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INVESTIGATION OF CEMENT-BASED NATURAL FIBER–REINFORCED COMPOSITES AS ALTERNATIVE THERMAL INSULATION MATERIALS

NESLIHAN AKIN[1], HACER MUTLU DANACI[2*]

[1] DR., AKDENIZ UNIVERSITY, FACULTY OF ARCHITECTURE, DEPARTMENT OF ARCHITECTURE, ANTALYA, TURKIYE
[2] PROF. DR., AKDENIZ UNIVERSITY, FACULTY OF ARCHITECTURE, DEPARTMENT OF ARCHITECTURE, ANTALYA, TURKIYE
EMAILS: [1] neslihanbardak89@gmail.com; [2] hacermutlu@gmail.com

Abstract— The construction industry is a major consumer of energy -particularly for heating and cooling- there is a growing emphasis on thermal insulation materials that are sustainable, low-impact, and safe for health. Numerous research and development studies have focused on alternative insulation materials, one of which involves reintroducing natural, locally sourced materials—proven effective in traditional architecture—into modern construction applications
This study aims to experimentally evaluate the thermal and mechanical performance of cement-based composites containing natural fiber reinforcements such as goat hair, hemp, and flax. The research also seeks to provide preliminary insights into the potential benefits of reusing natural fibers in architectural applications.
The experimental program consisted of four series of samples. In all mixtures, the water-to-binder ratio (w/b) was fixed at 0.5, and natural fibers were incorporated at 30% of the binder volume. The specimens underwent physical, mechanical, and thermal tests. The hemp composite exhibited the lowest thermal conductivity (0.193 W/mK). Although none of the fibers achieved full homogeneity within the matrix, goat hair displayed the best interfacial bonding. Flax and hemp performed similarly across all tested properties.
Overall, this study demonstrates that incorporating natural fibers into cementitious matrices can lead to the development of environmentally improved alternative materials, thereby increasing awareness among architects regarding sustainable material selection. Moreover, the results suggest that further research on cement-based mortars containing natural fibers for use as alternative thermal insulation materials is both relevant and promising.
Keywords— cementitious material, physical properties, goat hair, hemp and flax fibres, thermal conductivity.

I. INTRODUCTION

Globally increasing environmental challenges have heightened the emphasis on energy-efficient material use. The construction industry is one of the major sectors contributing to overall energy consumption, with most of the energy used in buildings devoted to heating and cooling processes. Therefore, in the selection of thermal insulation materials, it is essential to prioritize products that minimize resource consumption and waste generation throughout their entire life cycle, are sustainable, have limited adverse environmental impacts, and pose no health risks.
Consequently, ongoing research and development activities aim to identify and improve alternative insulation materials. One of the prominent approaches focuses on reintroducing natural, locally sourced materials—proven effective in vernacular architecture—into contemporary construction applications.
According to the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN), materials with a thermal conductivity coefficient below 0.065 W/mK are classified as thermal insulation materials, while those exceeding this value are considered construction materials (TS 825). Desired properties of insulation materials include low thermal conductivity, low bulk density, fire resistance, vapor diffusion resistance, low water absorption, adequate compressive strength, chemical durability, resistance to decay and pests, and economic viability (Özer & Özgünler, 2019).
Beyond improving energy efficiency, thermal insulation contributes to indoor comfort and human health, as properly insulated spaces maintain appropriate temperature and humidity levels, preventing moisture-related deterioration. Consequently, thermal insulation applications are employed across building envelopes, including facades, terraces, roofs, basements, separating walls, ground-contact surfaces, floors, and ceilings (Kocagül, 2013).
Historically, humans have used natural materials for thermal protection since as early as 7000 BCE, when nomadic societies utilized animal hides, fur, and wool—originally intended for clothing—as primitive insulation materials. With the advent of settled life around the 19th century CE, more durable materials such as earth, wood, and brick became common, often combined with plant-based fibers like straw, seaweed, and reeds.

By the late 19th century, following the Industrial Revolution, the concepts of energy conservation and heat loss calculations began to emerge, leading to the industrial-scale production of insulation materials. Between 1950 and 2000, plastic-based insulators became widespread; however, after 2000, growing awareness of their environmental impacts prompted renewed interest in natural materials. Recent advancements have led to the development of high-performance materials such as aerogels and vacuum insulation panels (Bozasky, 2010).

In modern construction, the environmental impact of material selection plays a crucial role in sustainable insulation strategies. Conventional insulation materials exhibit several ecological drawbacks throughout their life cycle. For example, mineral wool, a widely used insulation material, is produced by melting dolomite, basalt, or diabase at 1400–1600 °C to form fibers. Similarly, glass wool is made by melting natural silica sand and recycled glass at 1300–1450 °C (Kırbıyık, 2012). Both materials require high energy input, and their production may cause skin and respiratory irritation due to dust and particulate emissions. Additionally, raw material extraction (limestone and silica) can adversely affect local soil quality, while their recycling processes may pose risks to air quality (Arslan & Aktaş, 2018).

Other insulation materials, such as expanded polystyrene (EPS) and extruded polystyrene (XPS), are petroleum-based products. EPS production requires petrochemical feedstocks, oil, and gas, resulting in high energy consumption and the generation of waste containing heavy metals. XPS exhibits similar environmental issues (Arslan & Aktaş, 2018).

Therefore, reducing the environmental impacts associated with insulation materials, minimizing natural resource consumption, and avoiding health hazards have led researchers to explore alternative insulation materials. One promising approach is the revival of natural, regionally used materials that have proven effective in harsh climatic conditions.

Vernacular architecture, inherently based on climate-responsive and environmentally adaptive principles, reflects a construction approach where structure, local characteristics, and available materials determine the form of the building rather than a predefined design method. Despite variations in technique and structure, natural or naturally derived materials have always been fundamental in vernacular construction (Sezgin, 2006). The climatic compatibility and natural origin of these materials result in positive environmental performance, making their adaptation for modern thermal insulation both sustainable and ecologically beneficial.

Accordingly, this study explores the potential of goat hair, a material deeply embedded in Turkish cultural practices, as a modern thermal insulation component. Additionally, the study investigates the incorporation of hemp and flax fibers, both plant-based and traditionally used in regional architecture, into cementitious composites. The primary aim is to develop environmentally friendly, cement-based composites reinforced with natural fibers (goat hair, hemp, and flax) and to experimentally evaluate their physical, thermal, and mechanical properties. Cement was selected due to its prevalence in construction and the recognized benefits of reducing its environmental footprint—since the production of 1 kg of cement releases approximately 1.0 kg of CO_2 and consumes about 1.5 kWh of energy (Bostancı, 2018). Consequently, the study focuses on producing eco-efficient mortars by reducing cement content within the binder composition.

A review of the literature revealed that studies on the integration of goat hair into modern construction technologies remain limited. Given its availability, cultural relevance, and potential to valorize animal waste, goat hair was selected as a key material. The use of goat-hair tents (kara çadır) in nomadic architecture demonstrates its excellent thermal insulation capacity.

Meanwhile, hemp, known for its adaptability to diverse ecological and topographical conditions, is increasingly cultivated for its fibrous yield (Göre & Kurt, 2021). Owing to its renewable nature, recyclability, and proven potential in composite production, both hemp and flax fibers were incorporated into this study. Laboratory-scale trials were conducted to determine optimal mix ratios for sample preparation. In particular, the proportions of hemp and flax fibers were adjusted to achieve satisfactory flowability and workability in the mixtures, limiting the fiber content to 30% of the cement volume.

II. Experimental Investigation of Alternative Thermal Insulation Materials

Although there are no direct examples in the literature of specific thermal insulation materials produced from goat hair, traditional practices indicate that this material exhibits excellent thermal insulation performance.

Ahmed et al. (2019) comparatively investigated the thermal performance of goat wool, sheep wool, and horsehair, reporting that goat wool demonstrated a low thermal conductivity of 0.0314 W/mK, highlighting its potential as a sustainable insulation material. Jayaseelan et al. (2017) developed epoxy-based natural composites reinforced with goat hair and found that the sample containing 37.5% goat hair achieved the highest mechanical performance. Gündüz and Atalayer (2019) emphasized the reusability of traditional goat-hair textiles in modern design, suggesting that the material can contribute both technically and aesthetically. Similarly, Şimşek (2021) observed improvements in mechanical and physical properties when goat hair, hemp, and other fibers were incorporated into lime mortar. Kanıt and Işık (2004) demonstrated that goat hair enhanced tensile strength, yielding positive outcomes in the restoration of historical arch systems.

Collectively, these studies indicate that goat hair is a natural, sustainable, and technically competent additive, holding significant potential for thermal insulation and other construction applications.

Hemp fiber has gained increasing attention in the field of construction materials due to its sustainability, low environmental impact, and favorable technical performance. Demir and Doğan (2020) reviewed multiple studies on hemp concrete, concluding that it is environmentally advantageous, cost-effective, and thermally efficient. Candamano et al. (2021) reported that hemp fibers pretreated with $Ca(OH)_2$ showed enhanced mechanical performance in cement mortars. Kaplan and Bayraktar (2021) explored the effects of fiber length and content on properties such as flowability, porosity, and strength, identifying 1–2% fiber content and 1 cm fiber length as the optimum parameters. Similarly, Çomak et al. (2018) found that using 2% hemp fibers (12 mm length) yielded the best overall performance in cement mortars. Fernea et al. (2019) reported that hemp fibers provided excellent thermal (0.061 W/mK) and acoustic performance, particularly in multilayer and fiber-dense composites. Juradin et al. (2021) noted that alkali-treated hemp fibers improved ductility in mortars but offered limited mechanical enhancement. Gencel et al. (2021) observed that adding 0.75–1.5% hemp fibers to foam concrete reduced thermal conductivity while increasing compressive strength in low-density mixtures. Balciunas et al. (2015) showed that mineral modifiers can mitigate the negative influence of hemp on cement hydration, achieving 8.03 MPa compressive strength at the optimum composition. Del Valle-Zermeño et al. (2016) reported that magnesium phosphate cement with 16–20% hemp content achieved low thermal conductivity (0.103–0.15 W/mK) but exhibited limited strength. Şahin (2022) demonstrated that hemp stalk residues grown in Türkiye improved unit weight and compressive strength when used in cement-only mixtures.

Overall, the literature confirms that hemp fibers possess substantial potential for thermal and acoustic insulation and environmentally sustainable construction, though achieving optimal mechanical performance requires careful adjustment of fiber content, length, mixing method, and chemical modification.

Flax fibers, recognized for their eco-friendly and biodegradable nature, have also emerged as sustainable reinforcement materials in cement-based composites. Langlet et al. (2007) incorporated 0–20% flax fibers into cement matrices and observed that increasing the fiber ratio reduced mechanical strength while producing lightweight building materials. Aamr-Daya et al. (2008) obtained similar results when using flax particles as aggregate replacements, recording up to a 67% reduction in compressive strength, though chemical additives could mitigate this effect. Tung et al. (2012) found that 30 mm flax fibers increased flexural strength by 60%, highlighting the role of fiber length. Zak et al. (2016) compared flax and hemp fibers in compressed earth blocks and found that flax improved ductility, whereas hemp reduced density and strength. Page et al. (2017) identified 1–2% fiber content as providing optimal flexural strength and workability. Smirnova (2017) reported that materials incorporating agricultural flax residues achieved thermal conductivity values of 0.074–0.085 W/mK and compressive strengths of 0.88–1.09 MPa, indicating eco-efficient, low-density materials. Brzyski et al. (2017) found that flax fiber–reinforced lime composites exhibited low density and thermal conductivity, although high water absorption remained a limitation. Kouta et al. (2020, 2021) demonstrated that incorporating flax fibers of various lengths and proportions improved crack control and tensile behavior, promoting ductile performance in earthen concrete systems. Page et al. (2021a) suggested flax oil coatings to reduce water absorption and enhance thermal efficiency, achieving thermal conductivity values of 1.23–1.68 W/mK with 3% fiber content. In the same study, increasing fiber content decreased compressive strength, but oil-treated fibers enhanced both density and thermal performance. Page et al. (2021b) examined alternative binders—metakaolin, slag, and calcium sulfoaluminate cement—and found that they improved fiber durability, particularly in metakaolin-based mortars during prolonged curing. Zhang et al. (2021) explored hybrid composites containing steel and flax fibers in ultra-high-performance concrete, revealing that flax fibers increased porosity and reduced strength, but this effect was counterbalanced by steel fibers. Gonzalez-Lopez et al. (2021) proposed that flax fiber–reinforced cement–metakaolin composites could serve as fire-resistant and low-smoke facade materials. Rahimi et al. (2022a, 2022b) reported that surface treatments (alkaline and hydrothermal) enhanced mechanical properties, minimized fiber agglomeration and shrinkage, and identified 0.3% fiber content as optimal.

In summary, the literature demonstrates that flax fibers contribute meaningfully to physical, thermal, and mechanical performance, but their efficiency is highly dependent on fiber proportion, length, surface treatment, and binder composition.

III. MATERIALS AND METHOD

In this study, CEM I 42.5 R type Portland cement, produced in accordance with TS EN 197-1 (2012), was used. The specific gravity of the cement was determined using the Le Chatelier flask method, and the value was found to be 3.09 g/cm³.

The goat hair used in the experimental work was obtained from traditional black tent weaving workshops located in Nazilli, Aydın (Türkiye). The goat hairs were cut into small pieces to achieve a more homogeneous distribution within the cement mixtures. The hemp and flax fibers used in this study were supplied from a local production facility in Ayancık, Sinop (Türkiye). These fibers were also processed into smaller pieces using a grinder to ensure a uniform dispersion in the cement matrix. Tap water available in the laboratory was used for all cementitious mixtures.

To improve the workability of mixtures containing hemp and flax fibers, a polycarboxylate-based superplasticizer was added. The superplasticizer has a density of 1.05–1.09 kg/L and can be used in proportions ranging from 0.5% to 2.0% of the binder mass, depending on the desired performance. In this study, it was added at a ratio of 1.5% of the binder weight.

Within the scope of this research, cement pastes were prepared with different fiber types added individually, and the experimental program was conducted accordingly.
A total of four different mixtures were prepared. Based on TS EN 196-1, the mix proportions included 225 g of water and 450 g of cement. Preliminary trials showed that increasing fiber content reduced workability; therefore, the fiber volume fraction was limited to 30% of the cement volume. Additional water was added to compensate for the absorption capacity of the fibers and maintain a constant water-to-binder ratio. The volumetric mix ratios of the prepared cementitious composites are shown in Table 1.

TABLE I VOLUMETRIC MIX RATIOS OF CEMENTITIOUS SAMPLES

Sample Code	**Goat H. (cm³)**	**Hemp (cm³)**	**Flax (cm³)**	**Cement (cm³)**	**Water (ml)**
C	0.0	0.0	0.0	145.5	225.0
K	43.6	0.0	0.0	145.5	225.0
KEN	0.0	43.6	0.0	145.5	225.0
KET	0.0	0.0	43.6	145.5	225.0

Sample codes are defined as follows: C: Control sample (cement + water), K: Cement + water + goat hair, KEN: Cement + water + hemp fiber, KET: Cement + water + flax fiber.
The mixtures were poured into 20×20×20 mm cube molds and silicone molds with a 57 mm diameter and 25 mm height, which had been pre-lubricated with oil to prevent adhesion.
After 24 hours of curing at ambient temperature, the samples were demolded and placed in a curing tank maintained at 20 ±1°C for 28 days, following the standard curing procedure. The dry bulk density of the specimens was determined using an electronic balance with an underhook weighing setup.
The true density of powdered samples was measured using a helium gas pycnometer, and the total porosity was calculated based on these values. The following formula was used to calculate the total porosity:

$$\text{Total porosity } (\%)=(1-(\rho_{bulk}/\rho_{true}))\times 100$$

ρ_{bulk}: bulk density of the sample (g/cm³), ρ_{true}: true density of the sample (g/cm³).
For the compressive strength test, cubic specimens (20×20×20 mm) were tested using a displacement-controlled testing machine. Each mixture group contained six specimens for compressive testing. The load was applied between metal platens until failure. Thermal conductivity tests were performed to determine the thermal conductivity coefficient (λ, W/mK) of the samples.

IV. EVALUATION OF RESULT

When goat hair, hemp, and flax fibers were added separately to the cement paste at 30% by volume of the binder, the dry bulk density values were found to be 1.34 g/cm³, 1.17 g/cm³, and 1.31 g/cm³, respectively.
For the control sample (C), which contained only cement and water, this value was 1.56 g/cm³. A reduction in dry density was observed with the inclusion of fibers. Compared with the control sample, the reductions were 14% for goat hair, 25% for hemp, and 16% for flax. Among all mixtures, the hemp-reinforced sample (KEN) exhibited the lowest density (1.17 g/cm³).
To determine the total porosity, the true density of the samples was first measured using a helium gas pycnometer. Each specimen was tested ten times, and the average values were recorded. The lowest true density was obtained for the hemp-containing sample (KEN) with a value of 1.99 g/cm³. This value was slightly lower than those of goat hair (K, 2.18 g/cm³) and flax (KET, 2.21 g/cm³) samples, while the control sample (C) exhibited a density of 2.01 g/cm³.
The total porosity of the samples ranged between 22.54% and 41.21%. Compared with the control specimen, the porosity values increased in the following order: K (38%) < KET (40.53%) < KEN (41.21%). Thus, fiber addition increased total porosity, although the difference among fiber types was not significant.
The compressive strength of the control specimen (C) was 39.33 MPa.
After fiber addition, compressive strength values decreased to 20.11 MPa for K, 16.45 MPa for KEN, and 12.70 MPa for KET.
The relationship between total porosity and 28-day compressive strength of the samples is shown in Figure 1.

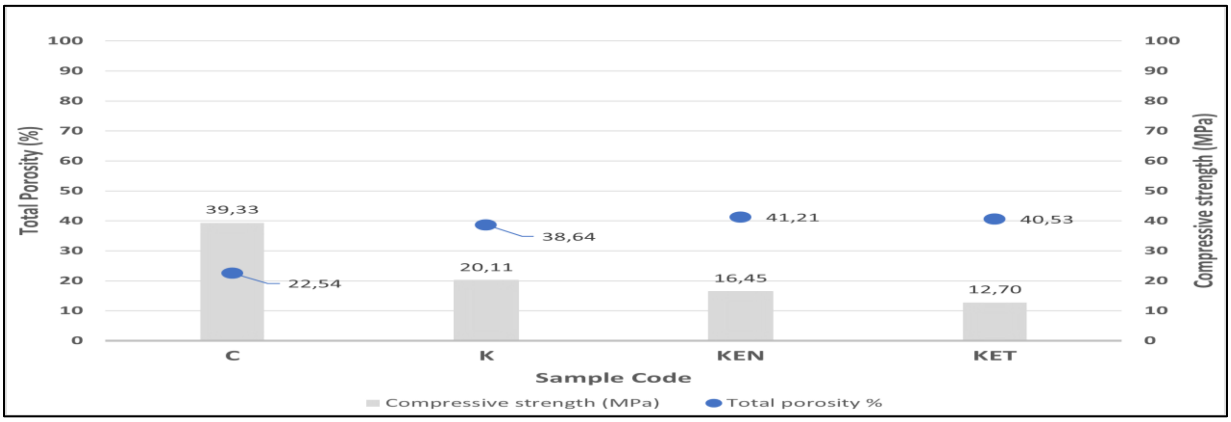

Fig. 1 Relationship between total porosity and compressive strength

The control sample (C) exhibited the lowest total porosity and the highest compressive strength. Compared to the control, the total porosity increased by 16% for goat hair, 18% for flax, and 19% for hemp additions. Although flax and hemp samples showed similar porosity levels, hemp fibers resulted in slightly higher compressive strength.
As expected, an inverse relationship was observed between total porosity and compressive strength. Fiber inclusion increased the porosity, thereby exerting a negative influence on mechanical performance. In cement-based composites, total porosity affects not only mechanical strength but also thermal conductivity. Generally, as total porosity increases, the thermal conductivity coefficient decreases, since pores filled predominantly with air act as heat transfer barriers. Air has a much lower thermal conductivity than the cement matrix, and the presence, shape, distribution, and connectivity of pores directly influence the overall thermal performance of the material.
The relationship between total porosity and thermal conductivity for the prepared samples is illustrated in Figure 2.

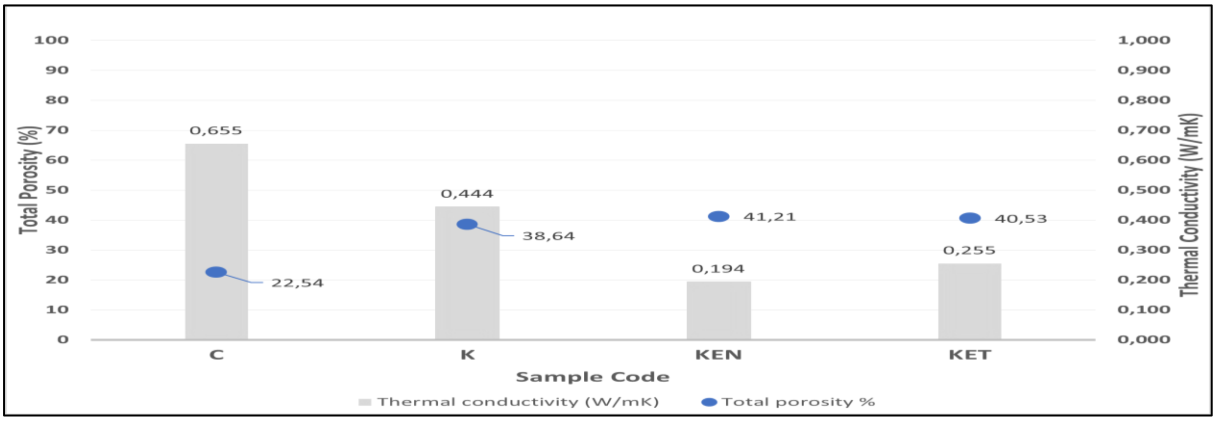

Fig. 2 Relationship between total porosity and thermal conductivity

As total porosity increased, the thermal conductivity values decreased accordingly. The control sample (C) exhibited the highest thermal conductivity coefficient, measured at 0.655 W/mK. With the incorporation of natural fibers, thermal conductivity consistently decreased in parallel with the increase in total porosity. Compared with the control specimen, the thermal conductivity coefficients were 0.444 W/mK for K (goat hair), 0.255 W/mK for KET (flax), and 0.193 W/mK for KEN (hemp). The addition of fibers increased the overall porosity and consequently reduced heat transfer, with this reduction being more pronounced in the hemp- and flax-reinforced composites. Although the inclusion of fibers led to a decline in compressive strength, it provided a notable improvement in thermal insulation performance. The thermal conductivity values obtained for hemp and flax fibers were relatively close to each other, while goat hair exhibited a less pronounced effect on heat reduction compared with the plant-based fibers.

A. **Conclusion**

This study experimentally evaluated four different cement-based composite mixtures incorporating natural fibers—goat hair, hemp, and flax—at a volumetric ratio of 30% of the binder. The analysis focused on total porosity, thermal conductivity, and compressive strength, aiming to identify the potential of these natural fibers as sustainable alternatives for thermal insulation materials.
The control sample (C) exhibited a total porosity of 22.54%, thermal conductivity of 0.655 W/mK, and compressive strength of 39.33 MPa. When natural fibers were added, density and thermal conductivity decreased while total porosity increased. The K specimen (goat hair) reached 38.64% porosity (a 71% increase) with a 32% reduction in thermal conductivity (0.444 W/mK) and a 49% decrease in compressive strength (20.11 MPa).

The KEN (hemp) and KET (flax) specimens showed the highest porosity values (41.21% and 40.53%, respectively), coupled with the lowest thermal conductivities of 0.193 W/mK and 0.255 W/mK—corresponding to reductions of 70% and 61% relative to the control. Their compressive strengths were 16.45 MPa and 12.70 MPa, respectively.

B. **Discussion and Conclusion**

The results clearly indicate an inverse relationship between porosity and both density and compressive strength, while thermal conductivity decreases as porosity increases.

Fiber addition created air-filled voids within the matrix, which disrupted structural continuity yet improved thermal insulation. This microstructural behavior is consistent with previous studies:

Jayaseelan et al. (2017) reported that natural fibers in epoxy composites improved flexibility but reduced strength; Candamano et al. (2021) observed similar trends for chemically treated hemp fibers in cement mortars; and Smirnova (2017) confirmed that air-filled pores significantly decrease heat transfer in flax-based composites.

Among the tested fibers, goat hair displayed the most homogeneous distribution and better bonding within the cement matrix, which contributed to higher compressive strength compared to plant-based fibers. However, hemp and flax fibers exhibited superior thermal insulation performance due to their finer structure and more irregular pore formation, which increased air entrapment within the matrix.

Although all fiber-reinforced composites exhibited lower mechanical performance, they provided significant improvement in thermal efficiency. These findings align with Gencel et al. (2021) and Page et al. (2017), who reported that hemp and flax fibers reduce thermal conductivity while decreasing compressive strength due to higher porosity.

From a microstructural standpoint, the incorporation of natural fibers into cement matrices causes distinct changes in pore distribution and interfacial bonding. Goat hair's cylindrical and smooth morphology provided better matrix adhesion, while the more fibrous structure of hemp and flax led to greater pore formation. This structural diversity underpins the observed variations in mechanical and thermal properties.

V. CONCLUSIONS

Incorporating natural fibers into cement matrices introduces both challenges and opportunities.

While homogeneous dispersion is difficult to achieve, careful mix design and possible surface treatments may improve matrix compatibility. Despite not meeting the ISO and CEN threshold for insulation materials (0.065 W/mK), the measured values (0.193–0.444 W/mK) represent a notable improvement over conventional cement paste.

The study demonstrates that:

All three fiber types induced micro-structural modifications; goat hair showed the best fiber–matrix compatibility, whereas hemp and flax had weaker bonding.

Hemp and flax fibers exhibited comparable physical and mechanical behavior, outperforming goat hair in thermal insulation.

Increasing porosity through fiber addition consistently reduced thermal conductivity, confirming their potential in low-load thermal applications.

Consequently, fiber-reinforced cementitious composites are most suitable for non-load bearing and thermally sensitive architectural elements, such as interior wall panels, partition layers, or insulation coatings, where mechanical strength is not the primary requirement.

From an environmental and architectural perspective, utilizing goat hair, hemp, and flax aligns with the principles of sustainable and vernacular material design. These fibers are renewable, locally sourced, and biodegradable, offering an eco-efficient alternative to industrial insulation products with high embodied energy such as mineral wool or polystyrene.

Integrating traditional natural fibers with modern cementitious systems presents a valuable opportunity for sustainable material innovation—linking vernacular knowledge with contemporary building technology.

Future studies should explore hybrid formulations combining natural fibers with advanced insulation materials (e.g., aerogels, geopolymer matrices, or vacuum panels), as well as surface treatments that enhance fiber–matrix bonding without compromising thermal performance.

Such approaches may lead to next-generation bio-based thermal composites that balance ecological responsibility, architectural applicability, and technical efficiency.

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