

ENHANCING THE COMPRESSIVE STRENGTH OF HEMP FIBER REINFORCED CEMENT AND EVALUATING THERMAL PROTECTION PERFORMANCE

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Abstract

This research aimed to enhance the properties of hemp concrete to comply with the non-load bearing block according to the standard criteria TIS 58-2533. Samples of hemp concrete blocks measuring 7.5×7.5×10 cm were produced with varying compositions of hemp ranging from 0-14.29% by weight of dry aggregate. Properties of hemp concrete were improved using $\text{Al}_2(\text{SO}_4)_3$, plasticizers, natural rubber, and polymers. Testing included compressive strength, dry density, water absorption, and calculation of the OTTV compared to standards set by the Ministry of Energy. Hemp concrete without property enhancement additives consistently exhibited lower compressive strength than 2.5 MPa. Enhancing hemp concrete with 20% $\text{Al}_2(\text{SO}_4)_3$ by weight of hemp, combined with polymer, yielded the highest compressive strength compared to other methods. Hemp concrete with 9.09% and 14.29% hemp by weight of dry aggregate, enhanced with 20% $\text{Al}_2(\text{SO}_4)_3$ by weight of hemp and 50% polymer by weight of water used for mixing mortar, exhibited compressive strengths of 3.41 MPa and 2.62 MPa, respectively. Water absorption were 377 kg/m³ and 407 kg/m³, and dry densities were 0.98 g/cm³ and 0.90 g/cm³, respectively. Both samples achieved OTTV less than 50 w/m². From this research, the production process of hemp concrete with 9.09% and 14.29% hemp by weight of dry aggregate was enhanced with 20% $\text{Al}_2(\text{SO}_4)_3$ by weight of hemp, and polymer was combined by 50% by weight of water used for mixing mortar. This resulted in a material with compressive strengths comparable to non-load bearing block and suitable for energy-efficient construction, particularly in office buildings.

Keywords: Hemp; Concrete; Construction Materials; Heat Transfer; Energy Saving

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Introduction

Human activities invariably caused the emission of greenhouse gases, both directly and indirectly, which had impacts on ecosystems, societies, and the environment. This led to numerous environmental issues such as climate change, global warming, droughts, floods, erratic weather patterns, and biodiversity loss. Construction was one of the major contributors to global warming due to the emission of pollutants from construction activities and the presence of pollutants embedded in construction materials. Developing construction materials with low carbon dioxide emissions emerged as a better option for environmentally friendly and sustainable construction practices (Huang *et al.*, 2018). Research reported that the production of bio-based construction materials resulted in fewer pollutants compared to conventional construction materials (Madurwar *et al.*, 2013). Bio-based construction materials helped reduce pollution and had low thermal conductivity properties, effectively preventing external heat from entering buildings. (Intata *et al.*, 2006) In Thailand, there were research efforts aimed at developing agricultural waste into bio-based construction materials with good insulation properties, such as vetiver grass, bamboo scraps (Pakdee and Rattanaplome, 2018) corn cob (Woraput *et al.*, 2016) and rice husks (Taemthong, 2013).

Hemp had been a newly recognized economic plant that had been legally cultivated in accordance with Thai law. The primary objective of growing hemp was to utilize the bark fibers, harvest the flower buds for extracting cannabidiol (CBD), and collect seeds for extracting hemp seed oil. In the past, there were legal restrictions on hemp cultivation, allowing it only in authorized areas. Primarily, the aim was to produce stem bark fibers for use in the textile industry, made the core of hemp stalks, which were called “hurd” into waste material. The hemp hurd was considered a type of biodegradable material, which had been developed into construction materials such as hempcrete and hemp concrete. There was an increasing cultivation of hemp for extracting CBD due to its legality under the new law. Cultivating hemp for CBD extraction typically took about 120 days, with the hemp stalks with bark as waste material. The leftover material could have been developed into construction materials similar to the hemp hurd. Since the fibers from the hemp stalks with bark were sticky, they were likely to enhance certain properties of hemp concrete. Therefore, there should be a study to use the hemp stalks with bark to produce construction

materials and improve its properties to be as strength as non-load bearing block.

The construction material produced from hemp shiv, aimed at reducing weight and enhancing insulation properties, had significant limitations. It exhibited low strength, making it suitable for applications with low load requirements (Sinsiri *et al.*, 2022). However, it had advantages in terms of heat resistance (Elfordy *et al.*, 2008; Ismail and Cüneyt, 2020) and permeability to water and vapor, reducing the risk of mold growth (Birjukovs *et al.*, 2022). It maintained a constant relative humidity level in the surrounding air (Bennai *et al.*, 2022), and importantly, it could absorb approximately 50% of its volume in carbon dioxide (Peev, 2012).

Hemp shiv, composed mainly of natural fibers, contained various components besides fibers, such as celluloses, lignin, pectin, and hemicelluloses, which affected the material's properties. To enhance the fiber's performance, the production of construction materials from hemp shiv required certain processes. Research on utilizing hemp as a component in composite construction materials in concrete mixtures found that surface treating hemp with aluminum sulfate ($\text{Al}_2(\text{SO}_4)_3$) and calcium hydroxide ($\text{Ca}(\text{OH})_2$) significantly increased the strength of hemp concrete up to 4 times compared to samples without treatment with $\text{Al}_2(\text{SO}_4)_3$ and $\text{Ca}(\text{OH})_2$ (Pantawee *et al.*, 2017a). Previous research on developing construction materials from hemp mainly concentrated on using hemp hurd without bark fiber as the main material for production. This approach involved combining the hemp shiv with various binding materials, including lime, cement, hydraulic cement, and plaster. However, these construction materials were significantly limited by their low strength.

Hemp concrete was categorized as a type of composite material, comprising a matrix phase material, which was mortar (a blend of cement, sand, and water), and a reinforced material, which was hemp. Hemp shiv as a fiber-reinforced material, characterized by discontinuous and randomly oriented fibers. The properties of hemp concrete were contingent upon the characteristics of the matrix materials, the reinforcing material, the mixing ratio between concrete and hemp shiv, and the interfacial force between hemp and concrete. In this study, hemp concrete was manufactured using hemp hurd with bark fiber, molded into specimens with steel molds measuring 7.5×7.5×10 centimeters. This production method did not involve energy-intensive processes such as burning, thus

conserving energy. The mixing of hemp aimed to reduce weight and enhance insulation properties while simultaneously improving the compression strength of hemp concrete to meet the standards of non-load bearing block.

The method for enhancing the strength of hempcrete was divided into two main approaches. 1) Improved the adhesion properties at the interface of hemp by adjusting the surface condition of hemp before production using an appropriate quantity of acid or alkali solution. The use of $\text{Al}_2(\text{SO}_4)_3$ and $\text{Ca}(\text{OH})_2$ to treat the hemp surface resulted in a significant increase in compression strength, up to 4 times higher (Pantawee *et al.*, 2017b). 2) Enhanced the properties of concrete with various additives aimed at increasing the compressive strength of construction materials produced from soil and cementitious materials. For instance, the use of plasticizers (Lambe and Moh, 1958) and polymer additives could improve the compressive strength of construction materials produced from cementitious materials. Both natural rubber polymers (Phetcharat *et al.*, 2021) and synthetic polymers (Sukprasert *et al.*, 2017) have been effective. Therefore, the development of hemp concrete production methods had to be appropriate to increase compressive strength to meet the standard requirements non-load bearing block, which stipulated a minimum compressive strength of 2.5 MPa.

Hemp concrete had to retain its original desirable properties, such as lightweight and suitable thermal properties for energy-efficient building materials. This required verification through calculations of the overall thermal transfer value (OTTV) as prescribed by the Ministry of Energy, compared to the criteria for energy-efficient buildings, particularly office buildings, which specified an OTTV of no more than 50 w/m^2 , as per the Ministry of Energy's regulations.

Materials and Methods

The hemp stalks with bark fiber, as shown in Figure 1, were chopped into small particles, were used as natural aggregate materials in the production of hemp concrete sample. Present the details regarding research materials, the production process of hemp concrete samples, and property testing and analysis in sections 1-3 sequentially.

Research Materials

The materials utilized in the production of masonry from hemp stalks with bark fiber were as follows:

- The matrix phase material consisted of Type 1 portland cement and sand in a weight ratio of 1:2. The sand had gradation as specified in Table 1, with the largest size not exceeding 4.750 mm and the smallest size not exceeding 0.075 mm, accounting for 2.75%.

- The hemp stalks with bark fiber, which were remnants from hemp cultivation for flower harvesting, had aged 120 days before being finely chopped into small particles. These particles comprised fibers of various sizes from the hemp hurd, including short fibers from the bark, as shown in Figure 2. The bark fibers could penetrate the voids of the hemp hurd, facilitating more effective mixing of hemp in the construction material compared to using hemp hurd without bast fiber. The ratio of hemp hurd with bark fiber by volume per unit weight was 5.6 cm^3/gram . The gradation was specified in Table 1, with the largest size not exceeding 9.525 mm and the smallest size not exceeding 0.075 mm, accounting for 0.12%.

- The surfactant treatment for hemp used was aluminum sulfate ($\text{Al}_2(\text{SO}_4)_3$).

- The additives used to improve hemp concrete properties included plasticizers manufactured for commercial use that were certified according to the Thai Industrial Standards Institute (TISI) standard, TIS 733-2530; natural rubber with a dry rubber content of 40%; and polymer. This polymer had a specific gravity of 1.0, a pH range of 8 to 10, and a solid content ranging from 28% to 32%.

Therefore, the present paper provides a comprehensive review on the torsional behavior of composite materials, critical parameters and testing methods. Analyses of the torsional properties of composites, such as torsional stiffness, toughness, and fatigue resistance is presented. Further, the recent developments, current challenges in applications of composites are explored for the future research work.

Table 1. Gradation of fine Sand and Hemp fiber

Sieve No.	Sieve Opening (mm.)	Percent Finer (% wt.)	
		Fine Sand	Hemp fiber
1/2"	12.500	100.00	100.00
3/8"	9.525	100.00	100.00
4	4.750	100.00	95.36
8	2.360	98.24	74.78
16	1.180	92.48	23.94
30	0.600	79.27	8.73
50	0.300	46.06	2.32
100	0.150	10.39	0.42
200	0.075	2.75	0.12



Figure 1. Hemp stalk with bark fiber

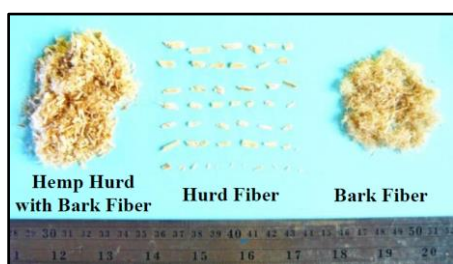


Figure 2. Hemp Hurd fiber with bark fiber

The production process of hemp concrete samples

• The production process of hemp concrete samples was outlined sequentially in steps 1 through 5, with the process of enhanced properties outlined in step 6) a-d, were as follows:

• The sand and hemp were dried before being weighed for sample production

• Assigned sample labels HC000 to HC500, each containing varying amounts of hemp ranging from 0 to 500 grams. HC000 represented the concrete block sample without hemp inclusion, while HCXXX represented samples with hemp inclusion of XXX grams per 4 pieces, as indicated in Table 2.

• The hemp was prepared in a mixing tray according to the specified quantities. Water, with a volume twice that of the weight of the hemp, was added, mixed, and allowed to stand for 5 minutes.

• The mortar was prepared by mixing sand, portland type 1 cement, and water at a ratio of 1:2:0.5 by weight to achieve a consistent texture. Then, the mixture was placed into the tray prepared with a screed in step 3 and blended thoroughly.

• The mixture was compacted into steel molds sized 7.5×7.5×10 cm, with 4 pieces per production. The hemp concrete samples exhibited characteristics as shown in Figure 3.

• Hemp concrete were produced with enhanced properties through surface treatment of hemp and the addition of additives. Hemp concrete samples labelled HC330 and HC500 were selected as case studies. These samples contained hemp as an inclusion at percentages of 9.09 and 14.26 by weight, respectively. The enhancement of hemp concrete properties in this research was demonstrated in steps a-d.

a) The hemp surface was treated with $Al_2(SO_4)_3$ at 10, 15, 20, and 25 percent by weight of hemp. The production process involved dissolving $Al_2(SO_4)_3$ in water before mixing it with hemp and allowing it to stand for 5 minutes. Then, the process followed steps 4-5 of the production process sequentially.

b) The quality of hemp concrete was enhanced by the addition of plasticizers at 5% by weight of portland cement. These plasticizers were mixed with the water used to mix the mortar.

c) The quality of hemp concrete was enhanced by 50% natural rubber by weight of water used for mixing mortar. Natural latex was mixed with water in step 4 of the production process before being combined with portland cement and sand. Then, the mixture was compacted into molds in step 5 of the production process.

d) Enhancing the quality of hemp concrete with 50% polymer by weight of water used for mixing mortar. The polymer was mixed with water in step 4 of the production process before being combined with Portland cement and sand. Then, the mixture was compacted into molds in step 5 of the production process.

Table 2. Ingredients for producing hemp concrete samples

Label	Weight of the Material (kg)					% wt. of Hemp
	Preparation of Hemp		Mortar Ingredients			
	Hemp	Water	Cement	Sand	Water	
1. HC000	0.00	0.00	3.20	6.40	1.60	0.00
2. HC200	0.20	0.40	1.50	3.00	0.75	4.26
3. HC250	0.25	0.50	1.38	2.76	0.69	5.70
4. HC300	0.30	0.60	1.25	2.50	0.63	7.41
5. HC330	0.33	0.66	1.10	2.20	0.55	9.09
6. HC350	0.35	0.70	1.06	2.12	0.52	9.92
7. HC400	0.40	0.80	1.02	2.04	0.51	11.56
8. HC500	0.50	1.00	1.00	2.00	0.50	14.29

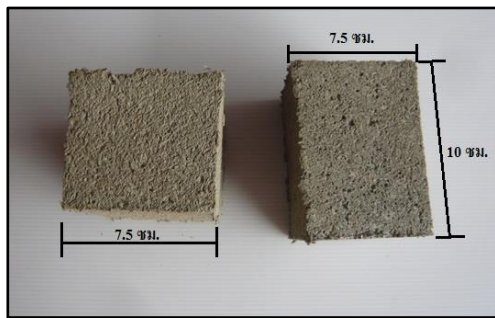


Figure 3. Hemp concrete sample

Property Testing and Analysis

- Testing the properties of hemp concrete samples after curing in air for 28 days involved compression strength testing, density testing, and water absorption testing for comparison with the TIS 58-2533 standard. This standard specifies that non-load-bearing block must have a compression strength of not less than 2.5 MPa, while load-bearing block standard must have a compression strength of not less than 7 MPa.

- Thermal properties testing includes thermal conductivity (k) and specific heat capacity (c_p) to determine the overall thermal transfer value (OTTV) according to the announcement of the Ministry of Energy

Results and Discussion

The study examined the effect of hemp volume on the properties of hemp concrete

The study involved various volumes of hemp in materials where quality had not been improved. There were a total of 8 labels, namely HC000, HC200, HC250, HC300, HC330, HC350, HC400, and HC500, with different percentages of hemp as follows: 0%, 4.26%, 5.70%, 7.41%, 9.09%, 9.92%, 11.56%, and 14.29%, by weight of the dry aggregate. The compressive strength of the samples, as shown in Figure 4, and the dry density and water absorption, as shown in Figure 5, were measured.

The test results for compressive strength, as depicted in Figure 4, indicated that sample HC000, devoid of any hemp mixture, was conventional concrete block, exhibited a compressive strength of 24.44 MPa, water absorption of 172.21 kg/m³, and dry density of 2.01 g/cm³. These properties met the standards set by the load bearing block standard, TIS

57-2553. However, samples containing hemp in all cases showed compressive strengths ranging from 0.41 to 0.82 MPa, lower than block concrete and below the minimum compressive strength standard of 2.5 MPa set for non-load bearing block. These test results demonstrated a significant reduction in compressive strength when using hemp concrete compared to samples without hemp. Therefore, it was crucial to utilize specific production methods to improve the strength of masonry material made from hemp, such as incorporating additives or modifying production processes.

The test results for dry density and water absorption, as shown in Figure 5, indicated a decrease in dry density with an increase in the amount of hemp, which was the main objective in producing hemp concrete. Hemp concrete had dry densities ranging from 0.79 to 1.21 g/cm³, which were lower than block concrete with a dry density of 2.01 g/cm³. Hemp was mixed in hemp concrete at percentages ranging from 4.26 to 14.29% of dry aggregate weight, and it could be used to reduce weight by 39.80% to 60.70%.

Regarding water absorption, the test results, as shown in Figure 5, revealed that concrete block had a water absorption rate of 172.21 g/cm³, while hemp concrete had water absorption rates ranging from 310.64 to 399.19 g/cm³. Increasing the amount of hemp in the mixture led to higher water absorption values for hemp concrete.

Based on the results of this research section, it was discovered that increasing the hemp content in hemp concrete yielded certain benefits, such as reducing the concrete's weight and enhancing water absorption, although the latter was neither desirable nor a critical requirement for non-load bearing blocks. However, the most significant drawback identified was the reduction in compressive strength to levels below the standard. Production of hemp concrete without the process of surface treatment of hemp and without adding additives resulted in properties unsuitable for use as a building material, primarily due to its lower compressive strength compared to the standard for non-load bearing blocks. This was a common issue with hemp concrete, which often suffered from weaknesses in terms of strength due to the addition of hemp to reduce weight and increase thermal insulation properties. Therefore, this research needed to improve the properties of hemp concrete to achieve characteristics comparable to those of non-load bearing concrete blocks standard.

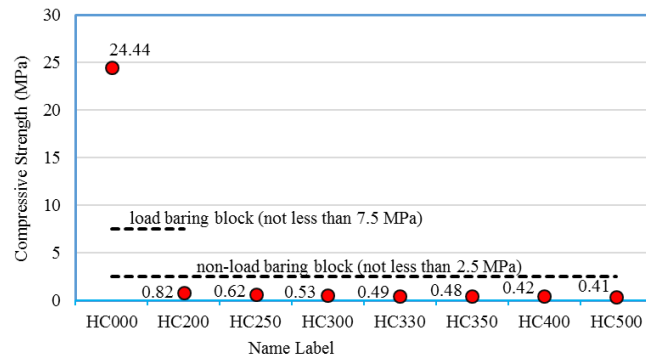


Figure 4. Compressive strength test results

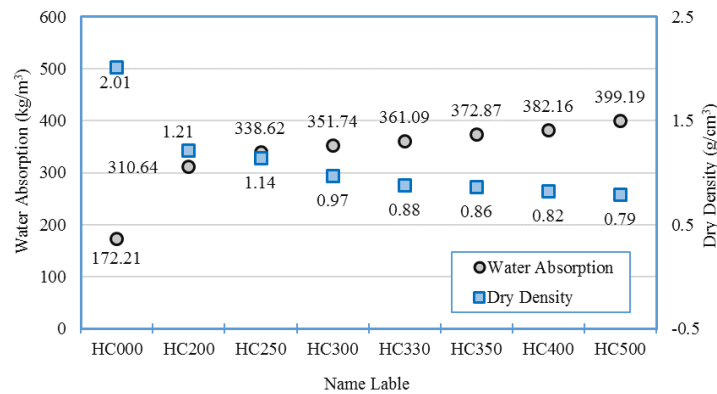


Figure 5. Dry density and water absorption test results

The results of enhancing the properties of hemp concrete through surface treatment of the hemp and the addition of additives

Improving the properties of hemp concrete was achieved through surface treatment of the hemp and the addition of additives. This method was tested with samples HC330 and HC500, representing 9.09% and 14.29% by weight of aggregate, respectively. The experimentation aimed to enhance the quality of hemp concrete by surface treating the hemp with varying quantities of $\text{Al}_2(\text{SO}_4)_3$, which were 0, 5, 10, 15, and 20 percent by weight of hemp. The selected additives used for enhancing the properties of hemp concrete were: plasticizers at 5 percent by weight of cement. Natural rubber and polymer were added to water at 50 percent by weight of the water mixed with mortar. These experiments were conducted to utilize both surface treatment of hemp and the addition of additives simultaneously.

The hemp concrete samples labeled HC330 and HC500 underwent enhancement through surface treatment of the hemp and the addition of additives. They were then tested for compressive strength,

water absorption, and dry density. The test results of the samples labeled HC330 and HC500, which had undergone quality improvement, were as follows: The compressive strength test results were depicted in Figure 6 and Figure 7, water absorption was illustrated in Figure 8 and Figure 9, and dry density was shown in Figure 10 and Figure 11. The results of the tests were presented in Figures 6-11, which displayed the mean values obtained from testing 5 samples, with error bars indicating the maximum and minimum values.

Upon analyzing Figure 6, it was found that the compressive strength of HC330 samples without surface treatment was 0.49 MPa. However, following the addition of additives in all types, namely plasticizers, natural rubber, and polymer, the compressive strength increased to 0.84, 0.92, and 1.02 MPa, respectively. Notably, enhancement with polymer yielded the most significant improvement in compressive strength, increasing it by 108% compared to untreated HC330 without additional additives.

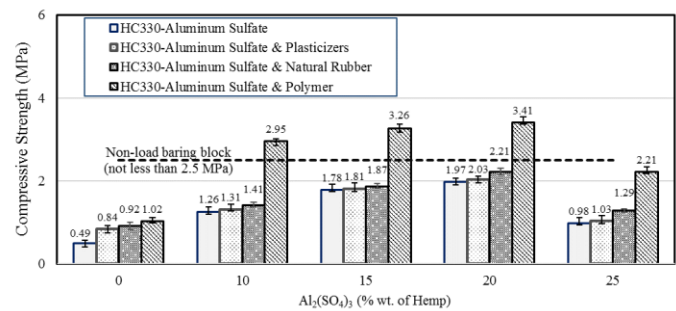


Figure 6. The compressive strength test results of the enhanced HC330

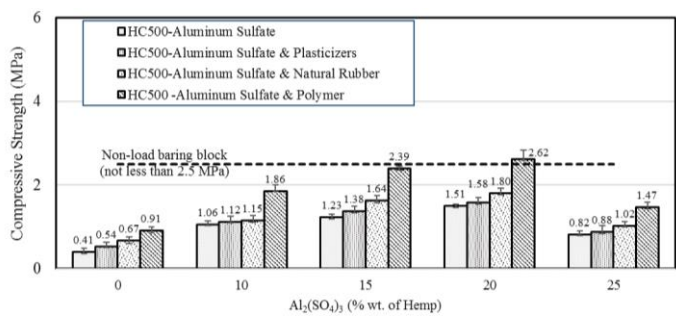


Figure 7. The compressive strength test results of the enhanced HC500

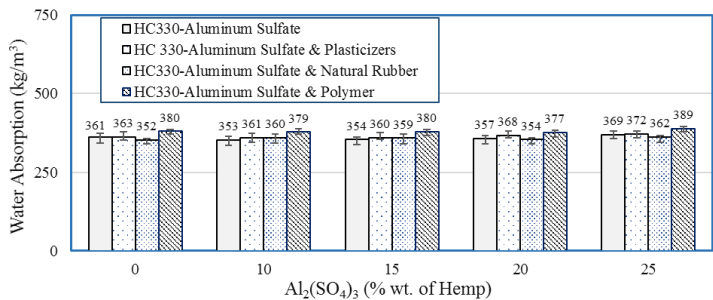


Figure 8. The water absorption test results of the enhanced HC330

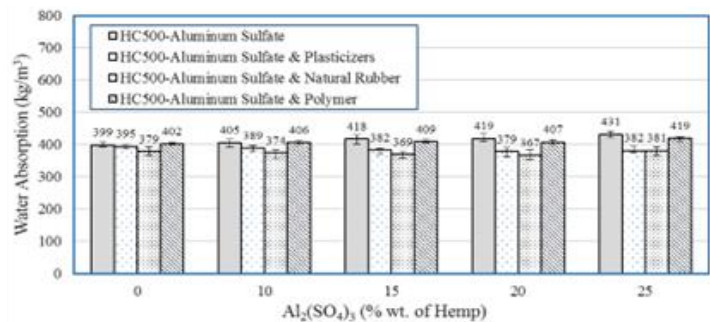


Figure 9. The water absorption test results of the enhanced HC500

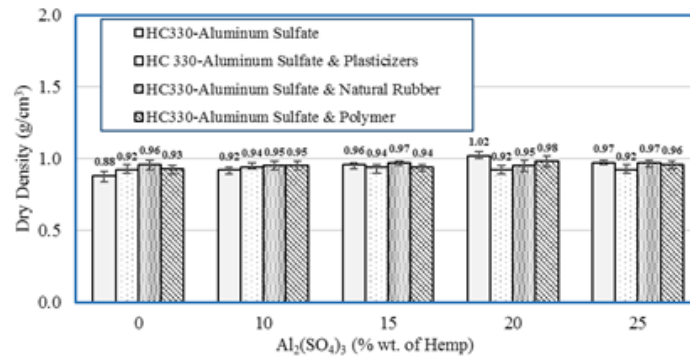


Figure 10. The dry density test results of the enhanced HC330

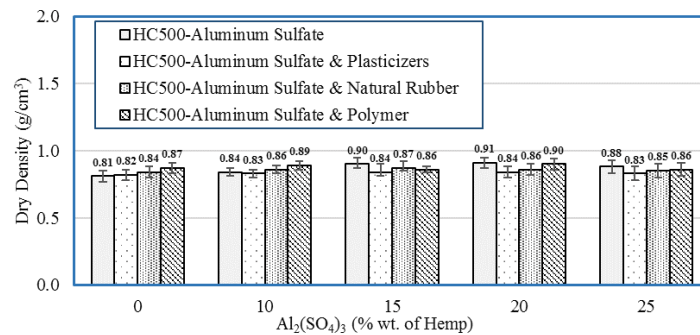


Figure 11. The dry density test results of the enhanced HC500

The compressive strength of HC330 samples, which had their hemp surface treated with $Al_2(SO_4)_3$ at quantities of 10, 15, 20, and 25% by weight of hemp, demonstrated the beneficial effects of using $Al_2(SO_4)_3$. This led to an increase in compressive strength when used in quantities of 10, 15, and 20%. However, when used up to 25%, it had adverse effects. The experiments in this regard demonstrated that the method yielding the highest compressive strength for HC330 was the treatment with 20% $Al_2(SO_4)_3$ by weight of hemp, combined with polymer. This resulted in a compressive strength of 3.41 MPa, an increasing it by 596% compared to untreated HC330. The compressive strength had exceeded the specified value of the non-loading block standard, making it suitable for masonry according to the standards. Additionally, other tested properties, including water absorption at 377 kg/m³ and dry density at 0.98 g/cm³, as shown in Figures 8 and 10 respectively, indicated that it had characteristics of a medium-lightweight block.

Figure 7 was observed that the compressive strength of HC500, which had undergone quality

enhancement, exhibited similar characteristics to HC330 samples. The addition of $Al_2(SO_4)_3$ at quantities of 10, 15, and 20% increased the compressive strength, while increasing it to 25% had adverse effects on compressive strength. The use of additives in all cases, including plasticizers, natural rubber, and polymer, contributed to the increased compressive strength of hemp concrete. Combining $Al_2(SO_4)_3$ with additives in all cases resulted in a further increase in compressive strength of hemp concrete.

The compressive strength test results of HC500, which had exhibited the highest compressive strength, were attained when it underwent surface treatment with 20% $Al_2(SO_4)_3$ with polymer. This resulted in a compressive strength of 2.62 MPa, the only condition surpassing the threshold of 2.5 MPa, which was the standard for non-load bearing concrete blocks. Other properties included a water absorption rate of 407 kg/m³ and a dry density of 0.90 g/cm³, as shown in Figures 9 and 11, categorizing it as a medium-lightweight block.

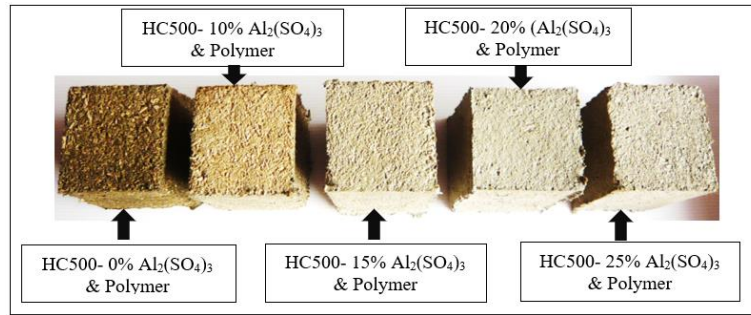


Figure 12. The characteristics of HC500 were enhanced through surfactant treatment with $\text{Al}_2(\text{SO}_4)_3$ and polymer additive

Both samples, HC330 and HC500, had high water absorption rates, measuring over 352 kg/m^3 for HC330 and over 369 kg/m^3 for HC500, as depicted in Figure 8 and Figure 9, respectively. However, these values did not meet the specifications for non-loading block standards. The results of the water absorption tests served as considerations for the limitations of using hemp concrete in construction, particularly in areas with high humidity.

The dry density values of both samples, HC330 and HC500, as shown in Figures 10 and Figure 11, were found to fall within the range of medium-lightweight materials. Specifically, they ranged from 0.88 to 1.02 g/cm^3 for all instances of HC330 and from 0.81 to 0.91 g/cm^3 for all instances of HC500. Increasing the amount of hemp in hemp concrete reduced its weight, but it also decreased its compressive strength.

From those experiments, it was evident that enhancing hemp concrete with a hemp content of up to 14.29% significantly increased its compressive strength. Specifically, the compressive strength increased by 539% compared to hemp concrete with the same hemp content but without enhancement. This improvement was achieved by incorporating 20% aluminum sulfate by weight of hemp, along with 50% polymer by weight of water mixed with mortar. The enhancement of HC500 with polymer showed the highest compressive strength in all cases, both when used alone and in combination with $\text{Al}_2(\text{SO}_4)_3$.

This illustrates an example of hemp concrete that was enhanced with aluminum sulfate at quantities of 0, 10, 15, 20, and 25%, along with 50% polymer of the mixing water, as shown in Figure 12. An observable difference was the increased fineness of the surface texture of the hemp concrete material when the quantity of $\text{Al}_2(\text{SO}_4)_3$ was increased. This resulted from the acidic properties of aluminum

sulfate when dissolved in water. When applied to hemp before production, it effectively eliminated some undesirable substances on the surface of the hemp, improving the interfacial bonding between the hemp and concrete. When used in appropriate quantities, it yielded favorable results. However, if excessive amounts of aluminum sulfate caused the hemp to become excessively disintegrated, resulting in the loss of its desirable properties as a reinforcement material, it consequently led to a reduction in compressive strength.

This research study on enhancing the properties of hemp concrete primarily focused on compressive strength. The findings indicated that incorporating 20% $\text{Al}_2(\text{SO}_4)_3$ and polymers resulted in the highest compressive strength for both HC330 and HC500. This outcome was attributed to $\text{Al}_2(\text{SO}_4)_3$, which was dissolved in water and acted as a mild acid, effectively removing undesirable substances from the hemp's surface when used in appropriate amounts. This surface treatment improved the wettability of the hemp, leading to better adhesion at the interfacial zone between the hemp and the mortar. However, excessive quantities of $\text{Al}_2(\text{SO}_4)_3$ caused the hemp to become mushy and disintegrate, thereby diminishing its reinforcement properties and adversely affecting compressive strength. Polymers, as bonding admixtures, enhanced the adhesion between the hemp and the mortar. Composite materials typically faced issues with interfacial adhesion between the reinforcing material and the matrix, which often led to reduced strength. Addressing these issues was known to improve the overall strength of the composite. Hemp concrete that was enhanced with 20% $\text{Al}_2(\text{SO}_4)_3$ and polymers had its interfacial adhesion problems between the hemp and the mortar effectively reduced. This enhancement led to an increase in the compressive strength of the hemp concrete.

Thermal properties and energy conservation efficiency as a construction material

The assessment of suitability for use as an energy-efficient construction material involved calculating the Overall Thermal Transfer Value (OTTV) of the building's exterior walls. This calculation method was specified by the Ministry of Energy, along with criteria, calculation procedures, and certification of assessment results for designing energy-conserving buildings for each system. It encompassed the overall energy consumption of the building and the use of renewable energy systems, as per the standards of 2021. Material properties utilized for calculations, aside from thermal conductivity coefficients (k), included specific heat capacity (C_p), density (ρ), and thickness (d).

The thermal conductivity of hemp concrete samples labeled HC330 and HC500, which were enhanced through surfactant treatment with $Al_2(SO_4)_3$ and polymer additives, and sized at 30×30 cm, was tested to evaluate their thermal conductivity. The results reported by the Department of Science Service showed that the thermal conductivity (k) value of HC330 was $0.249 \text{ W/m}^\circ\text{C}$, while HC500 had a value of $0.168 \text{ W/m}^\circ\text{C}$. The specific heat capacity (C_p) testing was conducted by sending samples to the National Metal and Materials Technology Center (MTEC). The reported C_p value of HC330 was $0.70 \text{ kJ/kg}^\circ\text{C}$. For HC500, the C_p value was reported as $1.24 \text{ kJ/kg}^\circ\text{C}$. The variables affecting the heat transfer of materials included parameters such as thermal conductivity, specific heat capacity, density, and Thickness, derived from testing the properties of hemp concrete. HC330 and HC500 exhibited thermal properties as shown in Table 3.

Table 3. Thermal Properties of HC 330 and HC 550 Enhanced with 20% Aluminum Sulfate and Polymer Additives

Sample label	k ($\text{W/m}^\circ\text{C}$)	d (m)	ρ (kg/m^3)	C_p ($\text{kJ/kg}^\circ\text{C}$)
HC330	0.249	0.075	980	0.70
HC500	0.168	0.075	900	1.24

To evaluate the thermal performance of hemp concrete under hot climate conditions, the OTTV was calculated. This involved methods specified by the Ministry of Energy, criteria, calculation procedures, and certification of assessment results for designing energy-conserving buildings for each system. It encompassed the overall energy consumption of the building and the use of renewable energy systems, as per the 2021 standards. This data, collected for statistical

purposes, had been used as a reference for calculations in Thailand, which was characterized by a tropical climate. Comparisons were made against construction criteria for office buildings, with an OTTV limit of 50 W/m^2 . For example, HC330 and HC500 had OTTV lower than 50 W/m^2 in all directions, with maximum OTTV values of 46.77 and 34.17 W/m^2 (calculated in the southeast wall face direction), as shown in Figure 13.

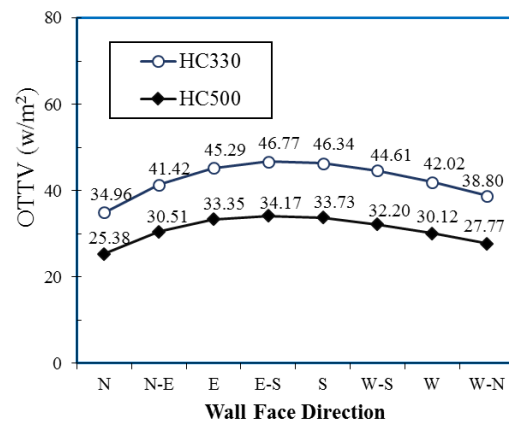


Figure 13. The results of the OTTV calculation for walls facing different directions

Therefore, the samples labeled HC330 and HC500 were considered suitable for use as construction materials to conserve energy, in accordance with the regulations established by the Ministry of Energy. Furthermore, based on the calculated OTTV, it was possible to design walls with lower OTTV, which could be achieved by increasing the thickness of hemp concrete production methods. Additionally, HC500 exhibited lower OTTV compared to HC330, indicating that increasing the proportion of hemp resulted in lower OTTV. This improves the efficiency of heat protection from the external environment.

Conclusions

This research involved producing hemp concrete using hemp stalks with finely chopped hemp bark as an ingredient, ranging from 4.26% to 14.29% by total dry aggregate. The mixture included Type 1 portland cement, sand, and water in a weight ratio of 1:2:0.5. The properties of hemp concrete were enhanced through surface treatment with aluminum sulfate, and additional additives such as plasticizers, natural rubber, and polymers. The findings of the study were summarized as follows

• Hemp concrete that had not undergone property enhancement exhibited compressive strengths lower than 2.5 MPa. Furthermore, increasing the hemp content resulted in a decrease in compressive strength.

• Prior to being utilized as an ingredient in the production of hemp concrete, the hemp underwent surface treatment with $\text{Al}_2(\text{SO}_4)_3$ at volumes of 5, 10, 15, and 20 weight percent of the hemp. This treatment was observed to enhance the compressive strength of the hemp concrete. The increase in the volume of aluminum sulfate to 25 percent led to a decrease in the compressive strength of the hemp concrete

• Enhancing hemp concrete with additional additives, including plasticizers at 5% by weight of cement, natural rubber at 50% by weight of the mixing water in the mortar, and polymers at 50% by weight of water used for mixing mortar, increased compressive strength.

• Surface treatment of hemp with $\text{Al}_2(\text{SO}_4)_3$ at 5, 10, 15, and 20 weight percentage of hemp, combined with additional additives such as plasticizers, natural rubber, and polymers, increased compressive strength.

• Adding 20% $\text{Al}_2(\text{SO}_4)_3$ by weight of the hemp, combined with polymers at 50% by weight of water used for mixing mortar, resulted in hemp concrete with hemp content of 9.09% and 14.29% by weight of total dry aggregate. This increased the compressive strength by 596% and 539%, respectively.

• Hemp concrete with 9.09% and 14.29% hemp content exhibited suitable properties for use as construction materials for energy conservation in office buildings. According to OTTV calculations, the highest values were 46.77 and 34.17 w/m^2 (lower than 50 w/m^2) in the southeast wall face direction when the thickness was 7.5 cm. Increasing thickness further reduced OTTV, while the addition of hemp to the material enhanced its heat protection property

• In this study, hemp concrete with 14.29% hemp content by weight of total dry aggregate met the compressive strength standards of non-load bearing block, while hemp concrete treated with 20% aluminum sulfate by weight of hemp, combined with polymers at 50% by weight of water used for mixing mortar, exhibited compressive strength of 2.62 MPa, water absorption of 407 kg/m^3 , and dry density of 0.90 g/cm^3 . The compressive strength was 539% higher than that of unenhanced hemp concrete, demonstrating its suitability as a construction material for energy conservation.

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