

ASSESSING THE PERFORMANCE OF HEMP CONCRETE IN WET-DRY CONDITIONS AND THERMAL PROTECTION EFFICIENCY

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Abstract

This article presented the experimental results of hemp concrete enhanced with $\text{Al}_2(\text{SO}_4)_3$ and polymers, focusing on compressive strength, durability under wet-dry cycles, and thermal insulation performance. The samples were tested according to TIS 109-2517 and evaluated against TIS 58-2560 standards. After 28 days of curing, the hemp concrete exhibited a compressive strength of 4.31 MPa, a dry density of 1,008 kg/m³, and a water absorption of 329 kg/m³. After 12 wet-dry cycles, compressive strength declined slightly to 4.27 MPa, dry density reduced to 934 kg/m³, and water absorption increased to 463 kg/m³. Despite these changes, the compressive strength remained above the minimum requirement of 4.14 MPa specified by TIS 58-2560. In evaluating the effectiveness of external heat protection, the hemp concrete sample showed a thermal conductivity of 0.14 W/m°C and a specific heat capacity of 1.02 kJ/kg°C. The maximum OTTV was 30.07 W/m² when the wall faced southeast. The heat transfer test results through the walls of the box-shaped building model aligned with the OTTV findings, suggesting that hemp concrete transfers less heat than lightweight concrete. The findings suggest that hemp concrete enhanced with $\text{Al}_2(\text{SO}_4)_3$ and polymers meets TIS 58-2560 standards for strength and durability while providing better thermal protection compared to lightweight concrete, making it an effective energy-saving building material.

Keywords: Energy Efficiency; Hemp; Hemp Concrete; Wet-Dry Testing

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Introduction

This research aimed to develop construction materials from bio-based or agricultural waste materials, which was an important option for reducing the environmental impact of construction activities. This was particularly significant when compared to traditional construction materials that involve high emissions. Bio-based construction materials were often produced from readily available natural materials, such as agricultural residues. In addition to helping reduce waste, these materials also contribute to lowering the use of resources that require high energy input during production (Madurwar *et al.*, 2013). The use of such bio-based materials also aids in reducing greenhouse gas emissions, which play a crucial role in global warming and climate change, two global environmental issues that affect the well-being of humans as well as other living organisms (Huang, 2018).

In addition to reducing pollution, bio-based construction materials also exhibit notable properties related to lower thermal conductivity compared to conventional construction materials (Intata *et al.*, 2006). This property helps to minimize heat transfer from the exterior to the interior of buildings, resulting in cooler indoor environments and reducing energy consumption for cooling. This aspect is a crucial factor for energy conservation in Thailand. The country has prioritized the development of energy-efficient construction materials, implementing regulations and supportive measures to promote more environmentally responsible construction practices.

The development of construction materials from agricultural waste has gained significant attention due to its potential to alleviate waste disposal burdens by repurposing agricultural residues, classified as bio-based materials, into construction materials with added value. Agricultural waste not only helps reduce the weight of construction materials but also demonstrates excellent thermal insulation properties compared to traditional heavier construction materials (Taemthong, 2013; Woraphut *et al.*, 2016; Pakdee and Ratnaporn, 2018). Hemp has emerged as a new economic crop that could be cultivated for various purposes, such as utilizing the fibers from the bark of the stalk, harvesting the flower clusters to extract Cannabidiol (CBD), and collecting seeds to extract hemp seed oil. Thus, the stalks became waste materials. The production of construction materials from hemp has garnered increasing interest in recent years. Hemp materials exhibit favorable properties, allowing for good moisture and vapor permeability,

which help reduce the likelihood of mold growth (Birjukovs *et al.*, 2022). Additionally, they maintain stable relative humidity levels in the air (Bennai *et al.*, 2022). Moreover, Hemp Shiv can absorb carbon dioxide at approximately 50% of its volume (Peev, 2012).

The core of the hemp stalk used for fibers contains other components such as cellulose, lignin, pectin, and hemicellulose, which often affect the adhesion properties of the materials, necessitating conditioning processes to enhance their performance (Thamjaree, 2013). The improvement of the strength of hemp concrete was classified into two main techniques: 1) enhancing the adhesion properties at the hemp's interfacial region by pre-conditioning the hemp surface before production with appropriate concentrations of acid or alkaline solutions, with the use of $\text{Al}_2(\text{SO}_4)_3$ and $\text{Ca}(\text{OH})_2$ resulting in an increase in compressive strength by up to four times (Pantawee *et al.*, 2017), and 2) improving the properties of concrete with various admixtures that increase the compressive strength of construction materials produced from soil and cement, such as waterproofing agents (Lambe and Moh, 1957). Polymer additives help enhance the compressive strength of cement-based materials, including natural polymers like latex (Phetcharat *et al.*, 2021) and synthetic polymers (Sukprasert *et al.*, 2017).

Construction materials made from agricultural waste face challenges regarding the durability of the produced materials, as these materials often exhibit different properties compared to traditional construction materials, potentially impacting the longevity and service life of the products. Issues related to durability include sensitivity to moisture (Gioffrè and Pepi, 2024). Agricultural waste materials typically comprise structures that can absorb significant amounts of water, leading to swelling or cracking when exposed to moisture or rapid temperature changes. Biological degradation is another concern, as naturally derived materials like plant fibers could be susceptible to damage from fungi and insects. Additionally, the weather resistance of these materials might not withstand environmental changes as effectively as conventional materials, such as exposure to heat, cold, or humidity, resulting in accelerated deterioration. The flexibility and load-bearing capacity of agricultural waste materials might fall below standard construction material requirements, making them unsuitable for certain applications. Moreover, the curing of these materials could take longer, impacting production and long-term

construction processes. Therefore, testing the durability of these materials is crucial, particularly using wet-dry cycle testing to assess the performance of the materials under frequently changing conditions and to identify methods to enhance the durability and suitability of the materials for use in various buildings and structures. Research and development in this area are essential for finding solutions to these issues and developing new standards for agricultural waste-based construction materials that will be durable and sustainable for the future.

This research produced hemp concrete to achieve compressive strength in compliance with TIS 58-2560 standards, which specify that non-load-bearing concrete blocks must possess a compressive strength of at least 4.14 MPa. This hemp concrete served as a sample for wet-dry cycle testing, conducted in accordance with ASTM D559, to evaluate its durability and performance under conditions that simulate outdoor environments. The Overall Thermal Transfer Value (OTTV) was also examined based on the guidelines from the Ministry of Energy, comparing results to energy-efficient building standards, which require OTTV to remain below 50 w/m² for office buildings (Ministry of Energy, 2021a). Heat transfer tests comparing hemp concrete with lightweight concrete were conducted using heat flux measurements through the walls of a box-shaped building model. The results aimed to provide a comparison between calculated OTTV values and actual heat transfer observations in the field, presenting data on the durability and thermal performance of hemp concrete under these conditions.

Materials and Methods

This section outlines the research materials, the production process for hemp concrete samples, the Wet-Dry methodology, and the procedures for testing and analysis.

Research Materials

1. Hydraulic cement was commercially available in Thailand.

2. The soil used as the primary material for producing hemp concrete was red loamy soil, sourced from Nakhon Ratchasima Province, Thailand, as shown in Figure 1. The physical properties of the soil were detailed in Table 1, and its soil gradation was presented in Table 2. The soil had a liquid limit of 36.1%, a maximum particle size of 4.750 mm, and a passing percentage through a sieve of size 0.075 mm (number 200) at 3.48%. Preliminary tests were conducted by producing soil

cement blocks, using a soil-to-hydraulic cement ratio of 5:1.2 by weight, which yielded an average compressive strength of 14.3 MPa. This compressive strength is higher than that of soil cement blocks produced from sand and finely ground lateritic soil with the same composition ratio, which led to the selection of this soil as the main material for producing hemp concrete samples. The red loamy soil was selected as the primary material for producing hemp concrete samples for this research.



Figure 1. Red loamy soil used for producing hemp concrete samples

Table 1. Properties of the soil

Engineering Property	Test Results
Liquid Limit (L.L.)	36.1%
Plastic Limit (P.L.)	24.7%
Plastic Index (P.I.)	11.3%
Optimum Moisture Content (OMC)	9.5%
Maximum Dry Density (λ_{dmax})	1.783 g/cm ³
The largest soil size	< 4.750 mm.
Mass passed sieve No. 200	3.48 %

Table 2. Gradation of the soil and hemp

Sieve size(mm.)/ Number of sieves	% passing by weight	
	Soil	Hemp fiber
9.525 (No 3/8)	100.00	100.00
4.750 (No. 4)	100.00	92.16
2.360 (No. 8)	98.18	69.28
1.180 (No.16)	97.64	51.92
0.600 (No.30)	91.50	33.51
0.300 (No.50)	61.59	10.37
0.150 (No.100)	28.25	4.71
0.075 (No.200)	3.48	-

3. Hemp used in the production of hemp concrete samples was derived from the dried stalks of hemp with bark, exhibiting characteristics as shown in Figure 2(a). The stalks were pulverized into small pieces using an electric crusher machine, resulting in finely chopped hemp. The hemp fiber comprised both hurd fiber and bark fiber components, as illustrated in Figure 2(b), with gradation detailed in Table 2.

4. The substances used to enhance properties included Al₂(SO₄)₃ and a polymer

solution. The polymer was a white liquid with a specific gravity of 1.0, a pH range of 8-10, and a solid content of 28%-32%.

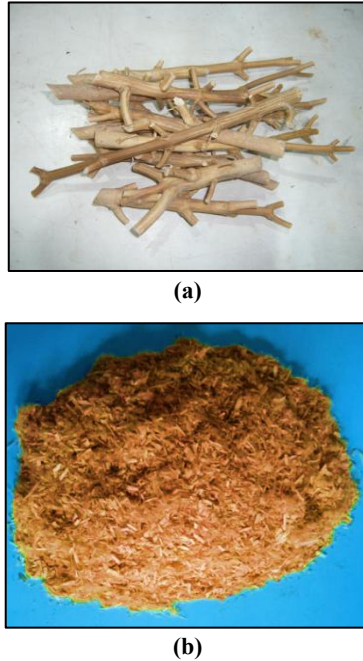


Figure 2. (a) Hemp stalk with bark fiber and (b) Hemp fiber

Production Process for Hemp Concrete Samples

The hemp concrete samples were produced in batches of 2 samples. The materials used for production are shown in Table 3. The production processes were as follows:

Table 3. Ingredients for the Production of Hemp Concrete Samples

Materials	Weight (g) for 2 Samples
1. Hemp	400
2. Hydraulic cement	800
3. Soil	1,600
4. Water (Hemp soaking)	800
5. $\text{Al}_2(\text{SO}_4)_3$ (20% wt. of Hemp)	80
6. Liquid for Concrete Mixing	
- Polymer Solution	200
- Water (Polymer mixing)	200

1. The soil and hemp were dried before the production of the hemp concrete samples, using a mix ratio of hemp: hydraulic cement: soil equal to 1:2:4.

2. The preparation of the hemp involved weighing 400 g and placing it in a tray. Subsequently, 80 g of $\text{Al}_2(\text{SO}_4)_3$ was dissolved in 800 g of water and mixed with the hemp, as shown in Figure 3(a). The mixture was then left to sit for 5 minutes. For the soaking process, the amount of

water used was twice the weight of the hemp, which was the optimal amount to adequately wet the hemp. This study indicated that the use of $\text{Al}_2(\text{SO}_4)_3$ dissolved in water resulted in a mild acidic effect, which, when used in appropriate amounts, had the role of removing undesirable substances from the surface of the hemp, thereby improving its adhesion to the concrete. This, in turn, enhanced the compressive strength of hemp concrete. Previous research demonstrated that the highest amount of $\text{Al}_2(\text{SO}_4)_3$ that could increase compressive strength was 20% by the weight of hemp (Phetcharat *et al.*, 2024). However, when used at 25%, it led to the degradation of the hemp, which negatively affected the compressive strength.

3. The soil was weighed at 1,600 g and added to the tray, where it was left for an additional 5 minutes before being mixed with the hemp, as shown in Figure 3(b).

4. Following this, 800 g of hydraulic cement was added to the mixing tray, as shown in Figure 3(c), and mixed thoroughly.

5. An admixture was prepared by combining 200 g of polymer solution with 200 g of water until a homogeneous liquid was obtained. This liquid was then added to the mixing tray and thoroughly mixed, as shown in Figure 3(d). The total liquid content in this step represented 50% of the weight of the hydraulic cement, which was considered an appropriate amount to facilitate molding. Regarding the polymer preparation, the liquid was formulated by mixing the polymer solution and water in a 1:1 ratio by weight, resulting in a final solution containing 50% polymer by weight, in accordance with the specifications provided on the polymer label.

6. The well-mixed materials were then poured into a steel mold measuring $7.5 \times 30 \times 10$ cm, as illustrated in Figure 4, which shows both the mold and the hemp concrete sample.

7. Finally, the samples were cured in the air by placing them in a shaded area for 28 days.

Wet-Dry Methodology

The wetting and drying process, following the ASTM D559 standard (ASTM, 2015), was used to test the environmental durability of hemp concrete. In this method, hemp concrete samples, aged for 28 days in air, were soaked in room-temperature water for 5 hours and then oven-dried at 70°C for 48 hours. After drying, the samples were allowed to cool to room temperature. Each full cycle of soaking, drying, and cooling was considered one cycle. This procedure was repeated for 12 cycles, with compressive strength, dry density, and water absorption evaluated every 2 cycles.



Figure 3. Process for Hemp Concrete Production: (a) Hemp soaked in water with dissolved $\text{Al}_2(\text{SO}_4)_3$ for 5 minutes (b) Soil added and mixed thoroughly (c) Hydraulic cement added and (d) Water mixed with polymer added and mixed thoroughly



Figure 4. Steel Mold and Hemp Concrete Block Samples

Testing Properties and Analysis

1. Hemp concrete was tested in accordance with the standard for sampling and testing concrete masonry units (TIS 109-2517) (Thai Industrial Standards Institute, 1974), which included assessments of compressive strength, dry density, and water absorption. The compressive strength was then compared to the standard for non-loadbearing concrete masonry units, which requires a minimum compressive strength of 4.14 MPa (TIS 58/2560) (Thai Industrial Standards Institute, 2017). Property tests were carried out after 28 days of curing, as well as after every 2 cycles of wetting and drying.

2. The thermal properties of hemp concrete were evaluated. Key material properties required for calculating the OTTV included thermal conductivity (k), tested at the Department of Science Service (DSS); specific heat (C_p), tested at MTEC; and density (ρ) and thickness (Δx), which were determined from the results of this experiment.

3. The thermal properties of hemp concrete were evaluated for energy-efficient building applications in compliance with the regulations established by the Ministry of Energy (Ministry of Energy, 2021b). This evaluation involved calculating the OTTV for opaque walls made from a single type of material, as specified in Equation (1). The heat transfer coefficient (U) was determined as a function of thermal conductivity (k) using Equation (2). Additionally, the equivalent temperature difference (TD_{eq}) was predefined

according to the announcement by the Ministry of Energy and established as a value dependent on the product of thermal conductivity (k), specific heat capacity (C_p), density (ρ), and thickness (Δx). These four variables used in the calculation were derived from the test results obtained in this research.

$$OTTV = (U)(TD_{eq}) \quad \text{w/m}^2 \quad (1)$$

$$U = \frac{k}{\Delta x} \quad \text{w/m}^2 \text{ } ^\circ\text{C} \quad (2)$$

4. Assessing thermal heat transfer behavior through box-shaped building models of hemp concrete compared to lightweight concrete involved the following steps:

a) Two rectangular box-shaped buildings, each with dimensions of $60 \times 60 \times 80$ cm (Phetcharat *et al.*, 2023), were constructed using lightweight concrete with a density of 620 kg/m^3 , as depicted in Figure 5. In the first box, one side was designated as the tested wall made of lightweight concrete (620 kg/m^3), which is commercially available at general construction material stores and is considered an energy-efficient construction material, providing good insulation against external heat. In the second box, the tested wall was made of hemp concrete, which was the focus of this study. The test walls were placed outdoors in an open area, without any shade from trees or buildings, and were oriented to face south.

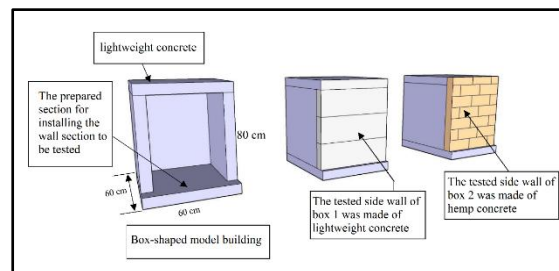


Figure 5. Model of Box-Shaped Building for Field Heat Transfer Testing

b) DHT22 temperature sensors were installed to measure the outdoor air temperature outside the box and the temperature on both the external surfaces (T_1) and inner surfaces (T_2) of the test walls. Temperature measurements should be taken every 5 minutes continuously for 24 hours. Compare temperature changes between the external and inner surfaces of the lightweight concrete wall and the hemp concrete wall, and compare the heat transfer calculated using Equation (3) (Poirier and Geiger, 1994). In this equation, 'q' represented the heat flux or heat transfer per unit area, similar to OTTV, but they differed in their translations. OTTV was used to calculate the overall heat perception of a building according to the regulations of the Ministry of Energy. Meanwhile, 'q' denoted the actual heat flux through walls in real weather conditions, which varied over time.

$$q = \frac{k}{L}(T_1 - T_2) \quad \text{W/m}^2 \quad (3)$$

Results and Discussion

Results of Hemp Concrete Properties and Effects of Wet-Dry Testing

Hemp concrete samples were tested for their properties, specifically those aged 28 days and those subjected to the wet-dry process every 2 cycles, up to a total of 12 cycles. The evaluated properties included compressive strength, water absorption, and dry density of the hemp concrete samples. The results were illustrated in Figures 6 and 7, respectively.

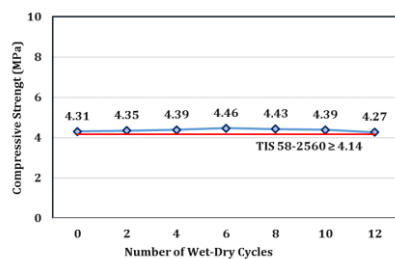


Figure 6. Results of Compressive Strength Testing

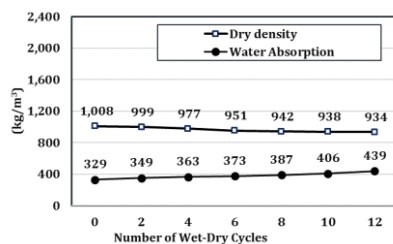


Figure 7. Results of Water Absorption and Dry Density Testing

The initial compressive strength test of the hemp concrete before undergoing the wet-dry process was 4.31 MPa, with a dry density of 1,008 kg/m³ and water absorption of 329 kg/m³. The properties of hemp concrete that needed to be considered included compressive strength, which met the standards of TIS 58-2560, requiring a minimum of 4.14 MPa. There were no specific requirements for water absorption and dry density for non-load-bearing blocks. The dry density of this hemp concrete was classified as light-weight material. The results of the tests on the properties of the hemp concrete that underwent the wet-dry process showed a noteworthy increase in compressive strength.

The compressive strength of the hemp concrete reached a maximum of 4.46 MPa in the 6th cycle, which was believed to be attributed to the ongoing hydration process that continued to enhance the strength of the material. However, the compressive strength began to decrease starting from the 8th cycle, eventually reaching 4.27 MPa in the 12th cycle. It was suspected that the mechanism causing the reduction in compressive strength due to the wet-dry cycling was a result of the changes in the condition of the hemp, which acted as the reinforcing material.

In terms of water absorption and dry density, significant changes were observed in the hemp concrete. Throughout the 12 cycles of testing, the dry density exhibited a continuous decrease, declining from 1,008 kg/m³ to 934 kg/m³. Meanwhile, water absorption increased from 329 kg/m³ to 439 kg/m³. This rise in water absorption was closely associated with the observed decrease in dry density, attributed to the degradation of the material during the wet-dry process.

The behavior of hemp concrete regarding water absorption is also linked to its tendency to expand and contract. As the material absorbs water, it expands due to the absorption of moisture into the hemp fibers, which can enhance its flexibility and impact resistance. However, this expansion can also lead to structural changes, making the material more susceptible to degradation during the wet-dry cycles.

Conversely, the contraction that occurs as the concrete dries out may result in the formation of micro-cracks or voids. These changes can further reduce the density and overall strength of the material, as observed in the decreasing dry density values. The combined effects of expansion and contraction during the wet-dry process underline the importance of managing moisture content to maintain the integrity of hemp concrete.

The increased water absorption observed suggests a weakening of the structural integrity of

the material, likely due to the degradation of the hemp fibers and their bonding with the matrix. This phenomenon highlights the need for careful consideration of the behavior of the material under varying moisture conditions to ensure its durability and performance in construction applications.

The test results demonstrated that the compressive strength of hemp concrete remained above the standard value, even after undergoing 12 wet-dry cycles. The TIS 58-2560 standard requires a minimum compressive strength of 4.14 MPa, and the hemp concrete samples met this criterion, showcasing their ability to withstand environmental challenges.

These findings highlighted the potential of hemp concrete for use in environments with fluctuating moisture levels. Further investigation into the mechanisms that drove these behaviors would enhance understanding and improve the performance of hemp concrete in real-world applications.

Energy Conservation Performance Evaluation for Construction Materials

The Ministry of Energy issued guidelines for energy conservation in building design. Regarding wall design, it stipulated that the OTTV must not exceed 30-50 w/m^2 , depending on the building type.

Specifically, for office buildings, the OTTV of walls was not allowed to surpass 50 w/m^2 . Materials with lower OTTV indicated higher efficiency in reducing heat transfer from the exterior. This section focused on calculating the OTTV of the hemp concrete sample and comparing it with lightweight concrete, a commonly used energy-efficient building material.

The variables used for calculating the OTTV value included the thermal conductivity (k), specific heat capacity (C_p), thickness (Δx), and density (ρ). For the hemp concrete, the values recorded were $k=0.14 \text{ w/m}^\circ\text{C}$, $C_p=1.02 \text{ kJ/kg}^\circ\text{C}$, $\Delta x=75 \text{ cm}$, and $\rho=1,008 \text{ kg/m}^3$. Meanwhile, the values for lightweight concrete were $k=0.18 \text{ w/m}^\circ\text{C}$, $C_p=0.84 \text{ kJ/kg}^\circ\text{C}$, $\Delta x=75 \text{ cm}$, and $\rho=620 \text{ kg/m}^3$. This comparison of OTTV involved materials with different properties but equal thickness. The physical characteristics and properties of both lightweight concrete and hemp concrete were illustrated in Figure 8, while the calculated OTTV values for the two materials were presented in Figure 9.

When comparing the OTTV of lightweight concrete and the hemp concrete sample in all eight directions, as depicted in Figure 9, it became evident that the OTTV value of lightweight concrete was consistently higher than that of the hemp concrete



Figure 8. Physical characteristics and thermal properties of (a) Lightweight concrete $\Delta x=75 \text{ cm}$, $k=0.18 \text{ w/m}^\circ\text{C}$, $\rho=620 \text{ kg/m}^3$, $C_p=0.84 \text{ kJ/kg}^\circ\text{C}$, and (b) Hemp concrete $\Delta x=75 \text{ cm}$, $k=0.14 \text{ w/m}^\circ\text{C}$, $\rho=1,008 \text{ kg/m}^3$, $C_p=1.02 \text{ kJ/kg}^\circ\text{C}$

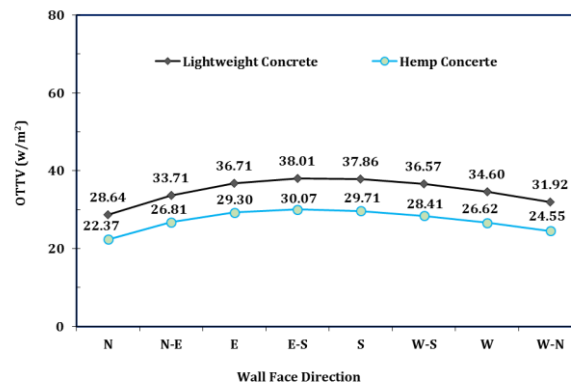


Figure 9. The results of calculating the OTTV of lightweight concrete and hemp concrete

sample. Notably, both materials exhibited their highest OTTV values when assessed for the southeast-facing wall, with the hemp concrete sample recording an OTTV of 30.07 w/m^2 , while lightweight concrete showed an OTTV of 38.01 W/m^2 . Since the hemp concrete sample demonstrated an OTTV of less than 30 w/m^2 , it could be concluded that it constituted an energy-efficient construction material suitable for various energy conservation projects, aligning with the regulations established by the Ministry of Energy.

Meanwhile, lightweight concrete, which demonstrated an OTTV lower than 40 w/m^2 , also exhibited properties that supported energy-saving building construction. However, it is important to note that this analysis calculated the OTTV of lightweight concrete walls without accounting for plastering. This approach aimed to facilitate a direct comparison of the inherent properties of both materials. In practical applications, lightweight concrete walls were typically plastered on both sides and painted, which could further enhance their performance in reducing heat transfer.

Results of Assessing Heat Transfer Behavior through Box-Shaped Building Models

The examination of heat transfer behavior between hemp concrete and lightweight concrete was conducted using box-shaped architectural

models, as illustrated in Figure 10. These models were positioned outdoors with one side facing south. The south-facing wall was designated as the testing wall for heat transfer, with the first model constructed from lightweight concrete and the second model made from hemp concrete, specifically labeled as the hemp concrete sample. The construction of the model buildings involved the stacking of materials for the tested walls, with lightweight concrete used for Box 1 and hemp concrete used for Box 2. An acrylic sealant was applied as a bonding material between the layers of lightweight concrete and hemp concrete at the joints to protect them from external weather effects and enhance the durability of both materials during the field test.

This wall served as the location for measuring temperatures along the exterior and interior surfaces, with readings taken every 5 minutes throughout a 24-hour period. The test results, shown in Figure 11, depicted the recorded temperatures of the outdoor air, the surface temperature of the exterior wall, and the surface temperature of the interior wall for both the lightweight concrete and hemp concrete walls.

According to the findings, the temperatures recorded on the exterior and interior wall surfaces of the hemp concrete wall were lower than those of the lightweight concrete wall during the daytime but



Figure 10. Constructing Box-Shaped Building for Field Testing of Heat Transfer

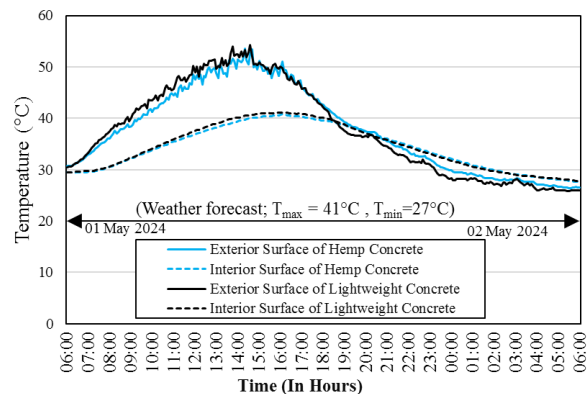


Figure 11. Temperature Comparison at Measurement Locations between Hemp Concrete and Lightweight Concrete

higher during the nighttime. This difference was attributed to the higher specific heat capacity and lower thermal conductivity of the hemp concrete sample compared to lightweight concrete, which influenced the heat transfer behavior. During the daytime, as the outdoor air temperature increased, the temperature of both the exterior and interior walls of the lightweight concrete rose more rapidly. Conversely, during the nighttime, as the outdoor temperature began to decrease, both the exterior and interior walls of the lightweight concrete were able to reduce their temperatures more swiftly than the hemp concrete sample.

An analysis of the temperature change data on the exterior and interior wall surfaces allowed for the calculation of the heat flux using Equation 3, as illustrated in Figure 12. It is important to note that this calculation represented an estimation of heat flux rather than precise heat transfer quantities. Nonetheless, it provided valuable insights into the overall heat transfer dynamics across both types of wall materials. Specifically, the calculated heat flux values offered a general understanding of the rate of heat transfer through the walls. These values indicated the direction of heat flow, with heat transferring from the exterior to the interior during the daytime and from the interior to the exterior during the nighttime periods.

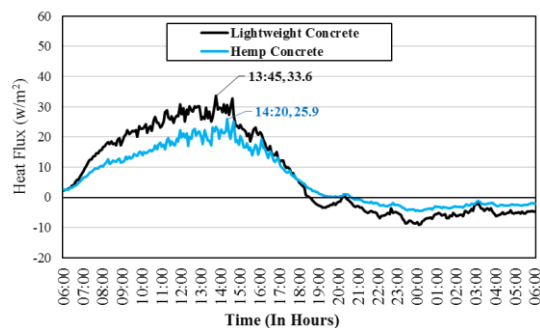


Figure 12. Heat Flux Comparison in Hemp Concrete versus Lightweight Concrete Walls

The analysis of the data in Figure 12 revealed that the peak heat flux between the hemp concrete and lightweight concrete walls exhibited a clear difference, with the hemp concrete showing a lower rate of heat transfer. Specifically, the peak heat flux for the hemp concrete occurred at 2:20 PM, reaching 25.9 W/m², while the lightweight concrete wall peaked earlier at 1:45 PM with a higher value of 33.6 W/m². This resulted in a 35-minute time lag for the hemp concrete. The time lag was attributed to higher specific heat capacity of hemp concrete, which slowed the rate of temperature change. Consequently, this behavior underscored the

superior heat resistance of hemp concrete compared to lightweight concrete.

In comparing the OTTV in Figure 9 and the heat flux in Figure 12, both of which described the heat transfer behaviors of the wall constructions, it is important to note that the OTTV was determined using the method specified by the notification from the Ministry of Energy, estimating maximum daytime heat transfer based on wall orientation. Meanwhile, heat flux was calculated using Equation 3 from temperature recordings over time. Despite the differences in methodologies, both OTTV and heat flux (q) pointed in the same direction, confirming that hemp concrete offers superior heat protection compared to lightweight concrete during the daytime when external temperatures are higher.

Summary and Conclusions

This research produced hemp concrete using hemp, hydraulic cement, and soil in a 1:2:4 weight ratio, with improved properties achieved by incorporating $Al_2(SO_4)_3$ at 20% by the weight of hemp, combined with a polymer. The mixture was then molded into hemp concrete blocks measuring $7.5 \times 30 \times 10$ cm. This hemp concrete met the TIS 58-2560 standard with the following properties: compressive strength of 4.31 MPa, water absorption of 329 kg/m³, and dry density of 1,008 kg/m³. The hemp concrete samples were tested for wet-dry cycling and evaluated for heat resistance performance, which effectively prevented heat transfer from the outside into the building. The results were summarized as follows:

- The test results of the hemp concrete under wet-dry cycling for 12 cycles showed a compressive strength of 4.27 MPa, a dry density of 934 kg/m³, and a water absorption of 439 kg/m³. Upon completion of the 12 cycles of wet-dry cycling, the compressive strength decreased. However, it continued to meet the standards specified in TIS 58-2560, confirming its durability against weather changes. These findings indicate that the hemp concrete retains its structural integrity and can withstand environmental fluctuations, making it a reliable material for construction.

- The thermal property test results of hemp concrete, which are essential for evaluating energy-saving performance, included a thermal conductivity of 0.14 W/m°C and a specific heat capacity of 1.02 kJ/kg°C.

- The assessment of thermal insulation performance using the OTTV indicated that the highest value was recorded in the southeast direction at 30.07 W/m², which was lower than the OTTV of lightweight concrete, measured at

38.01 w/m² in the same direction. Both materials had OTTV values that met the notification from the Ministry of Energy concerning low thermal transfer. However, the experimental results demonstrated that hemp concrete exhibited superior heat resistance performance compared to lightweight concrete, highlighting its suitability for energy conservation in various types of buildings.

- The results of temperature measurements comparing hemp concrete with lightweight concrete using a box-shaped simulation building revealed that lower heat flux occurred through hemp concrete walls compared to lightweight concrete walls during the daytime. The calculated heat flux results aligned with the OTTV, indicating that both methods of assessing heat transfer rates suggested that hemp concrete offers superior heat insulation properties for buildings compared to lightweight concrete.

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