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Innovative earth–hemp–hydraulic lime bio- and geo-based composite for sustainable seismic applications

Abdelhamid Elmountassir[1*], Khalid Elkhalidi[2], Hanane Ait Hmeid[2], Fatima Majid[3], Abdelilah Mihraje[2], Mohammed Lamrani[5], Fouad Belhora[1], Said Laasri[1,5]

[1] Energy Science Engineering Lab, National School of Applied Sciences (ENSAJ), Chouaib Doukkali University, El Jadida, Morocco
[2] Laboratory of Marine Geosciences and Soil Science (LGMSS-URAC 45), Faculty of Sciences (FS), Chouaib Doukkali University, El Jadida, Morocco
[3] Laboratory of Nuclear, Atomic, Molecular, Mechanical and Energetic Physics, Faculty of Sciences (FS), Chouaib Doukkali University, El Jadida, Morocco
[4] Mohammed V University of Rabat, EST de Salé, Salé, Morocco
[5] Polydisciplinary Faculty of Sidi Bennour, Chouaib Doukkali University, El Jadida, Morocco
* Corresponding author's e-mail: elmountassir.a@ucd.ac.ma

ABSTRACT

The construction sector requires environmentally sustainable materials that reduce embodied carbon while maintaining adequate mechanical performance for practical applications. This study aimed to investigate the influence of crushed Moroccan hemp shives on the physicochemical and mechanical behavior of a locally sourced earth–lime composite and to determine its optimum formulation for sustainable non-load-bearing building applications. The investigated composite was produced using soil collected from Eljadida, Casablanca–Settat Region (Moroccan Meseta), stabilized with 15 wt.% hydraulic lime and incorporating 0–6 wt.% crushed Moroccan hemp shives. The raw materials were characterized by particle-size distribution, Atterberg limits, methylene blue value, X-ray diffraction (XRD), moisture content, density, and SEM–EDX analyses. Composite specimens were cured for 28 days and tested to determine dry density, capillary water absorption, compressive strength, flexural strength, and deformation behavior. The results demonstrated that the incorporation of hemp significantly modified the physical and mechanical properties of the composite. Dry density decreased from 1277 to 1193 kg/m³ as hemp content increased from 0 to 6 wt.%. The optimum formulation contained 4.5 wt.% hemp, achieved a compressive strength of 0.76 MPa (approximately 29% higher than the reference composite) and a maximum flexural strength of 5.32 MPa (approximately 139% improvement), together with markedly enhanced ductility and post-peak deformation capacity. Increasing the hemp content to 6 wt.% reduced both compressive and flexural strength because of excessive porosity and reduced matrix cohesion, while capillary water absorption increased with hemp content, highlighting the importance of moisture protection during service. The study is limited to laboratory-scale characterization after 28 days of curing and does not include long-term durability or life-cycle assessment. Nevertheless, the results demonstrate the feasibility of producing a locally sourced earth–lime–hemp composite with an improved balance between density, strength, and ductility. The proposed formulation offers a sustainable alternative for non-load-bearing building applications by valorizing local soil and agricultural hemp residues while reducing dependence on conventional construction materials. The integration of comprehensive physicochemical characterization with mechanical and hygroscopic evaluation provides new experimental evidence supporting the optimization of Moroccan earth–lime–hemp composites for sustainable construction.

Keywords: local geo-materials, earth, hydraulic lime, hemp fibers, mechanical behavior, hygroscopic behavior.

INTRODUCTION

In a context of growing concerns about environment and the climate emergency, the construction sector is under unprecedented pressure to reduce its ecological footprint; according to numerous studies, construction is one of the biggest energy consumers and contributors to GHG (greenhouse gas) emissions, both through the construction, operation, and maintenance of structures and the production of materials used in construction (Jannat et al., 2020).

This situation requires not only the improvement of energy efficiency for buildings during their operational phase, but also, and most significantly, a very large reduction of the energy consumption and GHG emissions associated with the production of construction materials.

In this context, the concept of embodied energy, representing the total energy consumed throughout the whole life cycle of a material, including raw material extraction, production process, delivery, construction, and management of end-of-life waste, has become a key indicator of sustainability.

Beyond reducing operational energy consumption, increasing attention is also being directed toward environmentally compatible construction materials that interact positively with natural ecosystems and indoor environmental quality. Recent studies have highlighted that sustainable engineering solutions should address not only energy efficiency but also the broader ecological functions of natural materials within the built environment (Amziane et al., 2016; Alam et al., 2026). This broader perspective further supports the development of bio- and geo-based construction materials as promising low-carbon alternatives.

Recent studies have also emphasized that environmental conditions strongly influence the physical, chemical, and biological properties of soils, which in turn affect their long-term performance and sustainability. This highlights the importance of a comprehensive characterization of local soils prior to their use in engineering and construction applications (Fabbri et al., 2022).

Several studies (Amziane et al., 2016) have demonstrated the multiple benefits of bio-based concrete, such as low embodied energy due to the fibers' ability to store carbon during their growth, their local availability, and the absence of industrial processing, which results in low energy demand, low production costs, and a reduced environmental footprint.

Current state of knowledge on earth–lime–hemp composites

The literature shows that the mechanical behaviour of hemp-based composites is influenced by several parameters, such as dry density, binder type and percentage, the hemp-to-binder ratio, curing conditions, compaction level, and hemp particle size. Reported dry densities generally range from 140 to 600 kg/m³ for lightweight hemp–lime composites and from 350 to 550 kg/m³ for hemp–clay composites, whereas heavily compacted lime mortars reinforced with hemp may exceed 1200 kg/m³. Correspondingly, compressive strength commonly varies between 0.10 and 1.20 MPa, although values above 3 MPa have been obtained for dense lime-based mortars containing low hemp contents.

Increasing the hemp content generally reduces the composite density and compressive strength because of the increase in total porosity and the reduction in the continuous mineral matrix. However, moderate hemp additions considerably improve ductility, crack resistance, and post-peak behaviour. Several authors reported that an optimum hemp content exists, beyond which fibre agglomeration, poor coating, and excessive porosity become detrimental to mechanical performance. This optimum generally lies between 2 and 5% for fibre-reinforced mortars, although it depends strongly on the binder composition and manufacturing process.

Unlike compression, flexural behaviour is usually enhanced by hemp incorporation. Hemp fibres and shives act as crack-bridging elements, delaying crack propagation and increasing fracture energy. Most published studies reported flexural strengths between 0.4 and 1.2 MPa, while higher values have been obtained for denser matrices and optimized fibre distributions. In most cases, hemp incorporation tends to improve the ductility and post-cracking behaviour of the composite more than its maximum compressive strength.

Another important characteristic of hemp-based composites is their excellent hygroscopic performance. The literature has reported Moisture Buffer Values (MBV) of approximately 2.1 to 3.6 $g \cdot m^{-2} \cdot \%RH^{-1}$, confirming the high moisture-regulation capacity of these materials.

Binder optimization is now receiving more attention from researchers. The contribution of replacing a certain proportion of hydraulic/hydrated lime with cementitious additives such as metakaolin, calcined clay, and waste brick powder in improving both strength and durability has been confirmed. The variety of hemp particle size usually leads to better homogeneity of the matrix and mechanical properties due to the reduced size of particles, but may increase the amount of water needed.

Table 1 summarizes representative studies published between 2016 and 2025 on hemp-based earth and lime composites. Overall, the literature demonstrates the great potential of utilizing hemp-based composites for sustainable construction, highlighting that achieving the right balance between density, compressive strength, flexural performance and hygroscopic behaviour requires careful optimization of hemp content,

Table 1. Summary of recent studies on hemp–lime, hemp–clay and earth–hemp composites (2016–2025)

Authors	Material	Hemp (%)	Lime (%)	Density (kg/m³)	Compression (MPa)	Flexural (MPa)	Hygroscopic behaviour	Main conclusions
Aymerich et al., 2016	Earth + hemp fibres	2 and 3%	—	—	—	Hem↑ fracture energy↑	—	Crack bridging
Mazhoud et al., 2017	Hemp–clay	H/B 0.40/0.75	—	350–550	0.39–0.68	—	Good	Stabilized clay improves strength
Tronet et al., 2016	Hemp–lime	B/H 2.0 to 3.6	Variable	200–840 literature	<2.0	—	—	Compaction controls strength
Mazhoud et al., 2016	Hemp–lime plaster	Sizes variable	Lime	720–880	—	—	MBV 0.67–1.64	Excellent moisture regulation
Hussain et al., 2019	Hemp insulation composite	Several formulations	starch and silica	175–240	Good mechanical performance	—	MBV up to 3.6	Excellent hygrotherm behaviour
Piątkiewicz et al., 2020	Hemp–lime	Variable	Variable	Average ≈380	0.32–0.57	—	Vapour permeable	Density controls strength
Abdellatef et al., 2020	Hemp–lime	Variable	Variable	300–400	0.09–0.57	Splitting tensile	MBV ≈2.8	Good balance of properties
Brzyski et al., 2020	Hemp–lime	Variable	Lime	—	↑ with fine shives	—	High absorption	Fine shives improve strength
Mazhoud et al., 2021	Hemp–clay	Variable	—	350–550	—	—	λ=0.089–0.120	Excellent hygroscopicity
Parcesepe et al., 2021	Lime mortar + hemp fibres	0.2%	NHL 3.5	1760–1880	3–6	1–2	Absorption increased	Fibres improve flexure
Zerrouki et al., 2022	Hemp concrete + metakaolin	Variable	85	—	Improved with metakaolin	Improved	Better durability	Pozzolanic reaction beneficial
Avudaiappan et al., 2023	Lime mortar + hemp	2–6	Lime	1273–1407	Up to 3.48	6.4–7.6	Higher porosity	Optimum ≈4% hemp
Zúniga et al., 2023	Hemp + bagasse + lime	75/25 bioaggregate	Lime	—	+19–24%	—	Absorption −35%	Hybrid bioaggregates beneficial
Łapka et al., 2023	Hemp + gum arabic	Variable	Lime	—	0.38–0.73	—	Improved	Better interface
Mahmood et al., 2024	Hemp–lime	30–70	Lime	140–200	↑ with density	—	MBV 2.12–2.47	Fine shives improve homogeneity
Ayati et al., 2024	Hemp–silica / hemp–lime	Variable	-	400–450	1.53–1.92	—	Good	Reactive binders improve strength
Haustein et al., 2018	Lime–cement–hemp	30	10–12	335–506	0.81–0.94	—	μ=3.6–4.0	Lower lime reduces density
Nair et al., 2025	Hemp + calcined clay+ limestone	Ratio 1:1.8:1:2	50 replacement	475–620	0.16–0.65 Improved	—	—	Low-carbon binder
Piątkiewicz et al., 2026	Hemp–lime	Variable	Variable	227–518	0.24–0.53	—	—	Testing method affects results

lime dosage and compaction process. Although hemp–lime and hemp–clay composites have been extensively investigated, research literature specifically focusing on earth–lime–hemp composites remains comparatively limited. Furthermore, most previous investigations have focused on individual aspects of material performance, such as mechanical properties, thermal behaviour or hygroscopic capacity, whereas comprehensive studies simultaneously integrating geotechnical characterization, physicochemical and microstructural analyses, together with compressive and flexural behaviour, remain scarce. In addition, only a limited number of investigations have examined composites manufactured entirely from locally available geo- and bio-based resources, despite their significant environmental and economic advantages. Consequently, establishing clear relationships between soil characteristics, binder composition, fibre incorporation and the resulting engineering performance remains a major scientific challenge. Addressing these issues through an integrated experimental methodology constitutes one of the principal contributions of the present study and provides new insights into the development of sustainable, locally sourced and earthquake-resilient earth-based composites.

These scientific gaps limit the establishment of reliable design guidelines for earth–lime–hemp composites and justify further comprehensive experimental investigations. To address these limitations, the present work adopts an integrated experimental approach by combining geotechnical characterization of a local Moroccan soil, physicochemical analyses, mineralogical investigations, mechanical characterization under compression and three-point bending, and hygroscopic evaluation within a single experimental programme. This multidisciplinary methodology provides a comprehensive understanding of the interactions between soil, hydraulic lime and crushed Moroccan hemp shives, thereby contributing to the development of sustainable, locally sourced and earthquake-resilient construction materials.

The objective of this study is to evaluate the feasibility of producing an earth–lime–hemp composite manufactured exclusively from locally available geo- and bio-based materials from the Casablanca–Settat region of Morocco and to investigate the influence of crushed Moroccan hemp shives and hydraulic lime on its physicochemical, mechanical and hygroscopic properties. The outcomes of this work contribute to the optimization of earth-based composites and to the broader development of locally sourced low-carbon construction materials for sustainable earthquake-resilient buildings.

To achieve these objectives, an integrated experimental programme was designed using locally sourced geo- and bio-based materials.

Preliminary mixtures of earth with 5 and 10 wt.% hydraulic lime were used, but the results of the 28-day compression tests showed little effect on the compressive strength of the mixture, so a 15 wt.% hydraulic lime content was chosen.

We first characterized the raw materials (granulometry, morphology, physicochemical composition, etc.), which will enable us to enrich existing databases for formulating local materials. Understanding the properties of the raw materials is crucial for the implementation of a high-performance construction material adapted to the particular use in the region (Mabrouk et al., 2022).

Moroccan hemp: culture, legislation, and impacts

Historically cultivated in the mountainous Rif region of northern Morocco, where the climate and soil are particularly suited, hemp, or traditional cannabis, “Beldia,” has long been a vital source of income for local communities, despite its cultivation being illegal. Law No. 13-21, enacted in 2021, marked a major turning point by authorizing the cultivation and exploitation of cannabis for medical, cosmetic, and industrial purposes, with oversight from ANRAC (National Agency for the Regulation of Cannabis-Related Activities). This legalization aims to transform the informal economy into a legal sector, offering new economic opportunities for farmers. The impact on the local population is highly significant, with the hope of improving living conditions, providing legal income, and reducing crime related to illicit trafficking (Uwikunda et al., 2024).

Hemp is a rapidly growing plant, with modest needs in terms of water, pesticides, or fertilizers, and its cultivation sequesters atmospheric CO_2 through photosynthesis during growth. Furthermore, the Moroccan “Beldia” variety has intrinsic advantages, such as its resilience to drought and its adaptation to arid climatic conditions. The use of its fibers in construction is therefore appropriate for sustainability goals and the reduction of the carbon footprint of buildings. The stalk’s woody part, or hemp shiv, is often considered a valueless product and is often thrown away or underutilized. Its multiple qualities for ecological construction applications make its revalorization not only relevant but also highly advantageous (Niyigena et al., 2017).

MATERIALS AND METHODS

Geological setting

Geographically, El Jadida is located in the coastal Doukkala–Abda region of western Morocco. From a geological perspective, it lies on the northwestern margin of the Moroccan Meseta (Figure 2). The bedrock consists of an ancient basement ranging in age from the Late Precambrian to the Cambrian, whose geological evolution is closely associated with the rifting of the Central Atlantic and the development of regional carbonate platforms (Medina, 1995; El Achheb, 2002).

Sampling

Before sampling, approximately 30 cm of the surface layer was removed to eliminate topsoil, organic matter, and plant debris that could affect the material properties. Preliminary site observations indicated that the underlying soil exhibited a uniform geological profile to a depth of approximately 1.50 m below the natural ground surface. Consequently, a representative volume of soil was collected from this layer for physicochemical and mechanical characterization Figure 1.

Materials characterization

To characterize the particle size distribution of the foundation soil, a granulometric analysis was carried out in accordance with ASTM D6913/D6913M and the Moroccan standard NM

Figure 1. Sampling area and foundation soil.

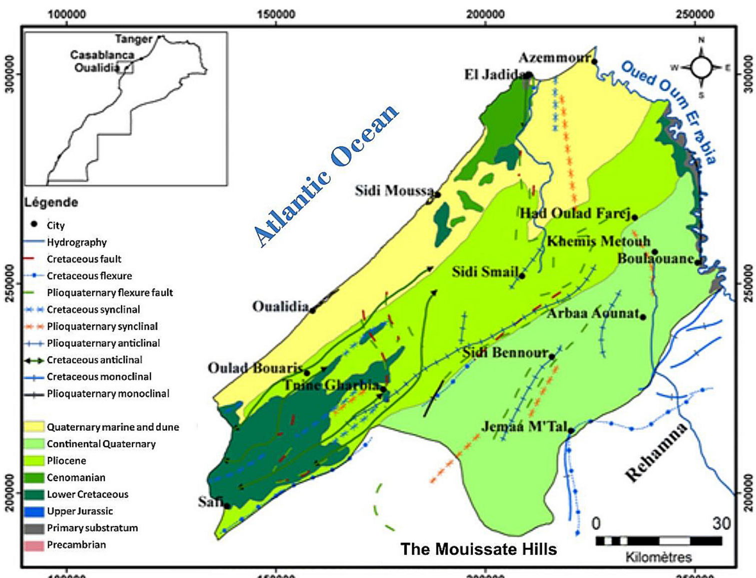

Figure 2. Simplified geological map of the study area, Doukkala sahel zone (Ferré and Ruhard, 1975)

13.1.008. This method consists of passing the sample through a series of sieves with decreasing mesh sizes, then determining the mass percentage of material retained on each sieve.

The fineness modulus (FM) gives us a quick idea of the dominant texture of the soil; it equals the sum of the cumulative percentages retained on the standard sieves (0.16, 0.315, 0.63, 1.25, 2.5, 5 mm), divided by 100. The sand equivalent (SE) of soil was obtained through the use of Moroccan Standard NM 933-8 for purposes of finding out the relative amounts of sand content in soil as well as fine clay-like particles.

The Atterberg limits were determined in accordance with ASTM D4318 and the Moroccan Standard NM 13.1.007. The liquid limit and plastic limit were measured to evaluate the consistency and plasticity characteristics of the soil. The methylene blue value (MBV) test was carried out in accordance with ASTM C837 and the Moroccan Standard NM 13.1.178 to assess the clay content and the activity of fine particles present in the soil.

Hydraulic lime: Composition and benefits

Based on the French standard NF EN 459, the main component of construction limes is calcium hydroxide ($Ca(OH)_2$). It also contains calcium silicates and calcium aluminates resulting from the reaction of calcium oxide (CaO) with alumina (Al_2O_3), silica (SiO_2), and iron oxide (Fe_2O_3) present in the original limestone (Ammari et al., 2017). These limes set and harden when exposed to water; they reabsorb carbon dioxide (CO_2) from the air through carbonation, thereby enhancing hardening. The hydraulic lime used is sourced locally and was chosen for its many benefits for earth-hemp plant-based concretes; a breathable material, when used indoors, naturally regulates ambient humidity, contributing to indoor comfort and preventing condensation and mold. In addition, it provides resistance to water and adverse weather conditions and has fungicidal and bactericidal properties that limit material degradation. Finally, its production, which is done by firing raw clayey limestone at temperatures between 900 °C and 1200 °C, is less energy-intensive and emits less CO_2 than that of cement, thus being part of a sustainable construction approach.

Mineralogy by XRD

The mineralogical composition of the untreated soil and hydraulic lime was characterized using a Bruker D8 ADVANCE ECO X-ray diffractometer (XRD). The diffraction patterns were analyzed, and the crystalline phases were identified using the International Centre for Diffraction Data (ICDD) database.

Moroccan hemp: Preparation of fibers

The hemp stalks are first cleaned to remove impurities and fines, then ground to produce aggregates that can be more effectively integrated into plant-based concrete. Additional grinding may be performed to obtain a suitable particle size. This preparation step ensures better homogeneity of the mixture and optimal interaction between the plant fibers and the hydraulic earth-lime binder.

Moisture content of the main aggregates: Soil and hemp

The moisture content of aggregates is a fundamental property of construction materials. The determination was made in accordance with standard NF EN ISO 181343 by calculating the difference between the soil's initial and dry weight (Mabrouk et al., 2022).

We used three soil samples with a diameter less than 2.5 mm and three hemp samples to conduct this test. Their initial weights in the presence of moisture and their dry weights after drying at 105 °C were measured. The test lasted 72 hours, and a series of measurements was taken until the dry mass and the moisture content stabilized.

The apparent density of the main aggregates

The dry bulk density of soil and hemp particles, defined as the mass of the material's dry particles divided by their total occupied volume, was measured using the [NF EN 1936] test standard (Mabrouk et al., 2022).

Preparation of samples of the Earth-lime-hemp composite material

To analyze the mechanical properties of the Earth-lime-hemp mixture, we prepared five formulations with different percentages of hemp

(0%, 1.5%, 3%, 4.5%, and 6%) and six samples of each formulation (three cubic samples 4 × 4 × 4 cm and three prismatic samples 4 × 4 × 8 cm). To obtain fine soil particles and improve the homogeneity of the composite, the soil was initially sieved through a 2.5 mm sieve. This procedure promotes a more uniform distribution of the lime binder and enhances the coating of the hemp shives within the earth matrix. The compositions of the earth–lime–hemp mixtures investigated in this study are summarized in Table 2. The hydraulic lime content was kept constant at 15 wt.%, while the hemp particle content was varied from 0 to 6 wt.% by partially replacing the soil fraction.

Cubic samples constitution

Regarding the cubes, the water quantities for the first three formulations were selected based on water-to-soil and water-to- (soil plus lime) ratios of 0.41 and 0.36, respectively. The fourth and fifth formulations, which are more concentrated in hemp, required more water; therefore, water-to-soil ratios of 0.47 and water-to- (soil plus lime) ratios of 0.41 were used (Table 3).

Prismatic samples constitution

The quantity of water used for the first three formulations was based on a water/soil ratio of 0.38 and a water/(soil plus lime) ratio of 0.33; in contrast, the fourth and fifth formulations, which contain a higher concentration of hemp, required more water, resulting in ratios of 0.41 for water/soil and 0.36 for water/(soil + lime), respectively (Table 4).

Samples preparation and curing conditions

The mixture was prepared using a mixer; a spatula and a metal ruler were used to spread and level the mixture. The soil and lime were first mixed, then the hemp particles were added; the three components were thoroughly mixed, then 50% of the total volume of water was incorporated, and the mixture was agitated thoroughly for one minute before gradually adding the remaining water; finally, the molds were filled with the previously prepared raw material. To simulate normal conditions on construction sites, the molds were manually compacted, and then the samples were kept for 28 days in the open air, in conditions of (17±2) °C temperature and a relative humidity of approximately 78%; Figure 3 shows prismatic samples of different formulations.

Water absorption test

The test for capillary water absorption was performed at ambient temperature (approximately 19 °C) on samples measuring 40 × 40 × 40 mm, previously dried in an oven for 72 hours at a temperature of 80 °C until a constant dry mass

Table 2. The constitution of the different formulations

Formulation	Soil	Hydraulic lime	Hemp particles
TCC 0	85.0	15.0	0.0
TCC 1.5	83.5	15.0	1.5
TCC 3	82.0	15.0	3.0
TCC 4.5	80.5	15.0	4.5
TCC 6	79.0	15.0	6.0

Table 3. The weight of the constituents in the different cubic sample formulations

Cubic samples	Soil weight (g)	Hemp weight (g)	15% lime weight (g)	Water weight (g)
TCC 0	51.39	0.00	7.71	21.10
TCC 1.5	51.31	0.89	7.70	20.45
TCC 3	51.33	1.79	7.70	21.21
TCC 4.5	51.33	2.67	7.69	24.11
TCC 6	51.28	3.55	7.70	24.35

Table 4. The weight of the constituents in the different prismatic sample formulations

Prismatic samples	Soil weight (g)	Hemp weight (g)	15% lime weight (g)	Water weight (g)
TCC 0	108.00	0.00	16.50	41.50
TCC 1.5	110.97	1.96	16.46	42.19
TCC 3	110.90	3.88	16.61	41.94
TCC 4.5	109.87	5.80	16.51	45.42
TCC 6	109.91	7.70	16.53	45.42

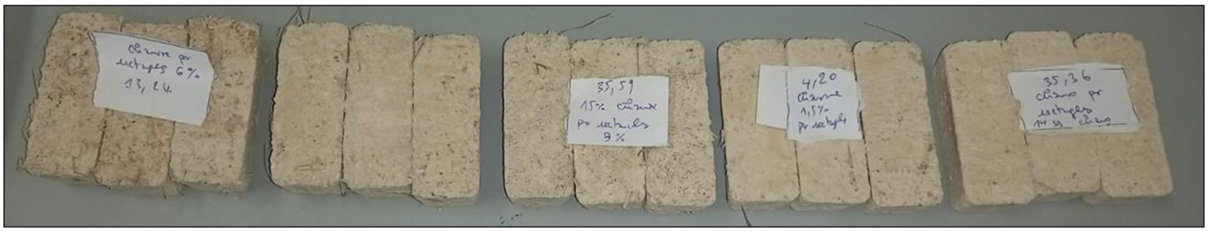

Figure 3. Prismatic samples with different contents of crushed hemp fibers

was achieved, then cooled to room temperature in a desiccator to avoid any absorption of moisture from the air. The side faces of the sample, except for the one that will be in contact with water, were covered with waterproof adhesive tape to ensure unidirectional absorption only from the lower face and to prevent any moisture exchange with the air (Amziane et al., 2023). The percentage of water absorption was therefore determined by calculating the change in the weight of the sample when immersed in water against its initial dry mass; the test was continued until the sample's saturated mass became stable, and lasted 80 minutes.

Density of the different formulations at 28 days

The density of the different composite material formulations at 28 days after curing was also determined; The results are listed in Table 6 in the results section.

SEM-EDX analysis

The microstructure analysis of a composite material sample was performed using a HIROX SH-5500P tabletop scanning electron microscope (SEM), designed for high-resolution surface analyses and observations. It is equipped with EDX (Energy-Dispersive X-ray Spectroscopy) analysis via an integrated system by BRUKER Nano, allowing elemental identification of samples.

Mechanical properties of the composite material

Compression tests on cubic specimens and 3-point bending tests on prismatic specimens

Figure 4. The mechanical tests using the MTS Criterion Model 43 machine, (a): The 3-point bending test, (b): The compression test

were performed using the MTS Criterion Model 43 machine (Figure 4), an electromechanical universal testing system (UTM) with a specific load capacity of 30 KN, designed to perform a wide range of mechanical tests (compression, bending, etc.) on various low- to medium-strength construction materials such as plant-based concretes, mortars, etc. It is equipped with high-precision force sensors to measure stress and with a sophisticated control system that allows testing at constant speed (deformation control) or constant load (load control). It also uses dedicated software for test programming, data acquisition, analysis, and report generation.

RESULTS

The results of the particle size analysis indicate that the percentage of fine particles (passing the 0.08 mm sieve) is 47%, that of particles smaller than 2.5 mm is 76%, and that of particles smaller than 20 mm is 98%. The Fineness Modulus of the soil gives a value of 2 and the sand equivalent test indicates a sand equivalent of 15%, corresponding to a soil with approximately 85% clay and silt; The Atterberg Limits of the soil show a liquid limit LL of 42% and a plasticity index PI of 17; The methylene blue value MBV obtained is 1.72 indicating a high proportion of fine particles and fine-to-medium sand; These characteristics are considered favorable for earth-based construction materials, because the clay and silt particles, combined with hydraulic lime, create a denser and more effective binding matrix by filling the voids between the sand grains and the hemp shives. A graphical representation of the data, using a logarithmic scale for sieve diameter, yields the granulometric curve of the foundation soil in Figure 5.

Soil classification

According to the LCPC classification (Central Laboratory of Bridges and Roads) (Bekkouche et al., 2016), the analyzed soil is a calcareous tuff Tf A2; it can also be classified as a silty sand according to the GMTR classification (MOROCCAN GUIDE FOR ROAD EARTHWORKS)(Ministère de l'Équipement et des Transports, 2001).

Moroccan hemp: Preparation of fibers

The resulting fibers have lengths ranging from 0.5 to 2.5 cm and thicknesses from 1 to 3 mm, with approximately 20% in the form of hemp wool or hemp tow, as shown in Figure 6.

Moisture content of the raw materials: local soil and hemp shives

The results of the moisture tests are presented in Table 5; The tests highlight that the average moisture content of the hemp samples is approximately 8.31%, and that of the soil samples is 1.55%.

The apparent density of the main aggregates

The results showed an apparent density of 65 kg/m³ for hemp and approximately 1037 kg/m³ for the soil sample.

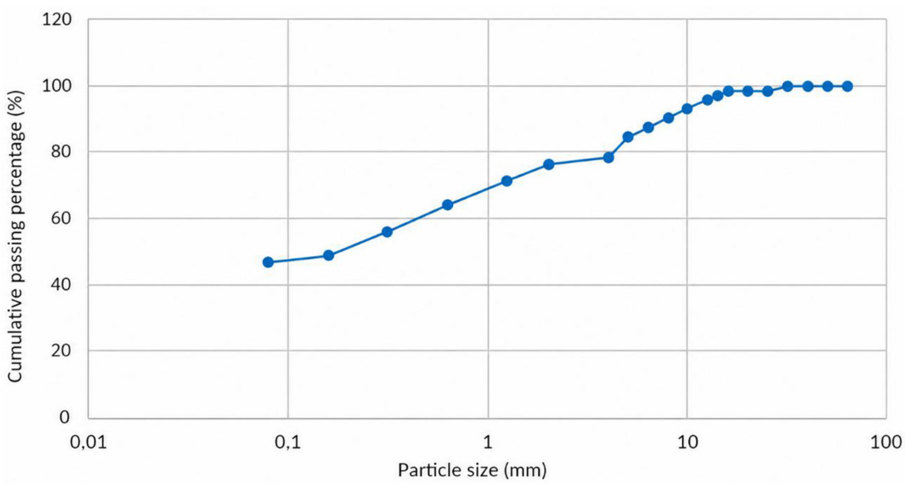

Figure 5. Granulometric curve of the foundation soil

Figure 6. Hemp fibers with approximately 20% in the form of hemp wool or hemp tow

Table 5. The results of the moisture tests of soil and hemp fibers

Material	Sample N	Moisture content (%)
	1	1.53
Soil	2	1.59
	3	1.54
	1	8.31
Hemp	2	8.21
	3	8.41

Mineralogy by XRD of raw soil and hydraulic lime samples

The X-ray diffraction (XRD) analysis indicates the mineralogical composition of the untreated soil (raw sample) and hydraulic lime (Figure 7).

Water absorption test

The water absorbed by plant-based concrete significantly affects its thermal behavior and mechanical strength. Plant particles such as hemp fibers are highly absorbent, which can cause separation between the particles and the matrix. Furthermore, during drying, water evaporation creates voids at the interfaces between plant particles, leading to a network of imperfections and, consequently, a significant reduction in the material's mechanical strength. Moreover, plant-based concretes dry quickly, leading to microcracks in the matrix that significantly reduce the material's durability (Mabrouk et al., 2022).

The maximum water absorption values found for the formulations are 13.7% for 0% hemp, 19.8% for 1.5% hemp, and 29.9% for 4.5% hemp. This demonstrates that increasing the concentration of

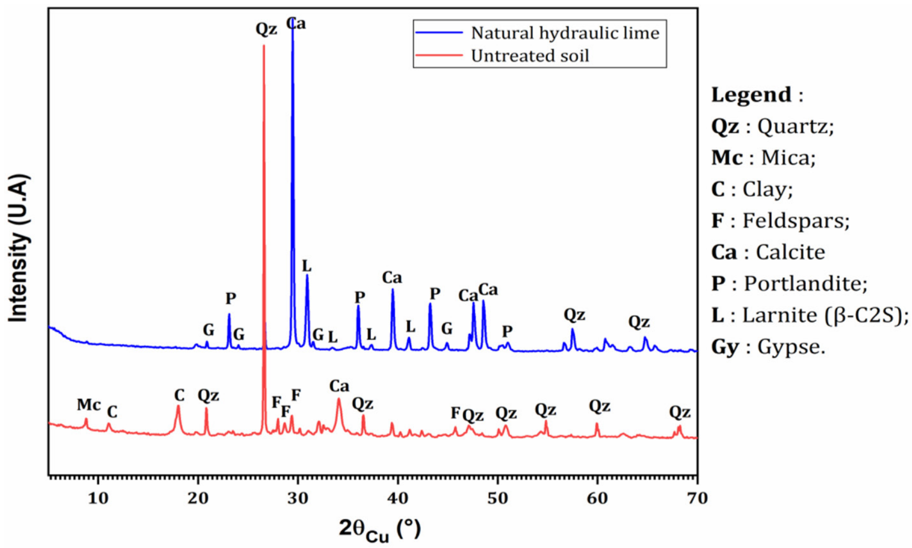

Figure 7. XRD patterns of raw soil and hydraulic lime samples

hemp particles increases capillary absorption capacity, and that adding hydraulic lime to the mixture considerably limits water absorption (Mabrouk et al., 2022; Derdour et al., 2023).

Earth-lime-hemp concrete has excellent hygroscopic properties, enabling it to absorb and desorb moisture from the surrounding air, thereby regulating indoor humidity and improving thermal comfort. However, excessive or prolonged exposure to liquid water or saturated water vapor can negatively affect its properties for several reasons:

Additional water can dilute the earth-lime binder, reducing its effectiveness in binding the earth particles and hemp aggregates.

The CO_2 absorption process through lime carbonation ($Ca(OH)_2$ reacts with CO_2 to yield $CaCO_3$ and H_2O, which is an essential long-term curing process, can be slowed or disrupted because the pores are saturated and hinder CO_2 diffusion.

Water can weaken the bonds between earth particles, hemp fibers, and hydraulic lime; clayey fines, which are particularly sensitive to water, may swell, lose cohesion, and even turn into mud under excessive moisture.

Hemp shives are relatively water-resistant due to their lignocellulosic structure and the alkalinity of the lime, but prolonged saturation may soften the fibres, reducing the composite's overall mechanical strength.

Moreover, a humid and poorly ventilated environment leads to the development of mould, fungi and bacteria, which can degrade plant fibers and progressively reduce the compressive strength, flexural strength and stiffness of the composite; Consequently, earth-lime-hemp concrete becomes softer and more brittle, progressively losing part of its load-bearing capacity with a significant increase in the overall thermal conductivity, and a reducing its insulating performance.

Furthermore, excessive water absorption increases the material's bulk density, the loads on the building's supporting structure; prolongs the material's drying cycle and delays the construction site's finishing stages; and increases the risk of drying shrinkage and cracking, creating internal stresses that can cause cracks or disintegration of the material.

This vulnerability to water requires the adoption of appropriate preventive measures, including the use of overhanging roofs; avoiding rising damp from the foundations by constructing solid and waterproof bases; exterior lime plasters that are breathable but resistant to rainwater; ensuring good ventilation to allow moisture to evaporate and keep the material dry; and careful control of the mixing water content and ensuring sufficient curing and drying before applying finishes.

Density of the different formulations at 28 days

The density results for the different composite material formulations are listed in Table 6.

The results show a significant decrease in the dry density of the composite material with increasing hemp content, ranging from 3.26% for the 3% hemp formulation to 6.59% for the 6% hemp formulation (Figure 8).

SEM-EDX analysis

Figure 9 shows the microstructure of hemp fibers incorporated into a soil-hemp matrix; The observed holes in the matrix give the material its capillary absorption capacity; this absorbent characteristic is enhanced by the incorporation of hemp particles; The addition of lime tends to limit this property by filling the voids and strengthening the adhesive bond between the earthy matrix and the hemp particles; grinding the hemp fibers reduces their dimensions and also facilitates their integration into the mixture; lime also contributes to the preservation of hemp particles by creating an alkaline environment that inhibits mould growth.

The results in Table 7 show the elemental weight and atomic percentages for the sample.

Table 6. The density of the different composite material formulations at 28 days

Sample	Sample 1	Sample 2	Sample 3	Average	Decrease %
TCC 0	1273.61	1275.00	1283.33	1277.31	0
TCC 1.5	1276.81	1261.39	1263.47	1267.22	0.79
TCC 3	1242.97	1225.25	1238.63	1235.62	3.26
TCC 4.5	1220.83	1214.58	1224.31	1219.91	4.49
TCC 6	1185.76	1195.33	1198.23	1193.11	6.59

Figure 10 represents the energy-dispersive x-ray (EDX) spectrum of the composite material, identifying its chemical elements.

Mechanical properties of the composite material

Compression test

The results of the compression test were summarised in the following Table 8. The stress-strain curve at 28 days is shown in Figure 11 for the samples with different hemp contents. The results indicate that the behavior of the material starts to turn nonlinear quite fast with increasing hemp content, even at quite low stresses, before the material reaches its maximum strength. The increase in the amount of grounded hemp particles increases the maximum compressive strength of the material, which increases from 0.59 MPa for TCC0 composite (control composite with 85

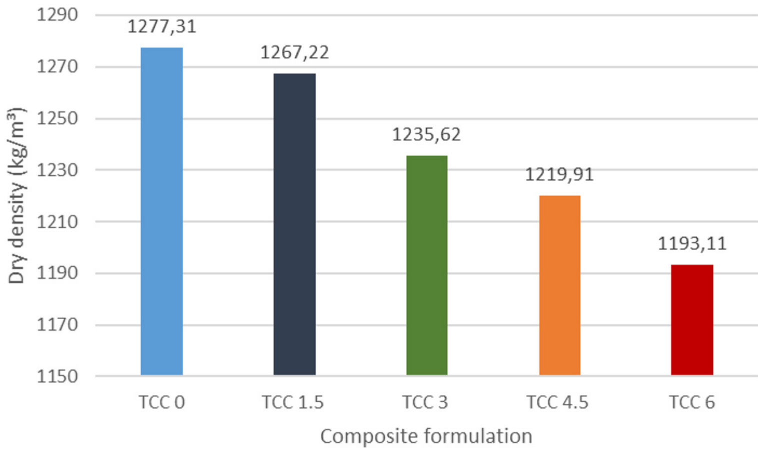

Figure 8. Variation of dry density with hemp content

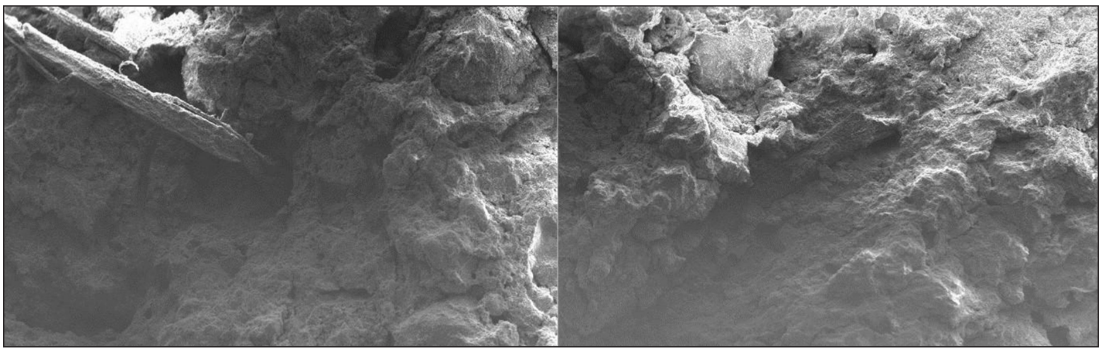

Figure 9. a–b: The microstructure of hemp fibers incorporated into a soil-hemp matrix, as seen with the SEM

Table 7. EDX results showing the elemental weight and atomic percentages for the sample

Element	Normal Mass	Atomic Mass	Absolute error [%] (1 sigma)	Real error [%] (1 sigma)
Carbone	15.76	23.87	0.67	5.27
Oxygen	52.74	59.97	2.08	4.9
Magnesium	1.87	1.4	0.1	6.78
Aluminium	1.94	1.31	0.09	6.02
Silicon	5.15	3.34	0.2	4.9
Potassium	0.43	0.2	0.03	9.68
calcium	21.17	9.61	0.7	4.12
Iron	0.95	0.31	0.08	10.84
Total	100	100	/	/

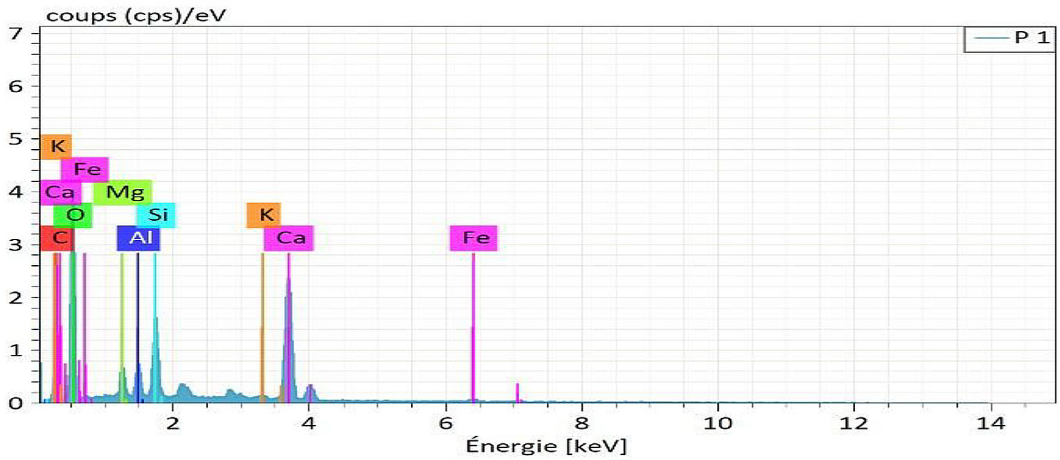

Figure 10. Energy-dispersive x-ray (EDX) spectrum of the composite material

Table 8. The results of the compression test

Sample	Maximum strength (MPa)	Elastic strength (MPa)	Ultimate strain %	Strain at break %	Elastic modulus (MPa)
TCC 0	0.59	0.47	2.18	3.45	44
TCC 1.5	0.61	0.49	4.10	5.70	20
TCC 3	0.63	0.50	6.95	10.00	12
TCC 4.5	0.76	0.61	7.70	9.15	10
TCC 6	0.52	0.42	6.90	10.00	8

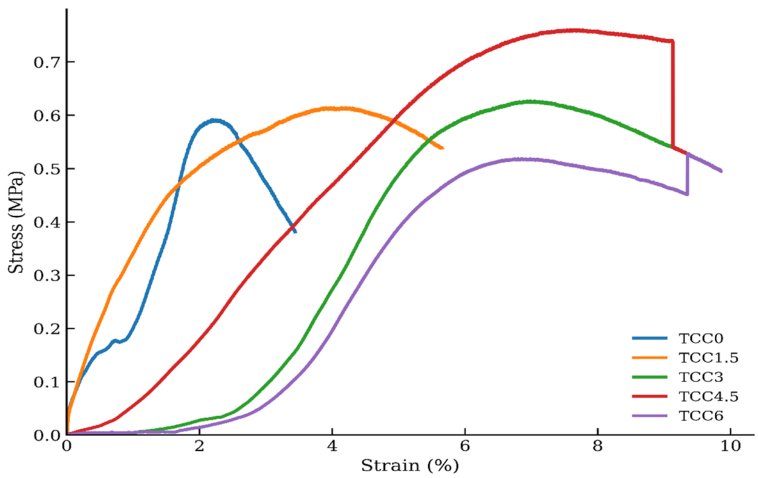

Figure 11. The stress-strain diagram at 28 days for different hemp particle compositions

wt.% soil, 15 wt.% hydraulic lime and no hemp) to 0.76 MPa for TCC4.5 (composite with 4.5 vol.% hemp particles). Further increase of hemp content to 6 vol.% reduces compressive strength to 0.52 MPa.

Ultimate and rupture strain capacities also increase significantly, with their values rising from 2.18% and 3.45% for the reference TCC0 composite to 7.70% and 9.15%, respectively, for the TCC4.5 composite. This corresponds to an increase of approximately 253% in ultimate strain and 165% in rupture strain.

The present composite presents a perfect compromise between lightweight and good mechanical properties, where a compressive strength of 0.76 MPa (for TCC 4.5 formulation) was achieved. This value exceeds the 0.39–0.68 MPa reported by Mazhoud et al. (2017) for hemp–clay composites.

Furthermore, the optimal content of hemp is equal to 4.5%, which corresponds to the results of Avudaiappan et al. (2023), who stated that optimal mechanical properties of hemp composite have been observed for hemp contents equal to 4%, and exceeding this value leads to a decrease in strength because of the rise of porosity.

The 3-point bending test

The results of the 3-point bending test are summarised in the following Table 9. Figure 12 presents the load-deflection curves after 28 days for the flexural behavior of the composites with different hemp shive contents, while the corresponding mechanical parameters are summarized in Table 9. As with the compressive behavior, the response becomes increasingly nonlinear as the hemp content increases, even at relatively low forces, before reaching maximum strength. The addition of ground hemp particles increases the flexural strength of the composite up to an optimum content of 4.5%.

An increase was observed in the maximum flexural strength from 2.23 MPa for the reference sample TCC0, to 5.32 MPa for TCC4.5, corresponding to an increase of approximately 139%. However, it then decreased to 0.46 MPa for TCC6. This indicates that the optimal content of ground hemp fibers has been exceeded, leading to a loss of composite cohesion. The deformation capacity also increased considerably with hemp incorporation. The ultimate deflection increased from 0.41 mm for TCC0 to 3.23 mm for TCC4.5, while the deflection at failure increased from 0.71 mm to 3.23 mm, corresponding to increases of approximately 688% and 355%, respectively.

Moreover, the load–deflection curves show that TCC 4.5 exhibits the largest deformation capacity before failure together with a pronounced post-peak response, reflecting a significant improvement in ductility.

DISCUSSIONS

The characterization of the raw materials provides valuable insight into how their physical, chemical, and mineralogical properties influence

Table 9. The results of the 3-point bending test

Sample	Maximum strength (MPa)	Elastic strength (MPa)	Ultimate deflection (mm)	Deflection at break (mm)	Elastic modulus (MPa)
TCC 0	2.23	1.79	0.29	0.51	142.0
TCC 1.5	2.95	2.36	1.04	1.42	78.1
TCC 3	3.65	2.92	1.9	2.29	42.7
TCC 4.5	5.32	4.26	2.31	2.31	45.5
TCC 6	0.46	0.37	1.67	1.92	5.2

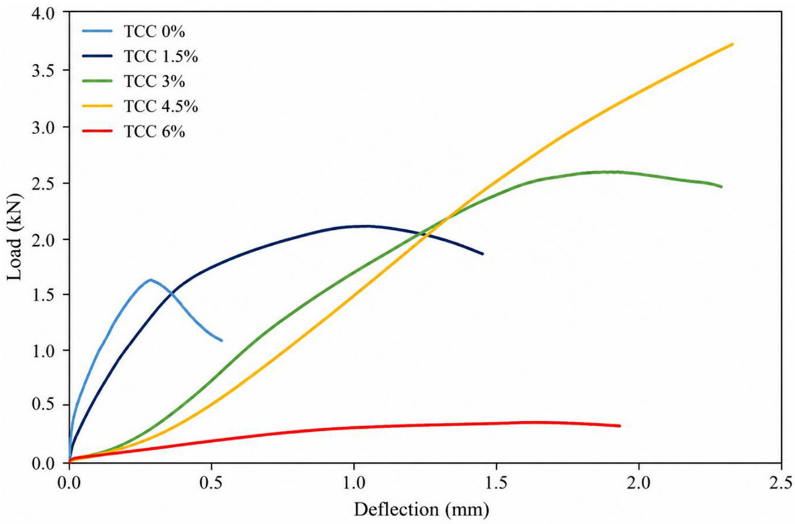

Figure 12. Bending test parameters

the overall behavior of the developed soil–lime–hemp composite. The results demonstrate that the combination of local soil, hemp shives, and hydraulic lime plays a decisive role in achieving an appropriate balance between density, hygroscopic behavior, cohesion, mechanical strength, and deformability. The particle size distribution indicates that the soil is composed predominantly of fine to medium sand associated with significant proportions of silt and clay. The fineness modulus of 2 confirms the predominance of fine sand. In addition, the low sand equivalent value (ES = 15%) and the methylene blue value (VBS = 1.72) indicate a silty soil containing a moderate amount of clay minerals. Such a mineralogical composition is advantageous because it limits excessive shrinkage–swelling phenomena while maintaining sufficient cohesion within the soil matrix. Excessive clay activity would increase water sensitivity and dimensional instability, which are undesirable for bio-based construction materials.

The Atterberg limits further confirm this behavior, with a liquid limit of 42% and a plasticity index of 17%, corresponding to a soil of medium plasticity. These values indicate a favorable compromise between cohesion and workability. The fine particles improve the bonding between the constituents, while adequate soil plasticity facilitates material workability and compaction (Magniont et al., 2023). Consequently, the clay and silt fractions contribute to the formation of a continuous matrix surrounding both the sand grains and the hemp particles.

The mineralogical composition determined by X-ray diffraction (XRD) reveals that quartz and calcite are the dominant crystalline phases, accompanied by minor amounts of feldspars, mica, and probably illite. The presence of calcite enhances the chemical compatibility between the soil and hydraulic lime, promoting mineral bonding during hardening.

The physical properties of hemp shives also have a significant influence on the composite behavior. Their very low bulk density (65 kg/m³), compared with that of the soil (approximately 1037 kg/m³), explains the progressive reduction in the composite density as the hemp content increases. Hemp incorporation therefore produces a lightweight material suitable for non-load-bearing applications while improving thermal insulation performance (Gharbage, 2025). However, this reduction in density is accompanied by an increase in internal porosity, as confirmed by SEM observations, which directly affects both water absorption and mechanical behavior. The initial moisture content also highlights the different hygroscopic characteristics of the constituents. Hemp shives exhibit an average moisture content of 8.31%, whereas the soil contains only 1.55%. This difference reflects the highly porous lignocellulosic structure of hemp, which is responsible for its high water absorption capacity (Islam and Hasan, 2025). Such hygroscopic behavior contributes to moisture regulation within the composite by allowing the progressive absorption and release of ambient humidity. Nevertheless, excessive moisture may alter the hemp–matrix interface, increase porosity, and reduce the adhesion between the constituents, ultimately affecting the mechanical performance.

The XRD analysis of hydraulic lime reveals the coexistence of calcite, portlandite ($Ca(OH)_2$), and hydraulic phases, particularly larnite (β-C_2S). This composition explains its dual hardening mechanism: an initial hydraulic reaction associated with the formation of calcium silicate hydrates (C–S–H), followed by the progressive carbonation of portlandite into calcium carbonate. Hydraulic lime therefore plays a fundamental role in improving the cohesion of the composite by strengthening the bonding between soil particles and hemp shives (Avudaiappan et al., 2023). Furthermore, calcium ions released by lime can react with clay minerals to form additional cementitious compounds, thereby improving the stability of the soil matrix (M'harzi Alaoui et al., 2026).

SEM–EDS observations provide further evidence of these interactions. Numerous micropores are mainly located at the hemp–matrix interfaces, confirming that hemp particles generate a porous network throughout the composite. EDS analysis also reveals the predominance of calcium, oxygen, and carbon, which confirms the coexistence of a carbonated mineral matrix and a lignocellulosic vegetal phase. These observations support the occurrence of carbonation and hydration reactions responsible for the progressive hardening of the material.

The incorporation of hemp progressively decreases the dry density from 1277 kg/m³ for TCC0 to 1193 kg/m³ for TCC6. This nearly linear reduction indicates that hemp particles gradually replace the denser soil–lime matrix. The decrease in density is mainly attributed to the low intrinsic density of hemp shives together with the increase in internal porosity generated by the lignocellulosic particles, in agreement with previous studies (Chabannes et al., 2018; Saleh et al., 2025).

Interestingly, the reduction in density does not necessarily result in lower mechanical performance (Figure 13). As the dry density decreases from 1277 kg/m³ to 1219 kg/m³, the compressive strength increases from 0.59 MPa to 0.76 MPa, reaching its maximum at a hemp content of 4.5%. This behavior indicates that an optimum balance exists between weight reduction and matrix cohesion. At this dosage, finely ground hemp particles are well dispersed within the matrix, acting as distributed reinforcement that limits microcrack propagation while hydraulic lime improves the interfacial bonding between the mineral and vegetal phases.

However, when the hemp content reaches 6%, the compressive strength decreases to 0.52 MPa despite the continued reduction in density. This decline is mainly attributed to excessive porosity and to the reduction in the relative amount of soil–lime binder surrounding the hemp particles. Consequently, the continuity of the mineral matrix is disrupted, reducing the efficiency of stress transfer throughout the composite.

The same trend is observed for the flexural behavior. The TCC4.5 formulation exhibits the best compromise between strength and deformability, with a compressive strength of 0.76 MPa and a flexural strength of 5.32 MPa (Figure 14). This improvement results from a balanced

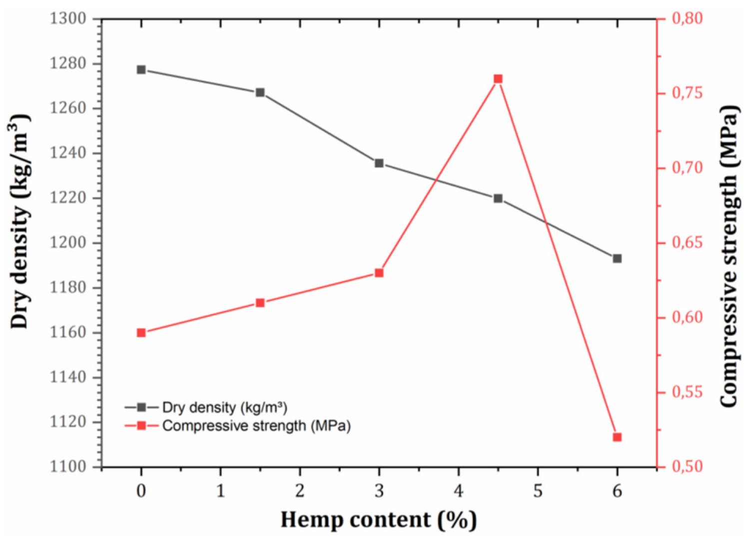

Figure 13. Influence of hemp content on the dry density of the soil–lime–hemp composite

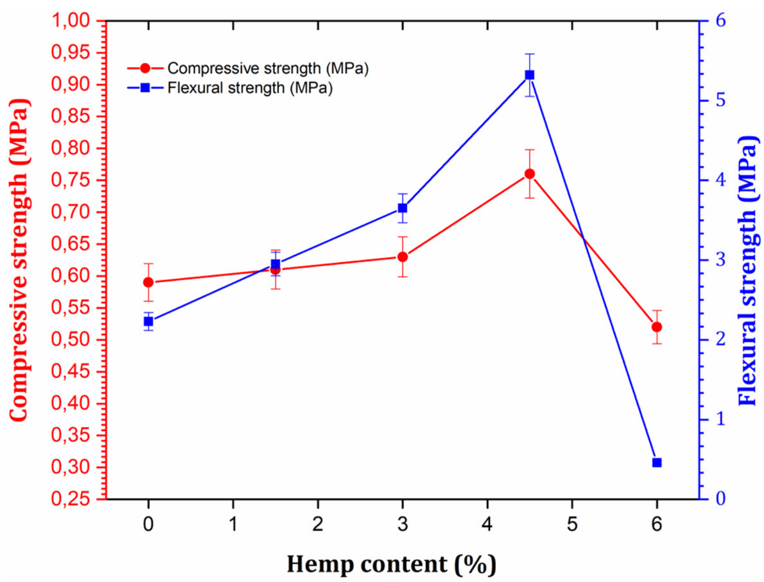

Figure 14. Correlation between compressive strength and flexural strength as a function of hemp content

interaction between sufficient hemp particles to bridge microcracks and dissipate mechanical energy while preserving adequate matrix continuity to ensure cohesion.

The evolution of the elastic modulus further confirms the influence of hemp incorporation. As the hemp content increases, the elastic modulus decreases, indicating a progressive reduction in composite stiffness. This behavior is directly associated with the simultaneous decrease in density and increase in internal porosity, which allow greater deformation under applied loads. Hemp particles therefore contribute to improving the ductility of the composite while reducing its rigidity.

Overall, porosity appears to be the key parameter governing the composite performance. It simultaneously explains the reduction in dry density, the expected improvement in thermal insulation due to the presence of entrapped air, the increase in deformability, and the decrease in elastic modulus (Figure 15). Nevertheless, excessive porosity beyond the optimum hemp dosage compromises the continuity of the soil–lime matrix and consequently reduces the mechanical strength.

In summary, the results demonstrate that incorporating 4.5% hemp provides the optimum balance between lightweight characteristics, mechanical performance, ductility, and expected hygrothermal behavior.

This formulation therefore represents the most suitable composition for developing sustainable bio-based composites for non-structural building applications; The compressive strength of 0.76 MPa is sufficient to ensure self-supporting capacity and dimensional stability after curing, making the material suitable for non-load-bearing interior walls within independent load-bearing structures (timber, rammed earth, or stone), as well as for cast-in-place or sprayed walls, prefabricated blocks, and insulating screeds; These results confirm its potential as a sustainable insulating material for non-structural building applications (Schroeder et al., 2016).

Beyond its mechanical performance, the proposed earth–lime–hemp composite also contributes to sustainable construction through the combined use of locally available soil and agricultural hemp by-products, thereby reducing dependence on conventional mineral- and cement-based construction materials. The incorporation of hemp shives partially replaces high-energy mineral constituents while promoting the valorization of renewable biomass and locally available resources. Such an approach is consistent with current strategies aimed at reducing embodied energy, greenhouse gas emissions, and the environmental footprint associated with the construction sector. Although a complete life-cycle assessment was beyond the scope of the present study, the experimental results demonstrate the technical feasibility of producing a locally sourced low-carbon composite with an appropriate balance between density, strength, ductility, and moisture-regulating capacity, making it particularly suitable for sustainable non-load-bearing building applications.

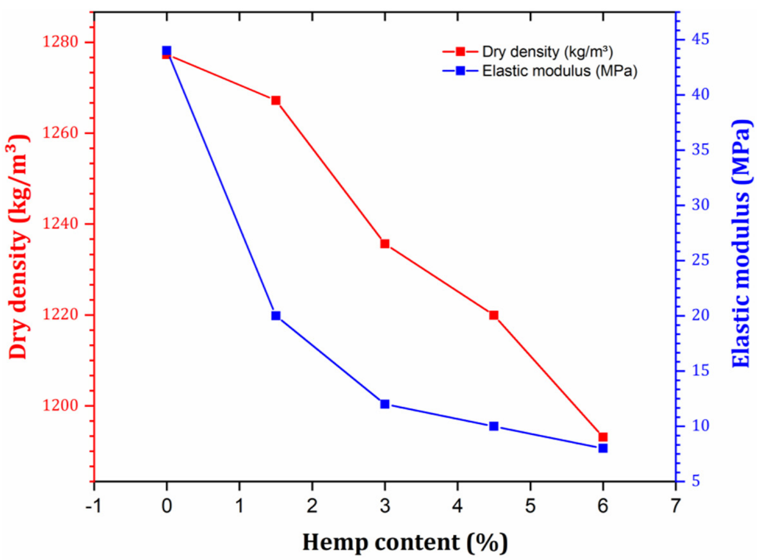

Figure 15. Evolution of elastic modulus as a function of dry density

CONCLUSIONS

The objectives of this study were successfully achieved. The experimental results demonstrated that incorporating ground Moroccan hemp shives into an earth–hydraulic lime matrix significantly influenced the density, mechanical behavior, and hygroscopic performance of the resulting composite. Among the investigated formulations, the composite containing 4.5 wt.% hemp and 15 wt.% hydraulic lime provided the best compromise between reduced density, enhanced compressive and flexural performance, and improved deformation capacity, whereas a further increase in hemp content resulted in a deterioration of the mechanical properties because of increased porosity and reduced matrix cohesion.

The main scientific contribution of this work lies in the comprehensive experimental evaluation of locally sourced Moroccan earth–lime–hemp composites through the combined application of geotechnical characterization, mineralogical (XRD), microstructural (SEM–EDX), hygroscopic, and mechanical analyses within a single study. This integrated approach provides new experimental evidence for optimizing the hemp content in earth–lime composites and contributes to the advancement of sustainable bio- and geo-based construction materials produced from locally available resources.

The obtained results confirm the suitability of the optimized composite for non-load-bearing building applications, including interior partition walls, cast-in-place or sprayed walls, prefabricated blocks, and insulating screeds, where low density, satisfactory mechanical performance, and high deformation capacity are required. At the same time, the study confirms that controlling moisture exposure remains essential for preserving the long-term performance of earth–lime–hemp composites. Future research should focus on long-term durability, thermal and acoustic performance, fire resistance, and life-cycle assessment to further support the large-scale implementation of these sustainable bio-based construction materials.

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