

Research Article

Aylin Özodabaş*

Reinforcement of cementitious mortars with hemp fibers and shives

<https://doi.org/10.1515/chem-2022-0335>

received March 13, 2023; accepted April 30, 2023

Abstract: Polypropylene, steel, and carbon fibers are used to increase the ductility and toughness of concrete materials. In recent years, studies on the use of natural fibers have increasingly continued. Among natural fibers, hemp fiber has the highest tensile strength value. The aim of this study was to discuss and present the results of the experimental study on the use of cement-based hemp shives and fibers to increase the ductility of mortars. Another aim is to increase the use of hemp in the construction field by using more economical and natural fibers. Various binders and different amounts of fibers and shives were added and their effects on flexural strength were investigated. Water absorption and flexural tests and scanning electron microscope and X-ray diffraction analysis were performed on the produced samples. Particle and hole size distributions and stereo microscope images of the samples are given. The use of hemp fibers was observed to improve flexural strength, while shives were not significantly improved flexural strength.

Keywords: composite material, hemp, fiber, shive, mortar, flexural strength

1 Introduction

Hemp concrete can be recycled at the end of the building's lifespan. In addition, hemp can be harvested in as little as 60 days. Hemp concrete is a better-than-zero-carbon material because it absorbs carbon from the atmosphere while the hemp plant is grown. It is one of the few materials that has the ability to absorb carbon even after it has been used in construction. In addition, the cannabis plant removes heavy metals from water and soil [1]. Hemp

and lime is a material that consumes CO₂ through carbonation inside the concrete matrix [2]. In a study, they found the total carbon sequestration amount of hemp concrete as 307.26 kg CO₂ per m³ (Figure 1) [2,3]. Hemp concrete is considered a green building material not only because of its low carbon content but also because of its ability to regulate heat, humidity, and relative humidity [4]. Hemp concrete is also known to exhibit acoustic insulation [5]. Response to fire is an important factor to consider as it relates to building safety. However, interestingly, all of the research has agreed that hemp concrete is suitable for fire resistance [6].

Hempcrete, also known as lime-hemp concrete, is a breakthrough concept that has attracted attention [7]. Lime is a binder that is 500°C lower than the temperature used to make cement (1,450°C) and is produced in a limestone kiln at 950°C. In addition, during the carbonation process that occurs during its hardening, most of the CO₂ released as a result of the chemical reaction that creates it is absorbed back into the system. Therefore, the carbon emission is significantly smaller or even negative than that of cement [8].

Hemp shives are a byproduct of the hemp fiber industry. They constitute 65–70% of the total production (by mass) of the hemp plant. The usage areas of the hemp plant are given in Figure 2. In a study that has been done, the 2-year evolution of the functional properties of two hemp concretes formulated with two different binders according to different environmental conditions was investigated. These binders are a natural cement (NC) and a lime-based binder (FL). Thermal conductivity increases during aging and this increase is greater for FL than for NC [9]. In this case, although lime is a sustainable building material, it could not provide durability such as cement mixtures in aging tests.

In the last few decades, several studies have been conducted on the use of natural fibers in cementitious concrete to improve properties [10]. Figure 3 shows the optimum replacement percentage of various natural fibers in cement concrete [11].

Different binders have been reported to produce hemp concrete, such as ordinary Portland cement, lime, and lime combination [12–14]. It is confirmed by a large number of

* **Corresponding author: Aylin Özodabaş**, Department of Civil Engineering, Faculty of Engineering, Bilecik Şeyh Edebali University, 1100 Bilecik, Turkey, e-mail: aylin.ozodabas@bilecik.edu.tr

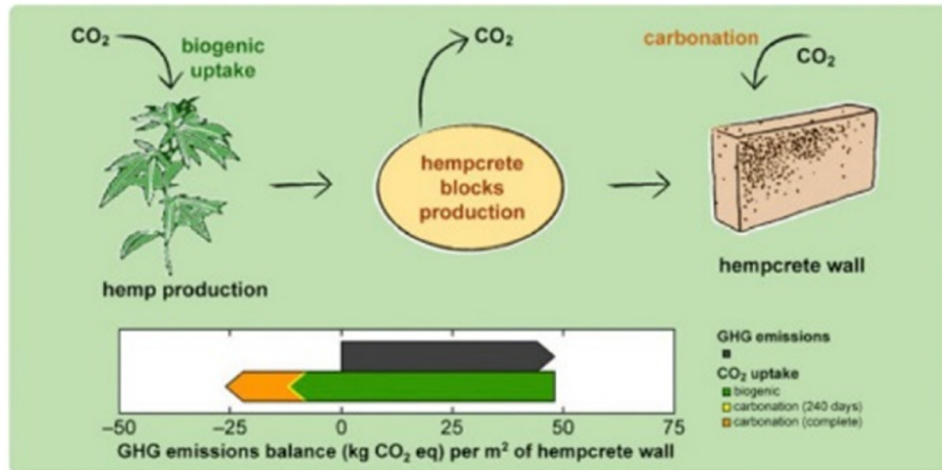


Figure 1: Net emission balance showing carbon negativity and carbon emission of hemp concrete [2,3].

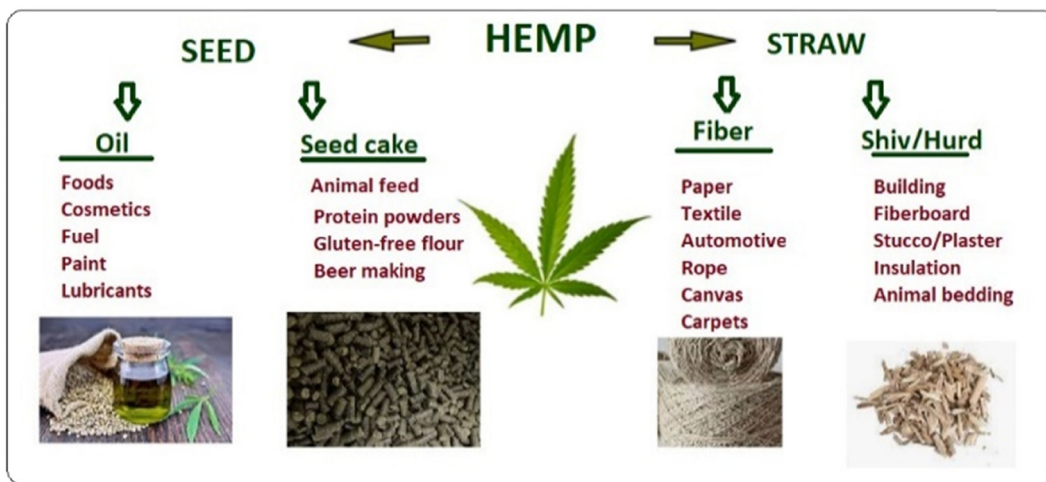


Figure 2: Uses of the hemp plant.

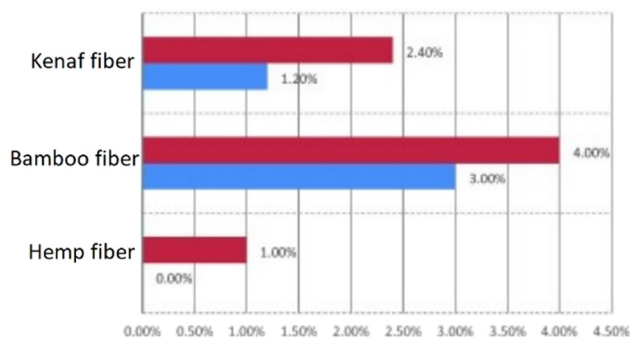


Figure 3: Optimum replacement percentage of various natural fibers in cement concrete [10].

studies and has mechanical properties that make natural fibers suitable for use in building materials [15–18]. It is also important to state that building materials made with natural

fibers have lower production costs than those made with synthetic fibers [19]. Hemp concrete is a viable solution to increase the energy efficiency of buildings [20].

As it is known, hemp fibers are one of the highest tensile strengths among natural fibers [10,21]. It has been shown that long sisal fibers are more effective than short sisal fibers in increasing the bending capacity of the sandwich panel [22]. Table 1 includes the mechanical properties of natural and synthetic fibers. It is seen that the tensile strength values of hemp are greater than other natural fibers but less than carbon and glass fibers. It can be used to increase toughness and ductility instead of using it as reinforcement in concrete. In addition, due to its good insulation properties, its usage areas can be increased as an insulation material. In this study, hemp was used as shive and fiber to increase the toughness and

Table 1: Mechanical properties of natural fibers compared to conventional reinforcement obtained from the literature [23–25]

Fiber	Density (g/cm ³)	Elongation at break (%)	Tensile strength (MPa)	Young's modulus (GPa)
Hemp	1.14–1.51	1.6	500–900	30–80
Flax	1.20–1.50	2.7–3.2	345–1,035	28–90
Sisal	1.45–1.50	2.0–2.5	67–635	4–22
E-Glass	2.50–2.60	2.5	2,000–3,500	70–80
Carbon	1.40–1.78	1.4–1.8	4,000–5,000	230–240
Steel	7.75–8.05	0.5–3.5	500–2,000	200–210

Table 2: Particle size distribution [5]

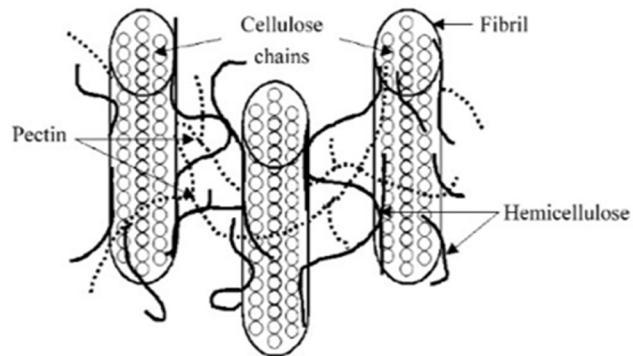
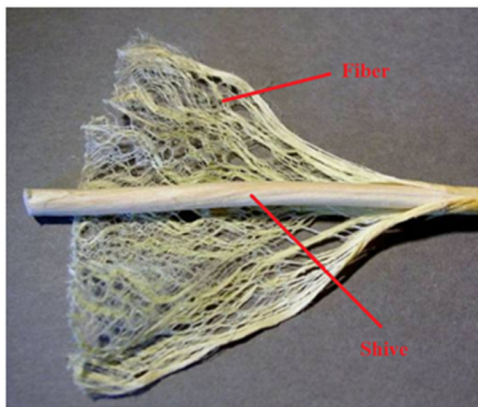
Particle length (mm)	Mass (g)	Quantity (%)	By mass (%)
Small ≤ 4 mm	0.8	50	17.02
Medium ≤ 8 mm	1.2	28	25.53
Large ≥ 9 mm	2.7	22	57.45

ductility of concrete. The effects of these two forms on concrete were investigated by mechanical experiments, X-ray diffraction (XRD) experiments, stereo microscope, scanning electron microscope (SEM) analysis, and gap and particle size distribution.

2 Materials and methods

2.1 Materials

Hemp shives and some fibers were soaked in water for 24 h before use due to their hydrophilic properties. The

**Figure 4:** Hemp stem image and hemp fiber architecture [26].**Table 3:** Chemical compositions and physical properties of hemp [10,27,28]

Chemical compound	Hemp	
	Fibers (%)	Shives (%)
Cellulose	81	77
Hemicellulose	20	44
Lignin	4	21
Pectin	0.9	1
Fat and wax	0.8	1
Physical Properties		
Diameter (μm)	8–600	8–600
Water absorption (%)	272	276

other shives were used in dry form to compare. Wet preservation of hemp is equivalent to other pre-treatment of hemp fibers [19]. The particle size distribution for a sample of hemp shives is listed in Table 2. The chemical compositions and physical properties of hemp fibers and shives are given in Table 3. Figure 4 shows the chemical forms found in hemp. Four different sizes of shives and fibers used in the samples are given in Figure 5. In Figure 6, samples containing shives and fibers are given.

2.2 Preparation of mortars

In this study, 32 series of concrete mixes were produced, in which the amount of materials used changed at certain rates. Due to the hydrophilic properties of cannabis, it was washed by soaking in water for 24 h before use. Two different types of hemp, shive and fiber, were used. In shive-containing samples; the effects of hydrated lime and brick dust in the K samples and gypsum in the I samples on the flexural strength and water absorption values were

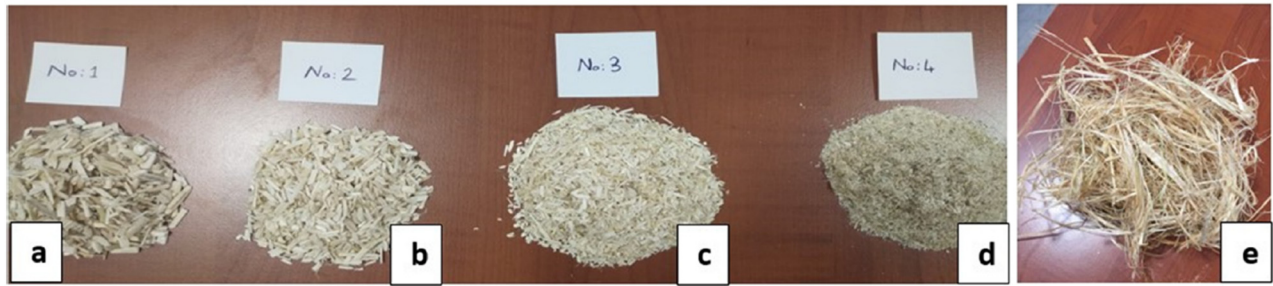


Figure 5: Shives of different sizes (numbered a: 1, b: 2, c: 3 and d: 4) and fibers (e) used in the experiments.)

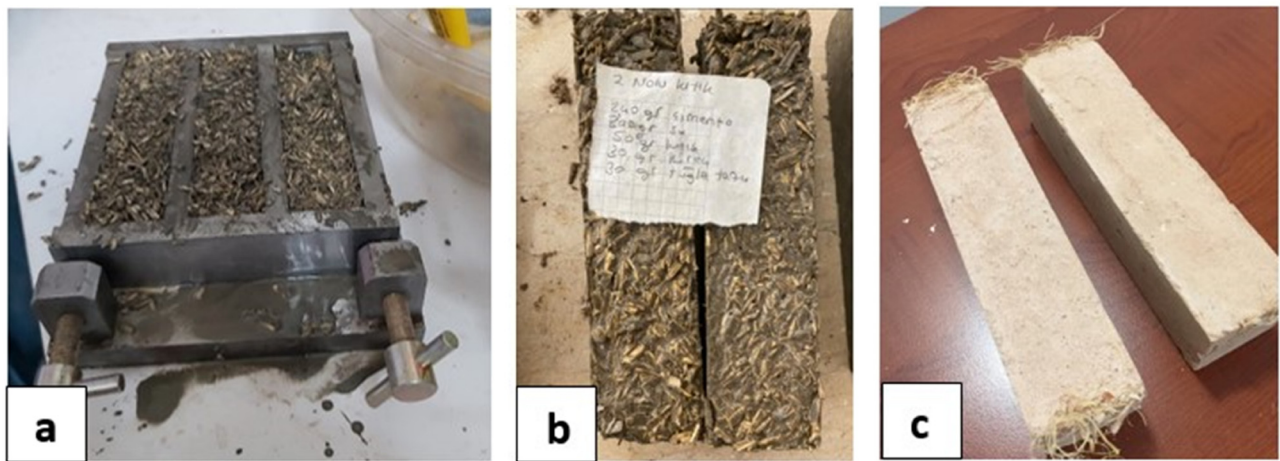


Figure 6: Samples with (a and b) shive and (c) fiber contents.

investigated. While some of the shives were used wet and some dry, all of the fibers were used wet. While hemp fibers were placed in longitudinal form in one group of

samples, they were placed in mixed form in the other group of samples. Figure 7 illustrates the classification of the materials used in the design of the mortar.

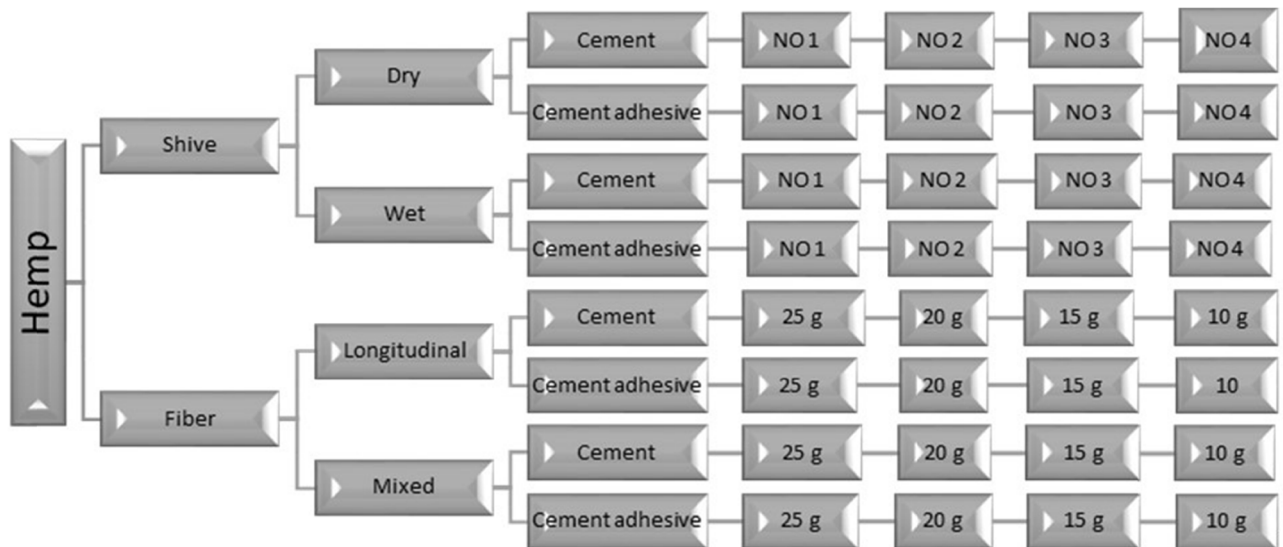


Figure 7: Classifications made in the production of the test samples.

Each experiment was performed three times. After 24 h, the poured samples were removed from their molds and cured under laboratory conditions for 28 days. The ratio of shives was fixed for comparison. The materials used in the samples with the shive content giving optimum values were then used in the fiber mixtures. The mixtures were prepared per the mixing procedure in the TS EN 196-1 standard. The content ratios of the materials used in the mortar mixture are given in Tables 4 and 5.

2.3 Experimental methods

To assess water absorption, the samples were immersed in a water bath at laboratory conditions (20°C) for 48 h. The percentage of water content was determined using the following equation:

$$W_c \text{ (%) } = (W_{wc} - W_{dc}) \times 100 / W_{dc}, \quad (1)$$

where W_{wc} is the weight of the water-saturated sample and W_{dc} is the weight of the dry sample.

Table 4: Mixture proportions with shive content

Samples	Shive condition	Water (%)	Gypsum (%)	Hydrated lime (%)	Shive (%)	Brick dust (%)	Cement (%)	Cement adhesive (%)
K1	Dry (No 1)	46	0	5	7	5	37	0
K2	Dry (No 1)						0	37
K3	Dry (No 2)						37	0
K4	Dry (No 2)						0	37
K5	Dry (No 3)						37	0
K6	Dry (No 3)						0	37
K7	Dry (No 4)					0	42	0
K8	Dry (No 4)						0	42
I1	Wet (No 1)	46	5	0	7	0	42	0
I2	Wet (No 1)						0	42
I3	Wet (No 2)						42	0
I4	Wet (No 2)						0	42
I5	Wet (No 3)						42	0
I6	Wet (No 3)						0	42
I7	Wet (No 4)						42	0
I8	Wet (No 4)						0	42

Table 5: Mixture proportions with fiber content

Samples	Fiber condition	Water (%)	Gypsum (%)	Fiber (%)	Cement (%)	Cement adhesive (%)
D1	Longitudinal fiber	33	7	2	58	0
D2	Longitudinal fiber			1.5	58.5	0
D3	Longitudinal fiber			1.0	59	0
D4	Longitudinal fiber			0.5	59.5	0
D5	Longitudinal fiber			2	0	58
D6	Longitudinal fiber			1.5	0	58.5
D7	Longitudinal fiber			1.0	0	59
D8	Longitudinal fiber			0.5	0	59.5
KL1	Mixed fiber	33	7	2	58	0
KL2	Mixed fiber			1.5	58.5	0
KL3	Mixed fiber			1.0	59	0
KL4	Mixed fiber			0.5	59.5	0
KL5	Mixed fiber			2	0	58
KL6	Mixed fiber			1.5	0	58.5
KL7	Mixed fiber			1.0	0	59
KL8	Mixed fiber			0.5	0	59.5

Three-point flexural tests were performed on three mortar prism samples with dimensions of 40 mm × 40 mm × 160 mm according to TS EN 196-1.

2.4 Characterization

SEM analysis was performed to examine the physicochemical and structural changes of the mortar samples and their surface properties were determined. A ZEISS Supra 40VP model was used for SEM imaging and energy-dispersive spectrometer (EDX) analysis. We conducted an X-ray diffraction (XRD) analysis using a Panalytical Empyrean X-ray diffractometer. In addition, the LEICA S6 D model was used for stereo microscope images.

3 Results and discussion

3.1 Water absorption

It was not expected that water absorption values of lime were higher than gypsum [29,30]. However, in the samples used in the shives, the gypsum-containing ones absorbed less water than those containing lime (Figure 8). Since the water absorption rate is higher in limes, only gypsum was used in the fibers. It was observed that the water absorption rate of the samples increased as the size of the shive used increased. Soaked shives exhibited better water absorption performance than dry shives. The best water absorption values; among the samples containing wetted shive, the I3 sample has a water absorption value of 7.14%. Among the fibrous samples, the D3 sample has the lowest fiber content and its water absorption value is 8.11%. The highest water absorption values; samples containing unwetted shive and samples with the highest fiber content.

It is observed that the water absorption values of the samples using cement adhesive are higher than that of cement. The water absorption values of the samples placed by mixing the fibers with mortar into the mold gave better results than the fibers placed straightly.

3.2 Flexural strength

As shown in Figure 9, the flexural strength values of the fibrous samples are higher than the samples with the shive content. The flexural strength values of the samples placed

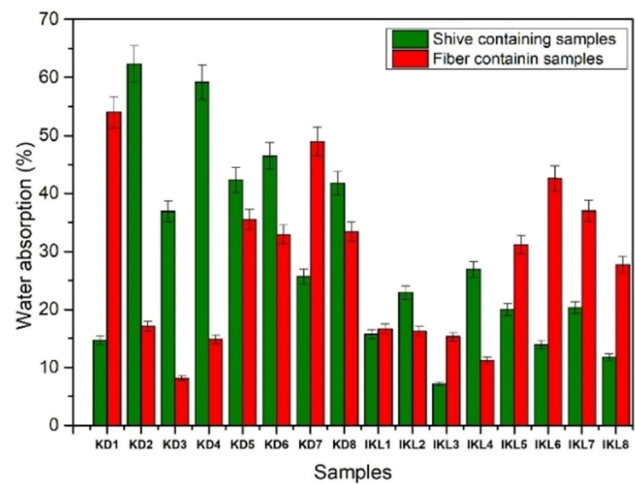


Figure 8: Water absorption rates of samples containing shive and fiber.

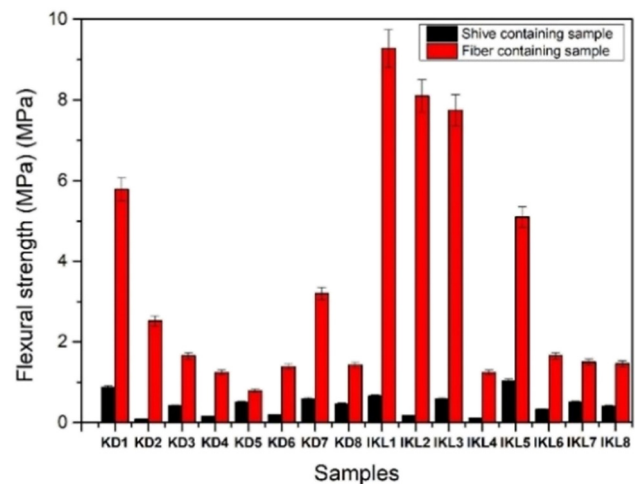


Figure 9: Flexural strength rates of samples containing shive and fiber.

by mixing the fibers with mortar into the mold gave better results than the fibers placed straightly. The highest flexural strength value among the shives was the I5 sample, which was 1.03 MPa. Among the fibers, the KL1 sample contains mixed fiber and cement and is 9.28 MPa. As the fiber ratios increased, the flexural strength values increased [31]. Cementitious ingredients gave better results than cement adhesive ingredients. In a study, cementitious composites containing hemp showed the best performance [32].

3.3 SEM analysis

SEM images of fracture surfaces of cured cement paste are shown in Figure 10. Block-shaped portlandite

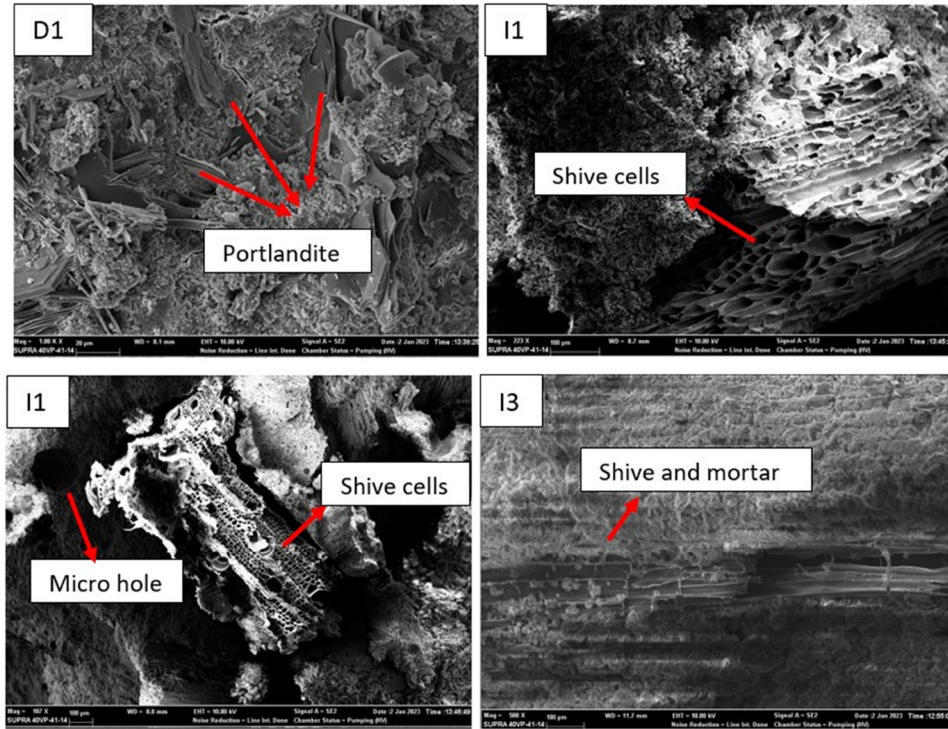


Figure 10: SEM images of samples containing fiber (D1) and shive (I1 and I3).

(calcium hydroxide) crystals exhibiting a typical cubic behavior are seen in sample D1. The tubular structure of the hemp was seen in sample I1 [33]. The images in

the I3 sample show that the bonding of the cellulose microfibers with the mortar is good due to the surface textures and non-deformable hemp fibers.

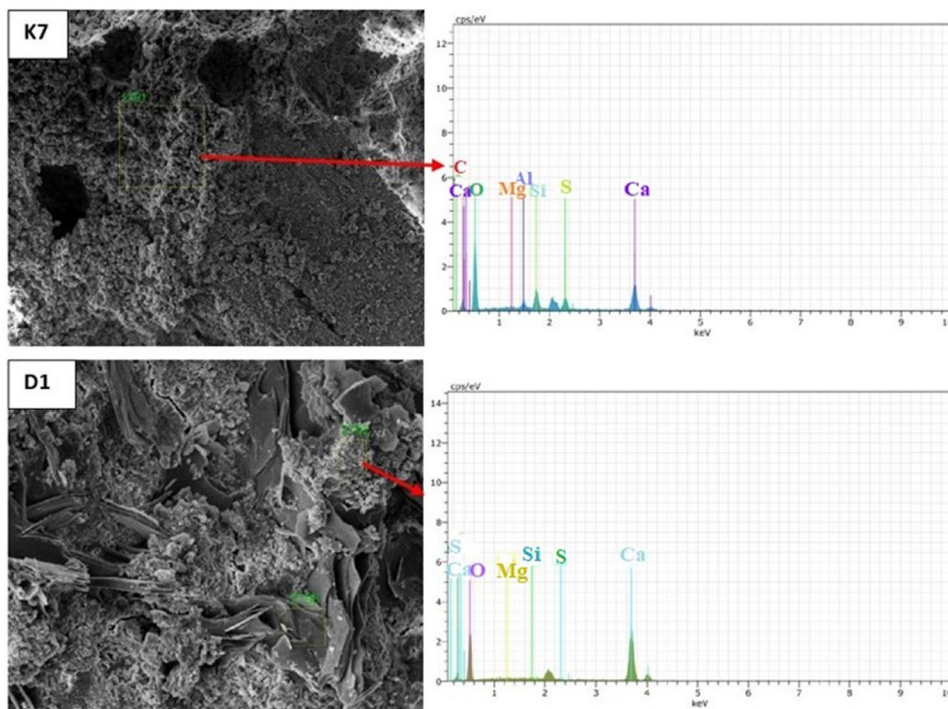


Figure 11: EDX analyses of samples containing shive (K7) and fiber (D1).

Figure 11 shows the results of EDX analyses confirmed by XRD analysis. The predominance of calcium, silicon, aluminum, and oxygen was determined. Figure 12 shows the holes in the shives samples. Large pore sizes have developed due to the presence of fibers. Despite these flaws, it increased the bending strength [34]. Figure 13 shows the hole size distribution of the K7 sample and the hole size distribution found in the cells of the hemp shive in the I1 sample. It is seen in both the SEM image and size distribution analysis that the gap size distributions of hemp cells are very different from each other.

3.4 Stereo microscope analysis

In Figure 14, the fibers used in the stereo microscope images are seen in the D1 and K1 samples and the shives in the I1 and I3 samples. Analysis of the fragment distribution of holes and shives is given in Figure 15. It is seen that the hole size distribution of the K7 sample obtained from SEM analysis in Figure 13 and the hole size distribution of the I3 sample obtained from the stereo microscope in Figure 15 are close to each other. In this case, it is seen that the stereo microscope and SEM images support each

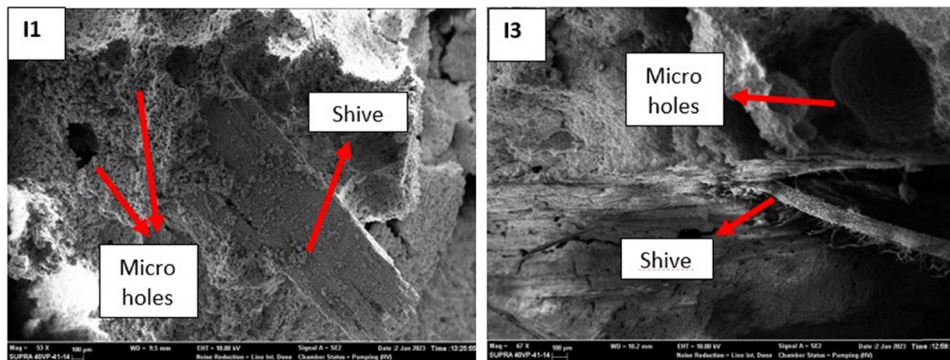


Figure 12: Holes in the shives of I1 and I3 samples.

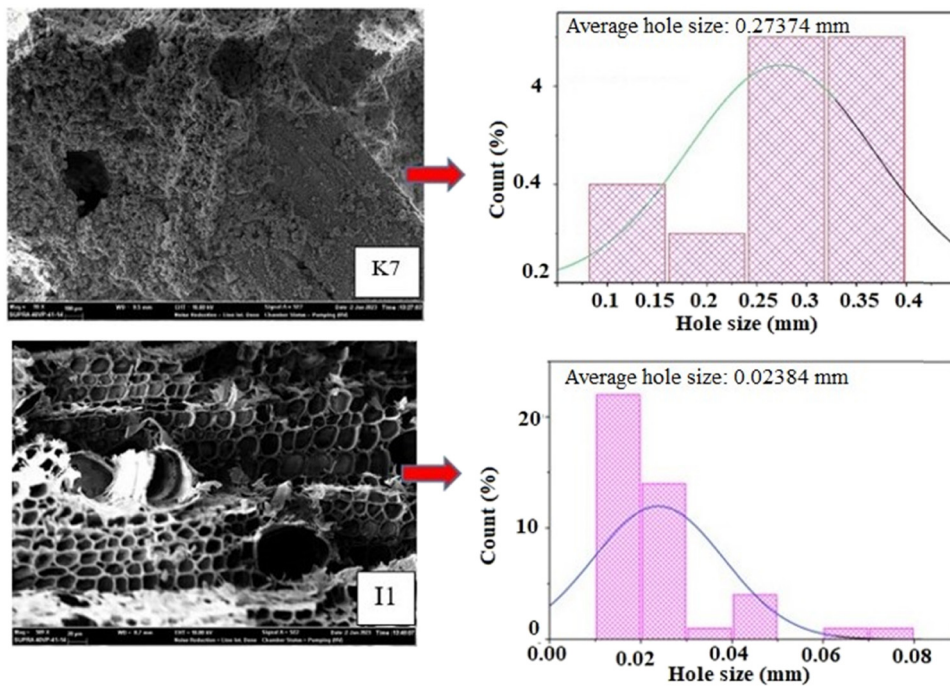


Figure 13: SEM analysis of hole size average of K7 sample and hemp shive cross-section in the I1 sample.

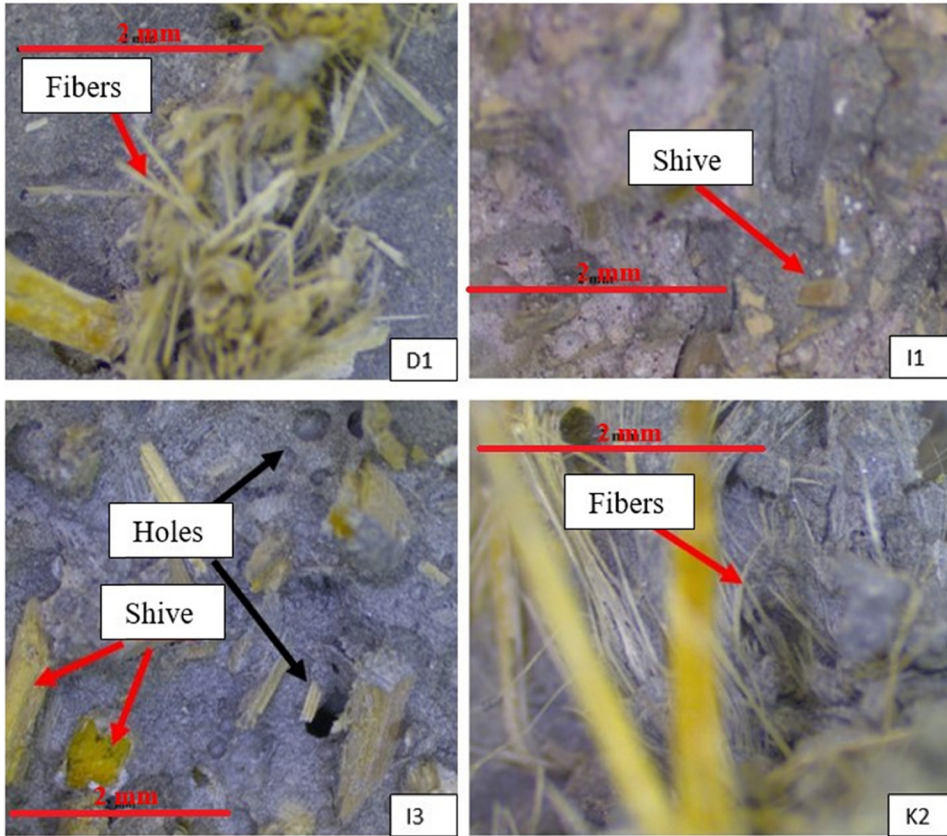


Figure 14: Stereo microscope images of D1, I1, I3, and K2 samples.

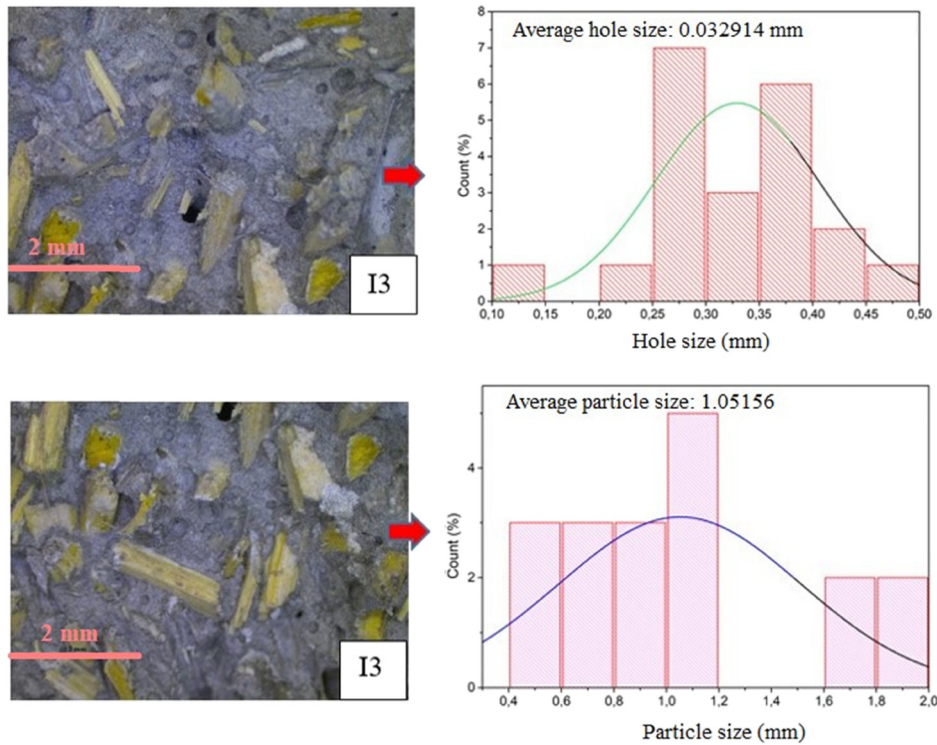


Figure 15: The distribution of the sizes of the holes and shives pieces of the I3 sample.

other. The presence of cavities significantly affects the mechanical behavior of concrete. As the cavity diameter increased from 0 to 20 mm, the compressive strength values of the samples containing the inner cavity decreased non-linearly [35].

3.5 XRD crystallography analysis

Analysis of the XRD data in Figures 16 and 17 shows that the crystal content of the wet shives (I1 and I3), dry shives (K2, K3, and K7), and fiber-containing (D1) mortar samples includes hematite (Fe_2O_3), cristobalite (SiO_2), portlandite ($\text{Ca}(\text{OH})_2 \cdot (3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2)$), quartz (SiO_2), and portlandite ($\text{Ca}(\text{OH})_2$). In the XRD spectrum of the

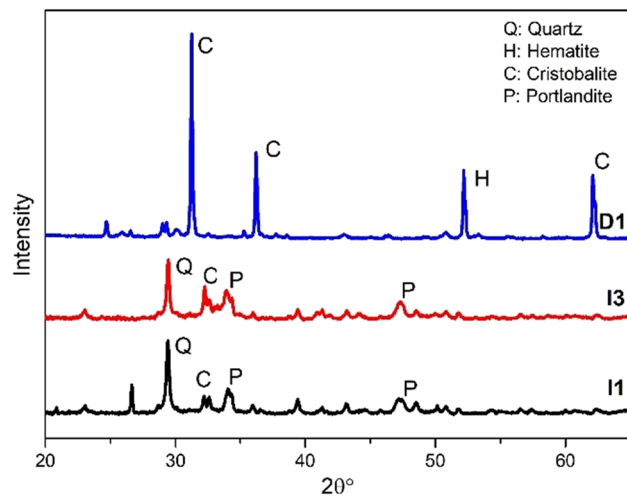


Figure 16: XRD analyses of samples (I1, I3, and D1).

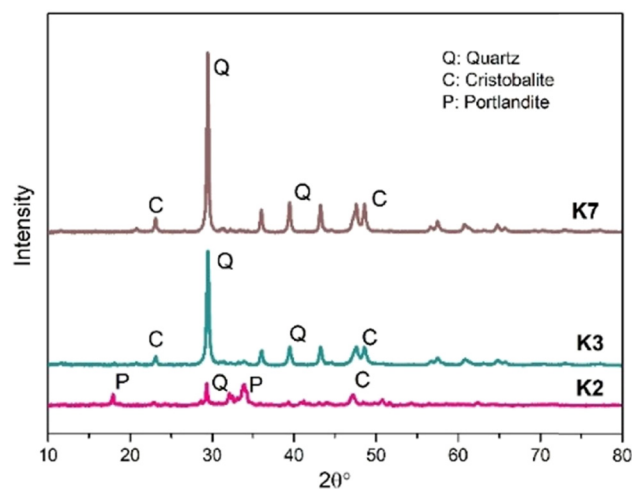


Figure 17: XRD analyses of samples (K2, K3, and K7).

samples, quartz traces with a wide peak were observed in the 20–30° 2θ region [36,37].

4 Conclusion

As expected, the flexural strength values of the fibrous samples in the produced samples gave nine times better results than the shive samples. The fibers increased the toughness of the samples compared to the shives samples. In fact, as the fibers' ratios increased, the flexural strengths increased even more. The use of hemp fibers can be a good alternative to steel and synthetic fibers. It was observed that the shives formed voids in the samples, lightening the sample, but decreasing the strength values. The water absorption and porosity of the shives were higher than the fibrous samples. In this case, research can be made for their use in thermal insulation materials to shed light on future studies.

Acknowledgments: The author would like to thank Bilecik Şeyh Edebali University Scientific Research Projects Coordinatorship for their support to the project numbered 2022-01.BŞEÜ.03-08 at Bilecik Şeyh Edebali University Central Campus.

Funding information: There is no funding for this article.

Author contributions: The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and article preparation.

Conflict of interest: The author declares no conflict of interest.

Ethical approval: The conducted research is not related to either human or animal use.

Data availability statement: Derived data supporting the findings of this study are available from the corresponding author on request.

References

- [1] Zhu S, Shi W, Zhang J. Effect of different ramie (*Boehmeria nivea* L. Gaud) cultivars on the adsorption of heavy metal ions cadmium and lead in the remediation of contaminated

- farmland soils. *Open Chem.* 2022;20:444–54. doi: 10.1515/chem-2022-0162.
- [2] Jami T, Karade SR, Singh LP. A review of the properties of hemp concrete for green building applications. *J Clean Prod.* 2019;239:117852. doi: 10.1016/j.jclepro.2019.117852.
- [3] Dlimi M, Agounoun R, Kadirli I, Saadani R, Rahmoune M. Thermal performance assessment of double hollow brick walls filled with hemp concrete insulation material through computational fluid dynamics analysis and dynamic thermal simulations. *E-Prime-Adv Electr Eng Electron Energy.* 2023;3:100124. doi: 10.1016/j.prime.2023.100124.
- [4] Latif E, Lawrence M, Shea A, Walker P. Moisture buffer potential of experimental wall assemblies incorporating formulated hemp-lime. *Build Env.* 2015;93:199–209. doi: 10.1016/j.buildenv.2015.07.011.
- [5] Kinnane O, Reilly A, Grimes J, Pavia S, Walker R. Acoustic absorption of hemp-lime construction. *Constr Build Mater.* 2016;122:674–82. doi: 10.1016/j.conbuildmat.2016.06.106.
- [6] Fernea R, Tămaş-Gavrea DR, Manea DL, Roşca IC, Aciu C, Munteanu C. Multicriterial analysis of several acoustic absorption building materials based on hemp. *Procedia Eng.* 2017;181:1005–12. doi: 10.1016/j.proeng.2017.02.500.
- [7] Arrigoni A, Pelosato R, Melià P, Ruggieri G, Sabbadini S, Dotelli G. 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.* 2017;149:1051–61. doi: 10.1016/j.jclepro.2017.02.161.
- [8] Barbhuiya S, Bhusan Das B. A comprehensive review on the use of hemp in concrete. *Constr Build Mater.* 2022;341:127857. doi: 10.1016/j.conbuildmat.2022.127857.
- [9] Ip K, Miller A. Life cycle greenhouse gas emissions of hemp-lime wall constructions in the UK. *Resour Conserv Recycl.* 2012;69:1–9. doi: 10.1016/j.resconrec.2012.09.001.
- [10] Delannoy G, Marceau S, Glé P, Gourlay E, Guéguen-Minerbe M, Amziane S, et al. Durability of hemp concretes exposed to accelerated environmental aging. *Constr Build Mater.* 2020;252:119043. doi: 10.1016/j.conbuildmat.2020.119043.
- [11] Abdalla JA, Thomas BS, Hawileh RA. Use of hemp, kenaf and bamboo natural fiber in cement-based concrete. *Mater Today Proc.* 2022;65:2070–2. doi: 10.1016/j.matpr.2022.06.428.
- [12] Stevulova N, Cigasova J, Estokova A, Terpakova E, Geffert A, Kacik F, et al. Properties characterization of chemically modified hemp hurds. *Mater (Basel).* 2014;7:8131–50. doi: 10.3390/ma7128131.
- [13] Kidalova L, Stevulova N, Terpakova E, Sicakova A. Utilization of alternative materials in lightweight composites. *J Clean Prod.* 2012;34:116–9. doi: 10.1016/j.jclepro.2012.01.031.
- [14] Arnaud L, Gourlay E. Experimental study of parameters influencing mechanical properties of hemp concretes. *Constr Build Mater.* 2012;28:50–6. doi: 10.1016/j.conbuildmat.2011.07.052.
- [15] Stella Mary F, Nithambigai G, Rameshwaran PM. Effect of binders and hemp fibre in concrete. *Mater Today Proc.* 2020;46:3791–4. doi: 10.1016/j.matpr.2021.02.029.
- [16] Malenab RAJ, Ngo JPS, Promentilla MAB. Chemical treatment of waste abaca for natural fiber-Reinforced geopolymer composite. *Mater (Basel).* 2017;106:579. doi: 10.3390/ma10060579.
- [17] Kirilovs E, Gusovius H-J, Kukle S, Emsins J. Performance of fibreboards made from wetpreserved hemp. *Mater Sci Text Cloth Technol* 2014;8:65. doi: 10.7250/mstct.2013.011.
- [18] Li Z, Wang X, Wang L. Properties of hemp fibre reinforced concrete composites. *Compos Part A Appl Sci Manuf.* 2006;37:497–505. doi: 10.1016/j.compositesa.2005.01.032.
- [19] Sáez-Pérez MP, Brümmer M, Durán-Suárez JA. Effect of the state of conservation of the hemp used in geopolymer and hydraulic lime concretes. *Constr Build Mater.* 2021;285:122853. doi: 10.1016/j.conbuildmat.2021.122853.
- [20] Bennai F, Ferroukhi MY, Benmahiddine F, Belarbi R, Nouviaire A. Assessment of hygrothermal performance of hemp concrete compared to conventional building materials at overall building scale. *Constr Build Mater.* 2022;316:126007. doi: 10.1016/j.conbuildmat.2021.126007.
- [21] Wambua P, Ivens J, Verpoest I. Natural fibres: Can they replace glass in fibre reinforced plastics? *Compos Sci Technol.* 2003;63:1259–64. doi: 10.1016/S0266-3538(03)00096-4.
- [22] Mercedes L, Bernat-Maso E, Gil L. Bending and compression performance of full-scale sandwich panels of hemp fabric reinforced cementitious matrix. *Eng Struct.* 2023;275:115241. doi: 10.1016/j.engstruct.2022.115241.
- [23] Mostefai N, Hamzaoui R, Guessasma S, Aw A, Nouri H. Microstructure and mechanical performance of modified hemp fibre and shiv mortars: Discovering the optimal formulation. *Mater Des.* 2015;84:359–71. doi: 10.1016/j.matdes.2015.06.102.
- [24] Bledzki AK, Gassan J. Composites reinforced with cellulose. *Bledzki_1999.pdf.* *Prog Polym Sci.* 1999;24:221–74.
- [25] Stamboulis A, Baillie CA, Peijs T. Effects of environmental conditions on mechanical and physical properties of flax fibers. *Compos Part A Appl Sci Manuf.* 2001;32:1105–15. doi: 10.1016/S1359-835X(01)00032-X.
- [26] Sedan D, Pagnoux C, Smith A, Chotard T. Mechanical properties of hemp fibre reinforced cement: Influence of the fibre/matrix interaction. *J Eur Ceram Soc.* 2008;28:183–92. doi: 10.1016/j.jeurceramsoc.2007.05.019.
- [27] Zimniewska M. Hemp fibre properties and processing target textile: A review. *Mater (Basel).* 2022;15:1901. doi: 10.3390/ma15051901.
- [28] Stevulova N, Kidalova L, Cigasova J, Junak J, Sicakova A, Terpakova E. Lightweight composites containing hemp hurds. *Procedia Eng.* 2013;65:69–74. doi: 10.1016/j.proeng.2013.09.013.
- [29] García-González J, Faria P, Pereira AS, Lemos PC, Juan-Valdés A. A sustainable production of natural hydraulic lime mortars through bio-amendment. *Constr Build Mater.* 2022;340:127812. doi: 10.1016/j.conbuildmat.2022.127812.
- [30] Naciri K, Aalil I, Chaaba A. Eco-friendly gypsum-lime mortar with the incorporation of recycled waste brick. *Constr Build Mater.* 2022;325:126770. doi: 10.1016/j.conbuildmat.2022.126770.
- [31] Al-Kheetan MJ. Performance improvement of hemp-shiv cementitious composites through hot water and steam treatment. *Constr Build Mater.* 2023;367:130315. doi: 10.1016/j.conbuildmat.2023.130315.
- [32] Candamano S, Crea F, Coppola L, De Luca P, Coffetti D. Influence of acrylic latex and pre-treated hemp fibers on cement based mortar properties. *Constr Build Mater.* 2021;273:121720. doi: 10.1016/j.conbuildmat.2020.121720.
- [33] Hakamy A, Shaikh FUA, Low IM. Effect of calcined nanoclay on the durability of NaOH treated hemp fabric-reinforced cement nanocomposites. *Mater Des.* 2016;92:659–66. doi: 10.1016/j.matdes.2015.12.097.

- [34] Le Hoang T, Boutouil M, Khadraoui F, Gomina M. Mechanical and microstructural characterization of flax fibre-reinforced cement composite. Proc 11th Japan-Korea- Fr Jt Semin Geoenvironmental Eng. vol. 11; 2012. p. 131–6.
- [35] Zhang K, Wang C, Zhao Y, Bi J. Experimental study on cracking behavior of concrete containing hole defects. J Build Eng. 2023;65:105806. doi: 10.1016/j.jobe.2022.105806.
- [36] Arivumangai A, Narayanan RM, Felixkala T. Study on sulfate resistance behaviour of granite sand as fine aggregate in concrete through material testing and XRD analysis. Mater Today Proc. 2020;43:1724–9. doi: 10.1016/j.matpr.2020.10.354.
- [37] Badgujar S, Kumar Dwivedi A. Microstructural analysis of self-compacting concrete – A review. Mater Today Proc. 2022;65:1250–9. doi: 10.1016/j.matpr.2022.04.185.