A Novel Hempcrete utilizing Calcium Aluminate Cement as a Binder

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ABSTRACT

Hempcrete is an eco-friendly, carbon-negative building material composed of hemp shives, a binder, and water. While traditionally bound with lime, its mechanical limitations hinder structural applications. This study explores the use of Calcium Aluminate Cement (CAC) as an alternative binder to enhance hempcrete's mechanical properties. Results indicate that CAC improves early strength, reduces setting time, and enhances compressive, flexural, and elastic properties compared to lime-based hempcrete. Microstructural analysis reveals denser packing and reduced porosity in CAC-based hempcrete, contributing to higher strength. However, CAC increases material costs and affects thermal and acoustic properties due to its density. Despite these challenges, CAC-based hempcrete is promising for applications requiring faster setting, higher strength, and improved durability, though further modifications, such as aggregate additions and compaction, may optimize performance.

Keywords-calcium aluminate cement; hemp hurds; hempcrete; compressive strength; microstructure

I. INTRODUCTION

In recent years, the production of sustainable bio-based building materials has become a priority research field because of the expanding needs for resources. Many bio-based materials, such as bamboo, palm kernel shells, coconut fiber, sawdust, straw bale, corn cob, have been incorporated into concrete [1-6]. Hempcrete is one such developing eco-friendly material which consists of hemp hurds (shives) combined with a binder and water. Hemp hurds, the woody inner core of the hemp stem, are a by-product of the hemp fiber industry. They are lightweight and have low thermal conductivity, making hempcrete an excellent insulation material due to porous nature [7-9]. Additionally, hempcrete exhibits good hygrothermal and acoustic properties [10-12]. The key fact in considering hempcrete is its carbon- sequestering ability, which makes it an ideal choice for sustainable construction [13, 14]. Some of the applications of Hempcrete include thermal and acoustic insulation panels, building blocks, non-load bearing infill walls, floor insulation, etc. [15-17].

In concrete, the binder is the most significant component. Initially, hempcrete was developed using lime as a binder due to its abundance and lower carbon emissions. However, the mechanical properties of hempcrete with lime as a binder have specific limitations. Lime absorbs a large amount of water in the matrix and obstructs the setting of the interior parts, thus affecting the mechanical, thermal, acoustic properties [18-20]. To enhance hempcrete's mechanical properties, researchers have explored various species of binders. Recent studies on hempcrete are minimal and its mechanical properties over the past five years are presented in Table I. Authors in [21] incorporated silica and dolomitic limestone aggregates into lime and utilized hemp fibers instead of shives achieving promising results. Additionally, in [22] authors improved mechanical performance by adding gum Arabic admixture to lime-metakaolin mixture. In [23], liquid sodium silicate was utilized as binder and the findings were proved more efficient than lime binder

TABLE I. MECHANICAL PROPERTIES OF HEMPCRETE DEVELOPED BY VARIOUS AUTHORS (LAST 5 YEARS)

Reference	Binder	Compressive Strength (MPa)	Flexural Strength (MPa)
[23]	Sodium Silicate	<2	-
[22]	Lime + metakaolin + gum arabic	4.81	1.55
[21]	Lime + silica sand +dolomitic limestone aggregates	6.2	3.03
[24]	Lime+ metakaolin	0.47	-
[25]	Tradical PF70	0.94	-
[26]	Lime+ Metakaolin	<0.6 MPa	-

In this study, various binders with lower carbon emissions were than Portland cement (PC) were investigated for use in hempcrete. Compared to Portland cement, lime, Calcium

Aluminate Cement (CAC), and gypsum are more sustainable alternatives as their carbon emissions are comparatively lower. CAC was selected because it develops high early strength, and its final setting time is shorter than other binders [27]. Comparing the environmental impact, CAC production has a lower impact than PC but a higher impact than lime [28]. CAC requires bauxite and limestone, leading to high energy consumption and CO_2 emissions (0.7-0.8 t CO_2 per ton) which, while lower than PC (0.8 t CO_2 per ton), remain significant due to reduced limestone calcinations [29, 30]. In addition, CAC's rapid strength gain can reduce overall material use in some applications, and it is also sulfate resistant [29]. Lime production (CaO) (0.7-1.2 t CO_2 per ton) has the lowest impact since it requires lower temperatures and emits CO_2 primarily from limestone decomposition [31]. Notably, lime products can partially offset their initial emissions by reabsorbing CO_2 from the atmosphere through a process called carbonation during their lifecycle, potentially offsetting a portion of the initial emissions.

In terms of durability, lime-based hempcrete performs well in most cases, except under freeze-thaw conditions, which applies to CAC binder as well [32]. Hempcrete's permeability makes it resistant to salt exposure and mold growth [17]. Due to CAC's sulfate resistance, CAC-based hempcrete is expected to be resistant in sulfate rich areas [29]. However, the alkali-silica reaction should be considered when CAC contains a significant amount of silica. The long-term durability of CAC-based hempcrete seems promising, particularly in regions with moderate moisture and temperature conditions. Proper curing ensures that the CAC hydrates completely, leading to more stable hydration products.

CAC has received limited attention in hempcrete applications, as hempcrete has traditionally been made with lime or lime-cement blends due to their compatibility with hemp shives. In addition, CAC is more expensive and sets faster than both lime and PC. While its quick setting time can accelerate construction in large-scale projects, it also reduces workability time, necessitating faster placement. This can be addressed by using chemical additives to decrease the setting time. Additionally, lower batch sizes and continuous supply chains can help to avoid premature setting. Despite these challenges, CAC could still be utilized in hempcrete applications that require faster setting times or higher early strength.

II. MATERIALS AND METHODS

A. Raw Materials

The hemp hurds utilized in this study were derived from Hemp Organization Pvt. Ltd., New Delhi. The collected hemp particles ranged in size from 0.5 mm to 50 mm. To refine the particle size distribution, the hemp hurds were sieved with a 0.6 mm sieve, and their bulk density was determined on air-dried samples based on mass and volume measurements without compaction (Table II). Due to naturally elongated shape of hemp hurds, the particle sizes after sieving do not correspond to the sieve size. However, the average length of particles in each group generally aligns with the size of the sieve used for separation.

TABLE II. BULK DENSITY OF THE MATERIALS USED IN BINDERS

Material	Hydrated Lime	Calcium Aluminate Cement	Hemp hurds
Bulk Density (kg/m^3)	470	874	112

Binders consisted solely of hydrated lime and CAC. Hydrated lime utilized in this study verifies Class B, which is suitable for lime concrete according to IS 712 [33]. Table II presents the bulk densities of the materials employed as binders. Hydroxyethyl Cellulose (HEC) is utilized as a water retention agent to keep moisture around hemp particles [34].

1) Setting Time

The setting time for hydrated lime and CAC was measured using a Vicat apparatus according to IS 4031 standards [35].

2) Specimen Preparation

Hempcrete specimens were prepared using sieved hemp hurds combined with hydrated lime and CAC as binders (Figure 1). The aggregate-to-binder ratio for both mixes was maintained at 1:2, making them suitable for wall and flooring applications [36, 37]. For water treatment, the hemp hurds were soaked in water for 24 hours and then surface-dried. For chemical treatment, they were immersed in a 3% sodium hydroxide solution for 24 hours before being surface-dried. HEC was added in 0.5% (by weight) of binder in the mix.

Fig. 1. Hempcrete cubes casted for compressive strength test.

TABLE III. MIX PROPORTION OF THE HEMPCRETES WITH LIME BINDER

Notation	Binder	Hemp: Binder: Water ratio (by weight)		
		H	B	W
LI	Lime + HEC	1	2	2.86
CAC	CAC + HEC	1	2	2.4

The mix proportions for hempcretes using lime and CAC are provided in Table III. The initial water content was calculated as 0.8% of the total weight of the hemp and binder (i.e., 3 x 0.8 = 2.4). Because there are no recognized guidelines for workability testing on hempcrete, additional water was added as needed to both mixes. The required water amount was determined based on the minimum quantity needed to form a small, tennis ball-sized mass without collapsing and achieving a slump value greater than 40 mm. For specimens casting, binder and HEC were mixed together, followed by dry mixing with hemp hurds. Water was then added and mixed to achieve a uniform composition. For cubes casting, mixed concrete was added in five layers and then compacted heavily. Casting involved hand compaction. Since hempcrete sets slowly, demolding took 1–2 days. The specimens were then air-cured at room temperature before testing.

3) Microstructure

The microstructure of the concretes was analyzed using SIGMA HV - Carl Zeiss with Bruker Quantax 200 - Z10 EDS detector after 180 days. The binder coating of the hemp shives was used for the study.

4) Mechanical Properties

(a)

(b)

Fig. 2. (a) Flexural strength test setup, (b) Young's modulus test setup.

After demolding, the specimens were stored at room temperature to cure before being evaluated for compression strength, flexural strength, and young modulus using an Automatic CTM with a capacity of 3000 kN. Each test result was based on the average values of three specimens. For compressive strength test, 100 mm cube; for flexural strength test (Figure 7(a)), prisms of size 100 mm x 100 mm x 500 mm and for Young's modulus test, a cylinder of 300 mm height and 150 mm diameter was used (Figure 7(b)). Although there are no standard codes for the mechanical strength tests on hempcrete, the tests were carried out in accordance with IS 516 [38].

III. III.RESULTS AND DISCUSSION

A. *Setting Time*

The setting time of both binders was tested, with the results presented in Table IV. The initial and final setting time of CAC was minimal compared to hydrated lime. The increased setting time of hydrated lime is due to the obstruction of moisture movement by lime which absorbs water and thus delays the setting.

TABLE IV. SETTING TIME OF BINDERS

Binder	Initial setting time	Finalsetting time
Hydrated lime	4 hrs.	49 hrs.
CAC	1 hr. 10 min	5 hrs. 21 min

B. *Microstructure*

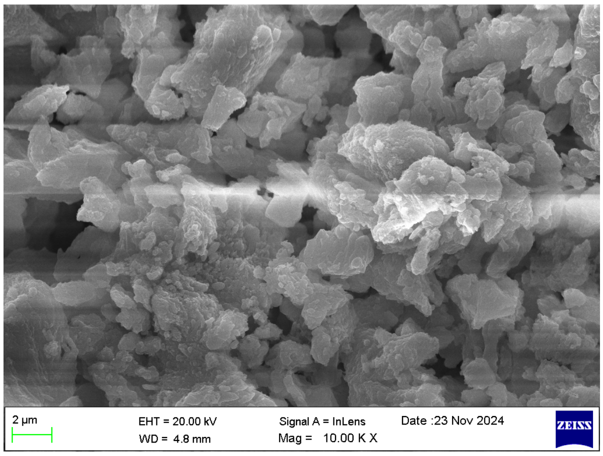

Fig. 3. FESEM image of LI.

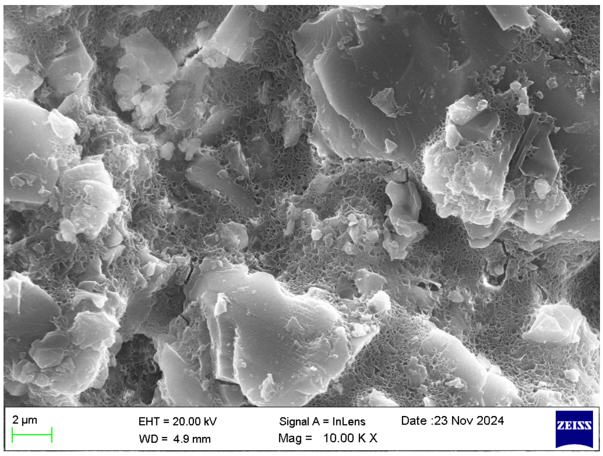

Fig. 4. FESEM image of CA.

Field Emission Scanning Electron Microscopy (FESEM) images of both hempcrete samples revealed the formation of carbonation and hydration products in the binder. In the LI sample (Figure 3), carbonation was primarily observed as carbonated lime with few hydrates. In contrast, the CAC sample (Figure 4) exhibited a dense surface due to the predominant development of calcium aluminate hydrates, which contribute to its early high strength. A comparison of the two images shows that CAC has fewer pores, whereas LI contains noticeably larger pores.

C. Mechanical Behaviour of LI and CA under Axial Compression

The mechanical behavior of hempcrete under compression is more like timber [39]. Upon load application, undergoes continuous compression, exhibiting a deformation pattern similar to that shown in Figure 5. In the LI mixture, deformation is significantly high, and failure occurs through crushing. In contrast, the CAC mixture exhibits minimal deformation, indicating greater resistance to compression.

(a)

(b)

Fig. 5. Typical failure of Hempcrete (a) CAC under compression, (b) LI under compression.

D. Effect of Binder on Density and Compressive Strength

Figure 6 and Table V illustrate the density and compressive strength of hempcrete at 7, 28, 56, 90 and 180 days of air curing. It is observed that the density of CAC is notably higher than that of the LI mixture throughout the curing period. At 7 days, CAC achieves a maximum density of 812 kg/m^3 while LI has a density of 752 kg/m^3. The rate of density is more pronounced up to 28 days, after which the reduction becomes minimal.

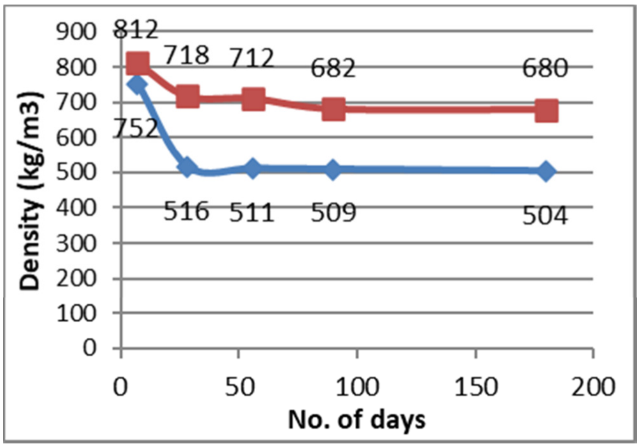

Fig. 6. Density of hempcretes LI (blue line) and CAC (red line).

TABLE V. COMPRESSIVE STRENGTH OF LI AND CAC

Time (No. of days)	Compressive strength (LI) (MPA)	COV	Compressive strength (CAC) (MPA)	COV
7	1.43	2.4	3.17	8.54
28	1.6	3.5	3.84	8.45
56	1.63	18.52	3.97	3.14
90	1.71	15.56	4.12	12.25
180	1.86	4.56	4.15	19.56

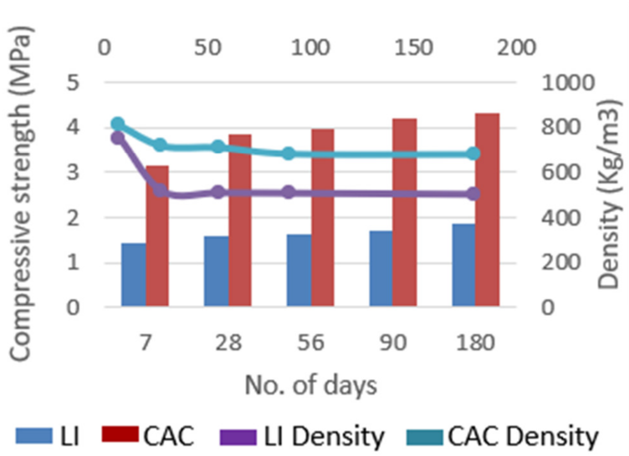

Fig. 7. Relation between compressive strength and density of LI and CAC.

From Table V, it is evident that the compressive strength of CAC is higher than that of LI throughout the curing period. At 28 days, CAC achieves a compressive strength of 3.84 MPa, which is more than twice the strength of LI. Both LI and CAC show a continuous increase in compressive strength, reaching 1.86 MPa and 4.15 MPa, respectively, at 180 days. When compared to the previous findings in Table I, CAC achieves a compressive strength greater than most of the studies, except for those by [21-22]. In [21] authors incorporated aggregates into hempcrete, which contributed to a higher density and, consequently, greater compressive strength.

Figure 7 illustrates the relationship between density and compressive strength for both LI and CAC. It is clear that CAC exhibits higher density and compressive strength than LI. In general, compressive strength tends to be higher when the density is greater, which can be attributed to the reduced porosity in higher-density mixtures. Additionally, CAC, as a binder with a high alumina content, contributes to higher early strength in the hempcrete.

E. Effect of Binder on Flexural Strength

Flexural strength is assessed in this study (Table VI) to evaluate the ability of concrete to resist bending stresses. The CAC mixture attains greater flexural strength than LI. According to IS 456 [40], the flexural strength of concrete is given by the characteristic equation:

$$fcr = 0.7\sqrt{fck}$$

where *fck* is the compressive strength of concrete. The values obtained in this study approximately align with the equation, confirming the consistency of the result.

TABLE VI. FLEXURAL STRENGTH AND YOUNG'S MODULUS OF L1 AND CA AT 28 DAYS

Mix	Flexural Strength (MPa)	COV	Young's modulus (MPa)	COV
LI	0.68	18.54	102	16.49
CAC	1.23	4.25	137	7.24

The greater flexural strength of CAC is mainly attributed to the high alumina content in the binder, which enhances the material's strength. The flexural strength of hempcrete reported by authors in [22] is somewhat closer to that of CAC, but the results from [21] exceed those of CAC. This can be attributed to the addition of aggregates, which likely contributed to the increased strength.

F. Effect of Binder on Young's Modulus

From the Table VI, it is notable that the young's modulus of CAC is greater than LI. Young's modulus is directly proportional to compressive strength in the case of L1 and CAC. As compressive strength of CAC is more than LI, young's modulus is also greater. Figure 8 illustrates both the flexural strength and the Young's modulus of the set up.

G. Cost Analysis

The cost of producing 1 m^3 of LI and CAC is presented in Table VII and Table VIII. The total cost of 1 m^3 of CAC ranges from ₹12,000 to ₹17,000, which is 47% higher than cost of 1 m^3 of LI. While LI is cheaper compared to CAC, it is non-load-bearing and requires curing over time. On the other hand, CAC is suitable for applications that require faster setting and high early strength**,** making it useful for structural applications, although the material is costlier.

TABLE VII. COST OF PRODUCING 1 m^3 OF LI

Material	Estimated Cost per Unit	Total Cost per m³ (approx.)
Hemp Shives	₹25–₹35/kg (depends on region)	₹6,000–₹8,000 per m³
Lime Binder	₹20–₹35/kg for hydraulic lime	₹1,500–₹2,500 per m³
Water	₹0	₹0 per m³
Total	-	₹8,500- ₹11,500 per m³

TABLE VIII. COST OF PRODUCING 1 m^3 OF CA

Material	Estimated Cost per Unit	Total Cost per m³ (approx.)
Hemp Shives	₹25–₹35/kg	₹6,000–₹8,000 per m³
CAC Binder	₹50–₹70/kg	₹6,000–₹9,000 per m³
Water	₹0	₹0 per m³
Total		₹12,000–₹17,000 per m^3

(a)

(b)

Fig. 8. (a) Flexural strength test setup, (b) Young's modulus test setup.

IV. CONCLUSION

This study aims to enhance the mechanical characteristics of hempcrete by utilizing an innovative binder known as Calcium Aluminate Cement (CAC). Among various options, CAC is a promising alternative due to its quick setting time and capacity to achieve high early strength, attributed to its elevated alumina content.

The results demonstrate that hempcrete with CAC achieves a compressive strength of 3.17 MPa in just seven days, which is considerably higher than the lime binder which only reaches 1.86 MPa after 180 days. The CAC binder generally exhibits an approximate compressive strength of 4 MPa, highlighting its superior mechanical performance. Additionally, the deformation observed during failure is significantly less than the total collapse of hempcrete cube samples using lime binder. At 28 days, the Young's modulus of CAC-based hempcrete is 137 MPa, surpassing the 102 MPa of lime-based hempcrete. Similarly, the flexural strength of hempcrete with CAC binder at 28 days is 1.23 MPa, compared to 0.68 MPa for the lime binder. In terms of density, CAC is denser than lime binder which may affect its thermal and acoustic properties While both types likely share similar insulation characteristics, lime-based hempcrete is more flexible and breathable, resulting in lower thermal conductivity and better sound absorption. On the other hand, CAC-based hempcrete is denser, making it slightly better at blocking sound transmission through walls.

Overall, CAC emerges as a viable alternative to lime, offering superior mechanical properties and faster setting times. However, its rapid setting present challenges for large-scale construction, which can be mitigated through retarders and batching in small sizes. CAC is better suited for precast elements, reducing on-site placement challenges. The primary drawback of CAC is its higher cost compared to lime and Portland cement. Additionally, while CAC improves mechanical properties, it is insufficient for use in load-bearing applications of hempcrete. To further enhance the strength of CAC-based hempcrete, reducing porosity through compression or compaction is recommended. Additionally, incorporating fine aggregates such as silica sand or M-sand could further improve density and mechanical performance. Future research should focus on optimizing these factors to expand the structural applications of CAC-based hempcrete.

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REFERENCES

[1] F. A. Olutoge, H. A. Quadri, and O. S. Olafusi, "Investigation of the Strength Properties of Palm Kernel Shell Ash Concrete," *Engineering, Technology & Applied Science Research*, vol. 2, no. 6, pp. 315–319, Dec. 2012, https://doi.org/10.48084/etasr.238.

[2] H. Archila, S. Kaminski, D. Trujillo, E. Zea Escamilla, and K. A. Harries, "Bamboo reinforced concrete: a critical review," *Materials and Structures*, vol. 51, no. 4, Jul. 2018, Art. no. 102, https://doi.org/10.1617/s11527-018-1228-6.

[3] J. Ahmad *et al.*, "Mechanical and Durability Performance of Coconut Fiber Reinforced Concrete: A State-of-the-Art Review," *Materials*, vol. 15, no. 10, Jan. 2022, Art. no. 3601, https://doi.org/10.3390/ma15103601.

[4] E. P. Aigbomian and M. Fan, "Development of wood-crete from treated sawdust," *Construction and Building Materials*, vol. 52, pp. 353–360, Feb. 2014, https://doi.org/10.1016/j.conbuildmat.2013.11.025.

[5] M. A. Ebaid, "Building for a sustainable future: investigating the thermal performance of innovative and local wall materials in an Egyptian housing unit," *Housing and Building National Research Center Journal*, vol. 19, no. 1, pp. 247–299, Dec. 2023, https://doi.org/10.1080/16874048.2023.2268290.

[6] J. Pinto *et al.*, "Corn cob lightweight concrete for non-structural applications," *Construction and Building Materials*, vol. 34, pp. 346–351, Sep. 2012, https://doi.org/10.1016/j.conbuildmat.2012.02.043.

[7] M. Safehian and A. A. Ramezanianpour, "Assessment of service life models for determination of chloride penetration into silica fume concrete in the severe marine environmental condition," *Construction and Building Materials*, vol. 48, pp. 287–294, Nov. 2013, https://doi.org/10.1016/j.conbuildmat.2013.07.006.

[8] R. Walker and S. Pavía, "Moisture transfer and thermal properties of hemp–lime concretes," *Construction and Building Materials*, vol. 64, pp. 270–276, Aug. 2014, https://doi.org/10.1016/j.conbuildmat.2014.04.081.

[9] B. Mazhoud, F. Collet, S. Pretot, and J. Chamoin, "Hygric and thermal properties of hemp-lime plasters," *Building and Environment*, vol. 96, pp. 206–216, Feb. 2016, https://doi.org/10.1016/j.buildenv.2015.11.013.

[10] R. K. Dahal, B. Acharya, and A. Dutta, "Mechanical, Thermal, and Acoustic Properties of Hemp and Biocomposite Materials: A Review," *Journal of Composites Science*, vol. 6, no. 12, Dec. 2022, Art. no. 373, https://doi.org/10.3390/jcs6120373.

[11] F. Ntimugura, R. Vinai, A. Harper, and P. Walker, "Mechanical, thermal, hygroscopic and acoustic properties of bio-aggregates – lime and alkali - activated insulating composite materials: A review of current status and prospects for miscanthus as an innovative resource in the South West of England," *Sustainable Materials and Technologies*, vol. 26, Dec. 2020, Art. no. e00211, https://doi.org/10.1016/j.susmat.2020.e00211.

[12] A. T. Le, A. Gacoin, A. Li, T. H. Mai, and N. El Wakil, "Influence of various starch/hemp mixtures on mechanical and acoustical behavior of starch-hemp composite materials," *Composites Part B: Engineering*, vol. 75, pp. 201–211, Jun. 2015, https://doi.org/10.1016/j.compositesb.2015.01.038.

[13] G. V. Kumar, R. Ramadoss, and G. S. Rampradheep, "A study report on carbon sequestration by using Hempcrete," *Materials Today: Proceedings*, vol. 45, pp. 6369–6371, Jan. 2021, https://doi.org/10.1016/j.matpr.2020.11.012.

[14] T. Jami, D. Rawtani, and Y. K. Agrawal, "Hemp concrete: carbon-negative construction," *Emerging Materials Research*, vol. 5, no. 2, pp. 240–247, Dec. 2016, https://doi.org/10.1680/jemmr.16.00122.

[15] E. Binega Yemesegen and A. M. Memari, "A review of experimental studies on Cob, Hempcrete, and bamboo components and the call for transition towards sustainable home building with 3D printing," *Construction and Building Materials*, vol. 399, Oct. 2023, Art. no. 132603, https://doi.org/10.1016/j.conbuildmat.2023.132603.

[16] T. Karche and M. R. Singh, "The application of hemp (Cannabis sativa L.) for a green economy: a review," *Turkish Journal of Botany*, vol. 43, no. 6, pp. 710–723, Jan. 2019, https://doi.org/10.3906/bot-1907-15.

[17] S. Barbhuiya and B. Bhusan Das, "A comprehensive review on the use of hemp in concrete," *Construction and Building Materials*, vol. 341, Jul. 2022, Art. no. 127857, https://doi.org/10.1016/j.conbuildmat.2022.127857.

[18] O. Kinnane, A. Reilly, J. Grimes, S. Pavia, and R. Walker, "Acoustic absorption of hemp-lime construction," *Construction and Building Materials*, vol. 122, pp. 674–682, Sep. 2016, https://doi.org/10.1016/j.conbuildmat.2016.06.106.

[19] F. Collet and S. Pretot, "Thermal conductivity of hemp concretes: Variation with formulation, density and water content," *Construction and Building Materials*, vol. 65, pp. 612–619, Aug. 2014, https://doi.org/10.1016/j.conbuildmat.2014.05.039.

[20] R. Walker and S. Pavía, "Physical properties and reactivity of pozzolans, and their influence on the properties of lime–pozzolan pastes," *Materials and Structures*, vol. 44, no. 6, pp. 1139–1150, Jul. 2011, https://doi.org/10.1617/s11527-010-9689-2.

[21] E. Parcesepe, R. F. De Masi, C. Lima, G. M. Mauro, M. R. Pecce, and G. Maddaloni, "Assessment of Mechanical and Thermal Properties of Hemp-Lime Mortar," *Materials*, vol. 14, no. 4, Jan. 2021, Art. no. 882, https://doi.org/10.3390/ma14040882.

[22] P. Brzyski, "The Influence of Gum Arabic Admixture on the Mechanical Properties of Lime-Metakaolin Paste Used as Binder in Hemp

Concrete," *Materials*, vol. 14, no. 22, Jan. 2021, Art. no. 6775, https://doi.org/10.3390/ma14226775.

[23] B. Ayati, A. Gutierrez, and A. Chandler, "Mechanical and hygrothermal properties of hemp-silica bio-composites," *Construction and Building Materials*, vol. 425, Apr. 2024, Art. no. 136077, https://doi.org/10.1016/j.conbuildmat.2024.136077.

[24] Y. Abdellatef, M. A. Khan, A. Khan, M. I. Alam, and M. Kavgic, "Mechanical, Thermal, and Moisture Buffering Properties of Novel Insulating Hemp-Lime Composite Building Materials," *Materials*, vol. 13, no. 21, Jan. 2020, Art. no. 5000, https://doi.org/10.3390/ma13215000.

[25] F. Benmahiddine, F. Bennai, R. Cherif, R. Belarbi, A. Tahakourt, and K. Abahri, "Experimental investigation on the influence of immersion/drying cycles on the hygrothermal and mechanical properties of hemp concrete," *Journal of Building Engineering*, vol. 32, Nov. 2020, Art. no. 101758, https://doi.org/10.1016/j.jobe.2020.101758.

[26] W. Piątkiewicz, P. Narloch, and B. Pietruszka, "Influence of hemp-lime composite composition on its mechanical and physical properties," *Archives of Civil Engineering*, vol. 66, no. 3, pp. 485–503, 2020, https://doi.org/10.24425/ace.2020.134409.

[27] J. H. Ideker, K. L. Scrivener, H. Fryda, and B. Touzo, "Calcium Aluminate Cements," in *Lea's Chemistry of Cement and Concrete (Fifth Edition)*, P. C. Hewlett and M. Liska, Eds. Oxford, UK: Butterworth-Heinemann, 2019, pp. 537–584.

[28] J. F. Zapata, A. Azevedo, C. Fontes, S. N. Monteiro, and H. A. Colorado, "Environmental Impact and Sustainability of Calcium Aluminate Cements," *Sustainability*, vol. 14, no. 5, Jan. 2022, Art. no. 2751, https://doi.org/10.3390/su14052751.

[29] J. Bizzozero, "Hydration and dimensional stability of calcium aluminate cement based systems," M.S. thesis, Material Sciences and Techniques, Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland, 2014.

[30] S. Frauke, K. Ioanna, S. B. Maria, R. Serge, and D. S. Luis, "Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide: Industrial Emissions Directive 2010/75/EU:(Integrated Pollution Prevention and Control," Belgium, 2013.

[31] E. Wu, Q. Wang, L. Ke, and G. Zhang, "Study on Carbon Emission Characteristics and Emission Reduction Measures of Lime Production—A Case of Enterprise in the Yangtze River Basin," *Sustainability*, vol. 15, no. 13, Jan. 2023, Art. no. 10185, https://doi.org/10.3390/su151310185.

[32] T. Jami, S. R. Karade, and L. P. Singh, "A review of the properties of hemp concrete for green building applications," *Journal of Cleaner Production*, vol. 239, Dec. 2019, Art. no. 117852, https://doi.org/10.1016/j.jclepro.2019.117852.

[33] *Specification for Building Limes*, IS 712, India, 1984.

[34] L. Patural, P. Marchal, A. Govin, P. Grosseau, B. Ruot, and O. Devès, "Cellulose ethers influence on water retention and consistency in cement-based mortars," *Cement and Concrete Research*, vol. 41, no. 1, pp. 46–55, Jan. 2011, https://doi.org/10.1016/j.cemconres.2010.09.004.

[35] *Methods of physical tests for hydraulic cement, Part 5: Determination of initial and final setting times*, IS 4031-5, India, 1988.

[36] J. Williams, M. Lawrence, and P. Walker, "The influence of constituents on the properties of the bio-aggregate composite hemp-lime," *Construction and Building Materials*, vol. 159, pp. 9–17, Jan. 2018, https://doi.org/10.1016/j.conbuildmat.2017.10.109.

[37] R. Bevan and T. Woolley*, Hemp Lime Construction: A guide to building with hemp lime composites*, Bracknell, UK: IHS BRE Press, 2008.

[38] *Methods of Tests for Strength of Concrete*, IS 516, India, 1959.

[39] S. R. Reid and C. Peng, "Dynamic uniaxial crushing of wood," *International Journal of Impact Engineering*, vol. 19, no. 5, pp. 531–570, May 1997, https://doi.org/10.1016/S0734-743X(97)00016-X.

[40] *Plain and reinforced concrete-code of practice,* IS 456, India, 2000.