

PROPERTY IMPROVEMENT OF HEMP-ENHANCED INTERLOCKING BLOCKS WITH DURABILITY EVALUATION AND ENERGY EFFICIENCY

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Received: October 22, 2024; Revised: January 12, 2025; Accepted: February 17, 2025

Abstract

This study focused on the property improvement and durability evaluation of hemp-enhanced interlocking blocks to meet the standards specified in TIS 58-2560. The blocks were produced using Type I Portland cement, soil, and hemp with a weight ratio of 1:2:0.4 and were formed using interlocking block-making machines. The properties were enhanced through the incorporation of $\text{Al}_2(\text{SO}_4)_3$, natural rubber latex, and polymers. Samples were air-cured for 28 days and subjected to 12 cycles of wetting and drying, after which they were tested for compressive strength, water absorption, and dry density. Thermal properties were also evaluated to calculate the OTTV. The results demonstrated that the incorporation of 15% $\text{Al}_2(\text{SO}_4)_3$ improved the compressive strength, with values of 5.41 MPa after air curing, which increased by 111.33% compared to the hemp concrete without improvement. After 12 wetting and drying cycles, compressive strength was 5.55 MPa, with both values meeting the TIS 58-2560 standards. Additionally, thermal conductivity was recorded at 0.16 W/m°C, with a specific heat capacity of 1.24 kJ/kg°C and a density of 1,260 kg/m³. The OTTV peaked at 19.97 W/m² when the walls faced southeast, which was lower than that of red bricks, concrete blocks, and lightweight concrete blocks. These findings indicated that hemp-enhanced interlocking blocks with 15% $\text{Al}_2(\text{SO}_4)_3$ not only met strength standards but also offered energy-efficient properties, making them suitable for sustainable construction. This material effectively reduced energy consumption from air conditioning due to its low OTTV values. As it utilized hemp, an agricultural waste product that would otherwise require disposal, it also contributed to waste reduction and minimized environmental impact.

Keywords: Concrete; Hemp; Interlocking block; Soil cement; Sustainable; Waste

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DOI: <https://doi.org/10.55766/sujst7161>

Suranaree J. Sci. Technol. 32(1):010351(1-11)

Introduction

Soil cement blocks or interlocking blocks are construction materials compressed using an interlocking block-making machine. The manufacturing process is not complicated and does not require fuel for production, thus saving energy otherwise used for firing bricks. This makes the production process environmentally friendly and minimizes waste. In Thailand, the production and distribution of interlocking blocks are predominantly for household industries. Many regions across Thailand have soil properties suitable for soil cement block production, resulting in blocks with varying attractive colors based on the physical characteristics of the soil. Soil cement blocks are an alternative construction material that could reduce construction costs by approximately 15 - 20 percent for buildings of the same area (Phetvipat, 2006). This reduction is achieved by minimizing the amount of construction material needed, reducing finishing work, shortening construction time, and saving labor costs. However, interlocking blocks tend to be characterized by their mass, high water absorption properties, and low heat insulation properties. Therefore, they are not classified as energy-saving construction materials according to the direction of modern construction material development, which emphasizes materials that conserve energy and have low carbon dioxide emissions. Construction contributes significantly to global warming due to the pollutants released from construction activities and embedded in construction materials. Developing construction materials with low carbon dioxide emissions is imperative for environmentally friendly and sustainable construction (Huang *et al.*, 2018). Research has indicated that conventional construction materials often produce substantial pollutants compared to bio-based materials (Madurwar *et al.*, 2013). The use of bio-based construction materials reduces pollution and has low heat conductivity, improving overall building energy efficiency (Intata *et al.*, 2006). This trend aligns with the importance Thailand places on developing energy-saving construction materials. The country has implemented regulations, oversight, promotion, and assistance to responsibly foster energy conservation.

Developing construction materials from agricultural residues is a way to enhance construction material properties by reducing weight and improving heat insulation. In Thailand, various agricultural residues such as reeds and bamboo residues (Pakdee and Ratnaporn, 2018) have been used. Corn stalks (Woraphut *et al.*, 2016) and rice

husks (Taemthong, 2013) have been studied for their potential use in construction materials. These materials offer improved insulation and lighter weight for construction. However, they frequently have limitations in compressive strength and may require specialized construction techniques. Hemp has emerged as a promising economic crop, legally cultivated within regulatory frameworks. Initially, it was grown for 90 days to extract fibers for the textile industry, leaving behind hemp stalk without bark fiber, also known as hemp hurd. This residue has been utilized in construction, notably in hempcrete and hemp concrete, suitable for low-load applications due to their low compressive strength (Sinsiri *et al.*, 2022). Despite this limitation, they offer advantages in thermal insulation properties (Elfordy *et al.*, 2008; Demir and Doğan, 2020). They are lightweight, low-density, and have the ability to sequester approximately 50% of their volume in carbon dioxide (Peev, 2012). Currently, hemp cultivation has increased for Cannabidiol (CBD) extraction due to updated regulations. Cultivating hemp for CBD involves a 120-day growth cycle, resulting in hemp stalks with bark fiber, which serves as agricultural residue. Further research is required to explore the potential of utilizing hemp stalks with bark as construction materials, aiming for strength comparable to non-load-bearing concrete blocks and suitable heat insulation properties for energy-efficient building construction. In Thailand, the design of energy-conserving buildings, particularly control buildings, must adhere to the regulations stipulated by the Ministry of Energy in the Notification on Criteria for Calculations, Certification of Assessment Results, and Energy Conservation Building Design Standards for Each System, Overall Building Energy Use, and Renewable Energy Use in Various Building Systems, B.E. 2564 (Ministry of Energy, 2021a). According to this notification, building designs must ensure that the Overall Thermal Transfer Value (OTTV) falls within the range of 30-50 w/m^2 (Ministry of Energy, 2021b), which may vary based on the building type. The OTTV is a metric utilized to evaluate the overall heat transmission of a building by considering the heat transfer characteristics of all building materials, including exterior surfaces. It serves as a measure of the average heat transfer into a building through the building envelope.

Hemp hurd consists of natural fibers that typically include other components beyond just the fibers themselves, such as cellulose, lignin, pectin, and hemicelluloses, which could adversely affect

the properties of the material (Thamjaree, 2013). These additional components not only influence the mechanical properties but also play a significant role in the overall performance of hemp-based construction materials. Producing construction materials from hemp hurd as a composite requires certain processes to enhance the performance of the fibers. Various techniques have been employed to extract and process hemp fibers, ensuring their optimal integration into composite materials. These processes involve mechanical separation, chemical treatment, and thermal processing to achieve the desired fiber characteristics.

Research on the utilization of hemp in construction materials has shown promising results in terms of its use as a composite material for the production of hemp concrete (Pantawee *et al.*, 2017). Hemp concrete, or hempcrete, has demonstrated excellent thermal insulation properties, durability, and environmental sustainability compared to traditional concrete materials. These attributes make it an attractive option for eco-friendly construction practices. It has been found that the surface treatment of hemp with aluminum sulfate ($\text{Al}_2(\text{SO}_4)_3$) and calcium hydroxide ($\text{Ca}(\text{OH})_2$) could significantly increase the compressive strength of hemp concrete by up to four times compared to samples that did not undergo surface treatment with these compounds. This surface treatment process altered the chemical composition of the hemp fibers, promoting better adhesion with the concrete matrix and enhancing overall structural integrity. Additionally, previous reports have demonstrated the effects of improving concrete by adding various additives that enhance its compressive strength, such as plasticizers (Lambe and Moh, 1957).

These additives serve to modify the rheological properties of the concrete mix, improving workability and reducing water content while maintaining or even enhancing mechanical strength. Furthermore, researchers have explored the use of natural polymers like natural rubber latex (Phetcharat *et al.*, 2021) and synthetic polymers (Sukprasert *et al.*, 2017) as additives in concrete formulations. These polymers act as binding agents, improving the cohesion and adhesion between concrete components, thereby enhancing the overall performance and durability of the material.

The production of hemp-based construction materials showed lower strength, and increasing the amount of hemp in the mix led to a reduction in compressive strength. The production of hemp shiv concrete mixtures, using 90% quicklime and 10% cement, with one part of hemp shives, achieved a compressive strength of only 698 kPa

(Šadzevičius *et al.*, 2023). In another case, the production of hemp concrete mixed with sand and Type I Portland cement, with 9.09 wt% hemp and 14.29 wt% of dry aggregates, and enhanced with 20% $\text{Al}_2(\text{SO}_4)_3$ and polymer, and molded into steel molds measuring $7.5 \times 7.5 \times 10$ cm, resulted in compressive strengths of 3.41 MPa and 3.62 MPa, respectively (Phetcharat *et al.*, 2024). These values met the TIS 58-2533 standard, which required non-loadbearing blocks to have a compressive strength of not less than 2.5 MPa. However, the current TIS 58-2560 standard raises the required compressive strength to 4.14 MPa. Research on hemp fiber-reinforced concrete for sustainable rigid pavements, classified as highway materials that were required to meet the specifications as per Standard No. DH-S 309/2544, produced samples with 0.5%, 0.75%, and 1% hemp content by concrete volume. The study found that the highest amount, 0.5% hemp content by volume (equivalent to 1.16% by weight of concrete), met the standards, achieving a compressive strength of 36.65 MPa and compressive toughness of 4.2 MPa (Hoy *et al.*, 2024). Therefore, research concerning hemp-based construction materials requires increasing the hemp content. However, improving the strength properties to meet the specific material standards remains a challenge, which should be addressed through further research.

This research focused on the production of concrete masonry materials utilizing hemp fiber-reinforced soil cement blocks, commonly referred to as hemp concrete. These innovative materials were manufactured using an interlocking block-making machine, which involved manual pressure to enhance the density and strength more effectively than the production of hemp concrete without applying pressure. This production process is environmentally friendly as it generates no waste and does not involve energy-intensive firing, thus conserving energy. Incorporating hemp aimed to reduce weight and enhance insulation properties while improving compressive strength to meet the standard requirements of non-loadbearing concrete masonry, which mandate a minimum compressive strength of 4.14 MPa, as specified by TIS 58-2560. Additionally, the thermal properties of the material were adjusted to align with energy-efficient building construction. Thermal performance was assessed to calculate the OTTV in accordance with the Notification by the Ministry of Energy. The OTTV was compared to the criteria for energy-conserving office buildings, which stipulate that the OTTV value must not exceed 30-50 w/m^2 , depending on the building type.

Materials and Methods

Hemp fiber-reinforced soil cement was formed by an interlocking block-making machine. This material, commonly referred to as hemp concrete, is classified as a type of concrete masonry material due to its composition and structural properties. The primary focus of this research endeavor was to enhance the quality of hemp concrete and thoroughly investigate its various properties. This included a comprehensive examination of its durability, strength, thermal properties, and any other relevant characteristics. The materials and methods section details the research materials, the process of producing hemp concrete samples, and the enhancement techniques applied to these samples, as well as the procedures for testing and analyzing the results clearly and sequentially.

Research Materials

- Type I Portland cement is commercially manufactured for distribution.
- The soil from Nakhon Ratchasima Province was red loamy soil, as shown in Figure 1, with physical properties listed in Table 1 and soil gradation in Table 2. A comparison with the Department of Highways standard no. DH-S 204/2533 found that it was suitable for soil cement production.



Figure 1. Red Loamy Soil

Table 1. Properties of the tested soil

No.	Engineering Property	Test Results
1.	Liquid Limit (L.L)	36.1%
2.	Plastic Limit (P.L.)	24.7%
3.	Plastic Index (P.I.)	11.3%
4.	Optimum Moisture Content (OMC)	9.5%
5.	Maximum Dry Density (λ_{dmax})	1.783 g/cm ³
6.	The largest soil size	< 4.750 mm.
7.	Mass passed sieve No. 200	9.32 %

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	96.33
2.360 (No. 8)	99.18	71.80
1.180 (No.16)	97.64	49.97
0.600 (No.30)	91.50	31.81
0.300 (No.50)	64.27	8.24
0.150 (No.100)	28.25	4.71
0.075 (No.200)	9.32	-

- Hemp, harvested at 120 days of age, using only the dried stalks with bark, as shown in Figure 2, was pulverized into small pieces using an electric crusher machine, as depicted in Figure 3. The resulting hemp fiber included hurd (shive) and bark fiber components, as illustrated in Figure 4, with gradation detailed in Table 2.



Figure 2. Dried hemp stalk with bark fiber



Figure 3. Electric Crusher Machine



Figure 4. Components of hemp fiber used in hemp concrete production

• Substances employed for enhancing properties included $\text{Al}_2(\text{SO}_4)_3$, natural rubber latex, and polymer, as illustrated in Figure 5(a-c), respectively.



(a) $\text{Al}_2(\text{SO}_4)_3$



(b) Natural rubber latex



(c) Polymer

Figure 5. Substances used to improve properties

Production Process for Hemp Concrete Samples

The production process for the hemp concrete samples was as follows:

1. The soil and hemp were dried and prepared for hemp concrete production, as specified in Table 3.

2. The hemp (0.40 kg) was soaked in 0.80 kg of water for 5 minutes to saturate, after which 2.0 kg of soil was added and left for 5 minutes before being mixed.

3. Portland cement (1.0 kg) was mixed with the materials from step 3 in a tray, followed by the addition of 0.50 kg of water. After thorough blending, the mixture was fed into an interlocking block machine (Figure 6) to produce blocks with dimensions of $30 \times 10 \times 12.5$ cm.

4. The samples were cured in the air by placing them in a shaded area for 28 days.



Figure 6. Example of hemp concrete formed using an interlocking block-making machine

Enhancement Processes for the Hemp Concrete Sample

The quality enhancement steps for the hemp concrete sample were as follows:

1. Quality enhancement with $\text{Al}_2(\text{SO}_4)_3$: During step 2, $\text{Al}_2(\text{SO}_4)_3$ was weighed as per Table 3, dissolved in 0.80 kg of water, and soaked with the hemp before proceeding with steps 3-4.

2. Enhancement with natural rubber admixture: A specified amount of natural rubber (0.25 kg) was mixed with 0.25 kg of water, then combined with the materials in the mixing tray in step 3, followed by mixing and molding.

Table 3. Proportions of ingredients in the production of hemp concrete samples and quality enhancement

Sample Label	The weight of the mixture components (kg) per sample							
	Hemp preparation			Sol cement ingredients				
	Hemp	Water	$\text{Al}_2(\text{SO}_4)_3$	Soil	Cement	Water	Natural Rubber Latex	Polymers
HC	0.40	0.80	0.00	2.00	1.00	0.50	0.00	0.00
HC-5A	0.40	0.80	0.02	2.00	1.00	0.50	0.00	0.00
HC-10A	0.40	0.80	0.04	2.00	1.00	0.50	0.00	0.00
HC-15A	0.40	0.80	0.06	2.00	1.00	0.50	0.00	0.00
HC-10A-NR	0.40	0.80	0.04	2.00	1.00	0.25	0.25	0.00
HC-10A-Po	0.40	0.80	0.04	2.00	1.00	0.25	0.00	0.25

3. Enhancement with polymer admixture: A specified amount of polymer (0.25 kg) was mixed with 0.25 kg of water and then incorporated with the materials in the mixing tray during step 3, after which the mixture was blended and molded.

Testing Properties and Analysis

1. According to the standard for sampling and testing concrete masonry units (TIS 109-2517) (Thai Industrial Standards Institute, 1974), testing properties included compression strength, dry density, and water absorption testing. Subsequently, the compression strength was compared to the standard for concrete blocks, which mandates a minimum compression strength of 4.14 MPa (TIS 58/2560) (Thai Industrial Standards Institute, 2017).

2. Evaluating the environmental durability of hemp concrete through wetting and drying methods followed the ASTM D559 standard (ASTM, 2015). Hemp concrete aged in the air for 28 days was soaked in room temperature water for 5 hours, then oven-dried at 70 degrees Celsius for 48 hours. Subsequently, the samples were cooled to room temperature. Each complete cycle of this process was considered as 1 cycle. The wetting and drying process was repeated for 12 cycles, with compression strength, dry density, and water absorption assessed every 2 cycles.

3. Thermal properties were evaluated for energy-efficient building applications according to the regulations set by the Ministry of Energy (Ministry of Energy, 2021a), which required the calculation of the OTTV from Equation (1). The OTTV was indeed a function of various parameters, including the heat transfer coefficient for opaque walls (U_w), the ratio of transparent walls (WWR), equivalent temperature difference (TD_{eq}), heat transfer coefficient for transparent walls (U_f), temperature difference between the inside and outside of the building (ΔT), The coefficient of solar heat transmission through transparent walls ($SHGC$), shading coefficient of the sunshade device (SC), solar radiation affecting the heat transmission through transparent walls (ESR). However, WWR was set to 0 in the case of using a single material for opaque walls. Therefore, Equation (1) was simplified to Equation (2) (Ministry of Energy, 2021a). The material properties required for calculating OTTV included thermal conductivity (k), specific heat (C_p), density (ρ), and thickness (Δx). These properties were essential variables in the calculation of U_w from Equation (3), and TD_{eq} was determined based on the material characteristics specified by guidelines from the Ministry of Energy.

$$OTTV = (UW)(1 - WWR)(TD_{eq}) + (Uf)(WWR)(\Delta T) + (WWR)(SHGC)(SC)(ESR) \quad w/m^2 \quad (1)$$

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

$$U = \frac{k}{\Delta x} \quad (3)$$

Results and Discussion

Results of Enhancing Hemp Concrete Properties

This study aimed to improve hemp concrete properties to meet the compressive strength standard for non-load-bearing concrete masonry in TIS 58-2560, which set a minimum requirement of 4.14 MPa. This was achieved through the surface treatment of hemp before production with $Al_2(SO_4)_3$ to enhance its wettability with the soil cement. Additionally, enhancement included the incorporation of natural rubber latex and synthetic polymers to further increase adhesion properties. Six samples of hemp concrete with different quality enhancements were studied. For explanatory purposes, the samples were labeled as follows: Hemp concrete block (HC), Hemp concrete block enhanced by 5% $Al_2(SO_4)_3$ (HC-5A), Hemp concrete block enhanced by 10% $Al_2(SO_4)_3$ (HC-10A), Hemp fiber reinforced soil cement block enhanced by 15% $Al_2(SO_4)_3$ (HC-15A), Hemp concrete block enhanced by 10% $Al_2(SO_4)_3$ and natural rubber latex (HC-10A-NR), Hemp concrete block enhanced by 10% $Al_2(SO_4)_3$ and synthetic polymers (HC-10A-Po). All six samples exhibited favorable physical characteristics with no visible cracks, as illustrated in Figure 7.

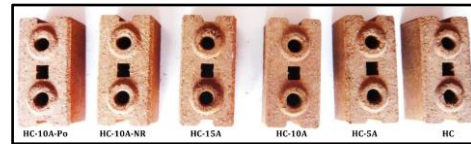


Figure 7. Physical characteristics of the six hemp concrete samples

The results of compressive strength testing for hemp concrete, after being cured in open air for 28 days, are depicted in Figure 8, demonstrating the positive effects of enhancing hemp concrete properties. The enhancement involved treating hemp with $Al_2(SO_4)_3$, natural rubber latex, and polymers, resulting in increased compressive strength in all cases. Two samples exhibited compressive strength surpassing 4.14 MPa, specifically sample HC-10A-Po and HC-15A, with strengths of 4.56 MPa and 5.41 MPa, respectively. Notably, HC-15A represented the sample with the highest strength. Additionally, using 15% $Al_2(SO_4)_3$ proved to be cost-effective, boosting the compressive strength by 111.33% compared to HC, which had a strength of 2.56 MPa.

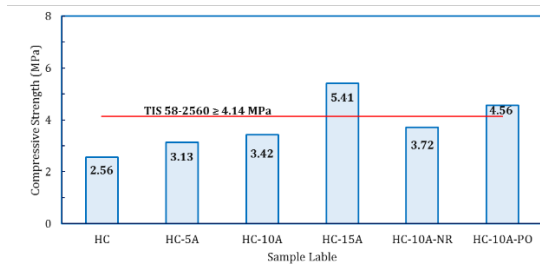


Figure 8. Compressive strength test results

The evaluation of compressive strength improvement in all cases showed an increase in compressive strength. The surface treatment of hemp using $\text{Al}_2(\text{SO}_4)_3$ effectively removed non-fibrous components such as cellulose, lignin, pectin, and hemicelluloses from the hemp surface (Thamjaree, 2013). This process resulted in the hemp surface becoming more suitable for adhesion with the binder material, enhancing the interfacial force between the reinforcement material and the matrix phase. The improvement of hemp concrete with $\text{Al}_2(\text{SO}_4)_3$ increased the compressive strength (Pantawee *et al.*, 2017). However, it was found that using an appropriate amount of $\text{Al}_2(\text{SO}_4)_3$ was crucial for achieving a surface with good adhesion. If used in excessive amounts, it could cause the hemp to become brittle, leading to a loss of its reinforcing properties. Previous studies found that the compressive strength of hemp concrete still increased when the amount of $\text{Al}_2(\text{SO}_4)_3$ was increased to 20%, but the compressive strength decreased when 25% was used (Phetcharat *et al.*, 2024). This study used samples improved with $\text{Al}_2(\text{SO}_4)_3$ at 5%, 10%, and 15%, all of which resulted in increased compressive strength, with the 15% improvement still meeting the standard compressive strength criteria.

The improvement with 10% $\text{Al}_2(\text{SO}_4)_3$ combined with both natural rubber and polymer resulted in an increase in compressive strength for both components. The natural rubber and polymer acted as binders, ensuring good cohesion in the cement, maintaining stable properties when mixed into the cement matrix, and enhancing the interfacial bonding within the matrix, which helped increase compressive strength. However, the improvement with 15% $\text{Al}_2(\text{SO}_4)_3$ resulted in a greater increase in compressive strength than in both cases and was a more cost-effective method. If further strength enhancement of hemp concrete was desired, the use of natural rubber and polymer combined with 15% and 20% $\text{Al}_2(\text{SO}_4)_3$ would have been considered, especially if increasing the hemp content in the hemp concrete mixture was a goal.

The water absorption and dry density testing results, as shown in Figure 9, indicated that hemp

concrete exhibited similar water absorption rates (213-254 kg/m^3) and dry densities (1,204-1,260 kg/m^3). Notably, HC-15A exhibited high compressive strength, with a water absorption rate of 215 kg/m^3 and a dry density of 1,260 kg/m^3 . This categorizes it as a lightweight construction material, with a density lower than 1,680 kg/m^3 (Thai Industrial Standards Institute, 2017). Nevertheless, enhancing hemp concrete with 15% $\text{Al}_2(\text{SO}_4)_3$ proved to be a feasible and cost-effective method compared to using polymers. Therefore, HC-15A was selected to demonstrate the effectiveness of enhancing the durability of samples against weather conditions, utilizing the wetting and drying method, and underwent thermal protection property testing in the subsequent phase of experimentation.

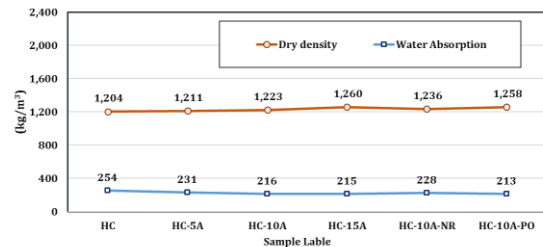


Figure 9. Water absorption and dry density test results

Evaluation of Environmental Durability of Hemp Concrete via the Wetting and Drying Method

The wetting and drying method involves subjecting samples of hemp concrete to alternating wet and dry cycles to mimic real-world environmental conditions. This testing procedure aims to evaluate how the material responds to moisture absorption and subsequent drying, which are critical factors influencing its long-term performance. The wetting and drying cycles are repeated multiple times to assess the material's response over extended periods. This iterative process provides valuable insights into the durability and resistance of the material to degradation caused by moisture-induced damage. From the compressive strength testing results of HC-15A, which exhibited the highest compressive strength at 5.41 MPa, it was chosen as the sample for testing its properties under wet-dry conditions. The HC-15A sample, aged 28 days, was soaked in water for 5 hours, subsequently cured at 70 degrees Celsius for 48 hours, and then allowed to cool to room temperature. Wet-dry testing was conducted for one cycle, requiring 4 days or 96 hours to complete, with a total of 12 cycles performed. The samples subjected to wet-dry conditions were subsequently assessed for compressive strength,

water absorption, and dry density every 2 cycles, as illustrated in Figures 10 and 11.

The results of compressive strength testing, as illustrated in Figure 10, provided intriguing insights into the behavior of HC-15A under wet-dry conditions. It was observed that the compressive strength of HC-15A experienced a notable increase when subjected to these conditions, peaking at 5.60 MPa during cycles 8 and 10, before decreasing slightly to 5.55 MPa in cycle 12. Importantly, even after undergoing wet-dry cycling, HC-15A maintained higher compressive strength compared to hemp concrete specimens that were not exposed to such conditions. The observed enhancement in compressive strength was attributed to the continued reaction of cement with water, known as hydration, which positively contributed to the overall strength of hemp concrete. The cyclic exposure to wet and dry conditions seemed to facilitate this reaction, thereby reinforcing the structural integrity of HC-15A.

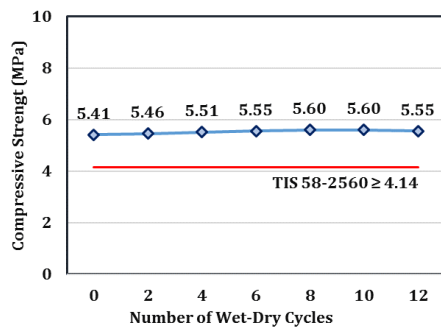


Figure 10. Compression strength test results for HC-15A under wet-dry conditions

The observed increase in the compressive strength of HC-15A under wet-dry conditions was further explained by the continuous hydration reaction that occurred between the cement and water during each wet-dry cycle. As water permeated the concrete structure during the “wet” phase, it activated the cement particles, leading to the formation of calcium silicate hydrate (C-S-H), which was the primary compound responsible for enhancing the strength of the concrete. This process was further supported by the presence of silica and alumina in the raw materials, which contributed to the formation of additional cementitious compounds, such as calcium aluminate silicate hydrate (C-A-S-H). These compounds filled voids within the concrete matrix, enhancing the strength and durability of the material. This continued hydration and the cyclic wet-dry exposure facilitated an ongoing strengthening process, reinforcing the structural integrity of HC-15A and

improving its performance over time. As seen in the test results, even after multiple wet-dry cycles, HC-15A maintained superior compressive strength compared to the hemp concrete specimens that were not exposed to such conditions. This confirms the beneficial effects of wet-dry cycling on the strength and durability of cement-stabilized materials, as reported in previous studies (Hoy *et al.*, 2023a; Hoy *et al.*, 2023b).

The water absorption and dry density testing results revealed significant alterations in HC-15A, as illustrated in Figure 11, following wet-dry cycling. Notably, there was a consistent reduction in dry density observed with each testing point. After undergoing 12 wet-dry cycles, HC-15A exhibited a dry density of 1,167 kg/m³, contrasting with 1,260 kg/m³ for the sample not exposed to wet-dry conditions, representing a reduction of 7.38%. Furthermore, there was a concurrent increase in water absorption as the number of wet-dry cycles increased. Starting at an initial water absorption of 215 kg/m³, it rose to 287 kg/m³ after completing 12 cycles. This rise in water absorption typically accompanies a decrease in material density.

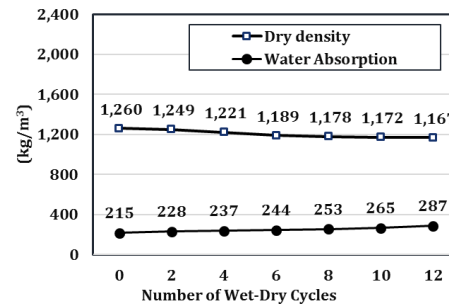


Figure 11. Water absorption and dry density test results for HC-15A under wet-dry conditions

The decline in the density of HC-15A hemp concrete after multiple wet-dry cycles primarily resulted from material loss due to the disintegration of both the concrete and hemp components, leading to a decrease in density. This reduction in dry density was mainly attributed to the loss of free water and the partial degradation of hemp fibers, which contributed minimally to the strength. Despite this, the compressive strength of HC-15A continued to increase, demonstrating the material’s resilience. The continued hydration of cement under wet-dry conditions resulted in the formation of calcium silicate hydrate (C-S-H) and other hydration products, which reinforced the material’s microstructure. Additionally, the hemp fibers likely helped distribute stresses more effectively within the concrete, mitigating the effects of reduced

density. The wet-dry cycles likely facilitated the formation of calcium carbonate (CaCO_3) through carbonation, further enhancing the material's structural integrity.

The decrease in density also led to an increase in porosity, which could have been beneficial for the material's long-term performance. While the reduction in density might have been seen as a drawback, the creation of smaller, disconnected pores during wet-dry cycling did not necessarily compromise the overall strength. These pores could have played a key role in accommodating the formation of C-S-H products and calcium carbonate, optimizing the internal structure of the material. The optimized porosity could have also helped maintain the material's overall stability while balancing the trade-off between strength and density, allowing HC-15A to maintain its compressive strength despite the observed reduction in density.

The production of hemp concrete for non-load-bearing masonry concrete units primarily prioritizes compressive strength, as stipulated in TIS 58-2560, which requires a minimum of 4.14 MPa. Remarkably, even after enduring 12 cycles of wet-dry conditions, the HC-15A sample remained compliant with this requirement, demonstrating its resilience to environmental challenges. These findings highlighted the potential advantages of incorporating HC-15A in construction applications, particularly in environments susceptible to fluctuating moisture levels. Further investigation into the underlying mechanisms driving this behavior could provide valuable insights for enhancing the performance of hemp concrete in diverse real-world scenarios.

Evaluation of Energy Conservation Performance for Construction Materials in Accordance with the Ministry of Energy's Prescribed Method

In Thailand, the Ministry of Energy issued guidelines for energy conservation in building design. Concerning wall design, it is stipulated that the OTTV must not exceed 30-50 w/m^2 , depending on the building type. Specifically, the OTTV of walls for office buildings must not surpass 50 w/m^2 . Materials with lower OTTV indicate higher efficiency in reducing heat transmitted from the exterior. In this section, the OTTV of Hemp concrete label HC-15A was calculated and compared with red brick, concrete block, and lightweight concrete block, which are commonly used building materials in Thailand.

The properties of the materials used as variables in calculating the OTTV value included thermal conductivity (k), specific heat capacity (c), thickness (Δx), and density (ρ). The sample

materials used for the OTTV calculation included red brick, concrete block, and lightweight concrete block, which were compared with hemp concrete (HC-15A). The physical characteristics and properties of these wall masonry materials are illustrated in Figure 12, with the properties of red brick, concrete block, and lightweight concrete block taken from the Ministry of Energy's Notification on Criteria for Calculations, Certification of Assessment Results, and Energy Conservation Building Design Standards for Each System, Overall Building Energy Use, and Renewable Energy Use in Various Building Systems, B.E. 2564 (Ministry of Energy, 2021a). In contrast, the properties of HC-15A were based on test results from this research. The calculated OTTV values for these materials are shown in Figure 13.



(a) Red Brick; $\Delta x = 65 \text{ cm}$, $k = 0.47 \text{ w/m}^\circ\text{C}$, $\rho = 1,600 \text{ kg/m}^3$, $c = 0.79 \text{ kJ/kg.C}$



(b) Concrete Block; $\Delta x = 65 \text{ cm}$, $k = 0.55 \text{ w/m}^\circ\text{C}$, $\rho = 2,210 \text{ kg/m}^3$, $c = 0.92 \text{ kJ/kg.C}$



(c) Lightweight Concrete Block; $\Delta x = 75 \text{ cm}$, $k = 0.18 \text{ w/m}^\circ\text{C}$, $\rho = 620 \text{ kg/m}^3$, $c = 0.84 \text{ kJ/kg.C}$



(d) Hemp Concrete (HC-15A); $\Delta x = 125 \text{ cm}$, $k = 0.16 \text{ w/m}^\circ\text{C}$, $\rho = 1,260 \text{ kg/m}^3$, $c = 1.24 \text{ kJ/kg.C}$

Figure 12. Physical and thermal properties of wall masonry materials

The comparison of the OTTV values in all eight directions for the materials shown in Figure 13 revealed that the highest OTTV values were observed when calculated for the southeast-facing wall. Red brick had an OTTV of 63.69 w/m^2 , concrete block = 70.04 w/m^2 , and lightweight

concrete block had an OTTV of 38.01 w/m^2 , while HC-15A had an OTTV of 19.97 w/m^2 . The OTTV calculations indicated that both lightweight concrete and soil cement blocks were considered energy-efficient construction materials, as both had OTTV values lower than 40 w/m^2 . Additionally, plastering and painting would have further reduced the OTTV values. Regarding HC-15A, with an OTTV of 19.97 w/m^2 , it could be concluded that HC-15A was an energy-efficient construction material suitable for various types of energy conservation projects, in line with the regulations set forth by the Ministry of Energy.

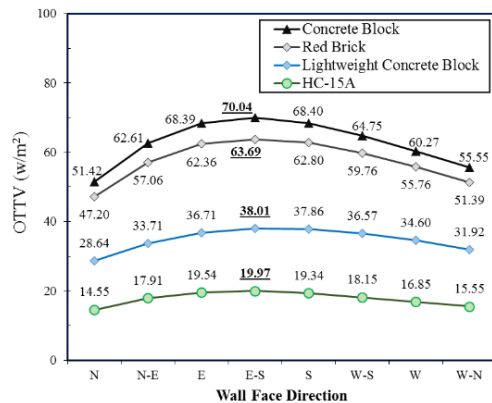


Figure 13. Results of calculating the OTTV of lightweight concrete and hemp concrete

This content emphasized the advantages of HC-15A as a building material, particularly its lower OTTV compared to red bricks, concrete blocks, and lightweight concrete blocks. This was attributed to its lower k-value, which resulted from the thermal insulation properties of hemp used as a component in HC-15A. Additionally, its design as interlocking blocks with greater thickness than the aforementioned materials effectively reduced the OTTV, especially when compared to lightweight concrete blocks with a similar k-value. OTTV represents the amount of heat transferred through a building's walls, which significantly impacts the workload of air conditioning systems. Building materials with good thermal insulation properties demonstrate low k-values, which consequently result in lower OTTV values. This reduction helps decrease electricity consumption for air conditioning systems and contributes to long-term energy cost savings.

The low OTTV value exhibited by HC-15A reflected the potential of hemp as an additive to enhance the thermal performance of concrete-based building materials. However, increasing the hemp content in the production of hemp concrete could have further reduced the OTTV, although it might

have negatively affected the compressive strength of the material. Therefore, further research is necessary to improve the compressive strength of hemp concrete while maintaining a balanced increase in the hemp content to optimize overall performance.

Summary and Conclusions

This research demonstrated the results of improving the quality of hemp concrete and assessed its suitability as an energy-saving construction material. The conclusions can be summarized as follows:

- Hemp concrete produced with Type I Portland cement, soil, and hemp at a weight ratio of 1:2:0.4 (with hemp comprising 11.76 wt% of the total dry composition) exhibited a compressive strength of 2.56 MPa, a dry density of 1,204 kg/m^3 , and water absorption of 254 kg/m^3 . Thus, it was classified as a construction material with lower compressive strength than the standard specified in TIS 58-2560.

- Hemp concrete enhanced with aluminum sulfate at 5-15% by weight of hemp, and additionally with aluminum sulfate at 10% by weight of hemp combined with latex rubber, or combined with polymers, resulted in increased strength in all cases. The highest compressive strength was achieved by surface treatment with aluminum sulfate at 15%. The method of enhancing hemp concrete with aluminum sulfate at 15% was considered interesting due to its ease of implementation and cost-effectiveness. This approach was tested for additional properties, as follows:

- After curing for 28 days, compressive strength was 5.41 MPa, which was increased by 111.33% compared to hemp concrete without quality enhancement. Other properties included a dry density of 1,260 kg/m^3 and water absorption of 215 kg/m^3 , exceeding the standards specified in TIS 58-2560. This categorized it as a lightweight construction material, with a density lower than 1,680 kg/m^3 .

- After 12 wet-dry cycles, compressive strength was 5.55 MPa, dry density was 1,167 kg/m^3 , and water absorption was 287 kg/m^3 , meeting the standard specified in TIS 58-2560 and indicating durability against weather changes.

- Thermal properties: Thermal conductivity was 0.16 $\text{w/m}^\circ\text{C}$, and specific heat capacity was 1.24 $\text{kJ/kg}^\circ\text{C}$.

- The assessment of thermal insulation performance using OTTV showed the highest value in the southeast direction at 19.97 w/m^2 , indicating its suitability for energy conservation in all types of buildings according to the notification by the Ministry of Energy. With a lower OTTV than red

bricks, concrete blocks, and lightweight concrete blocks, it was shown to be an energy-efficient construction material that effectively reduced heat transfer into buildings, thereby decreasing energy consumption and reducing the workload of air conditioning systems.

Acknowledgment

The authors wish to express their gratitude for the research funding received from the Faculty of Engineering, Srinakharinwirot University, for the fiscal year 2022, under research grant No. 310/2565.

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