://doi.org/10.1016/j.conbuildmat.2007.07.016.