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Development of fibre-based soil–cement block with low thermal conductivity

Joseph Khedari *, Pornnapa Watsanasathaporn, Jongjit Hirunlabh

Building Scientific Research Center, King Mongkut's University of Technology Thonburi, Bangmod Rasburana, 91 Pracha U-thit Road, Thungkru, Bangkok 10140, Thailand

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Abstract

The development of a new type of soil–cement block using coconut coir with low thermal conductivity is the main purpose of this study. Various mixture ratios were considered and five specimens per sample were fabricated using local hand-made manufacturing process widely used in the country. Investigation was limited to the specimens' thermal conductivity, compressive strength, weight and bulk density. It was concluded that the use of coconut fibre as an admixture can reduce the block thermal conductivity and weight. The optimum volume ratio of soil:cement:sand to produce good properties is 5.75:1.25:2. The ratio of coconut coir is 20% of cement corresponding to 0.8 kg/block. The average specimen properties are as follows: thermal conductivity of 0.6510 W/m K, compressive strength of 39.55 kg/cm^2, weight of 4.85 kg and bulk density of 1586.77 kg/m^3. When compared to commercial soil–cement block, the corresponding decrease of thermal conductivity and weight are fairly significant, 54% and 750 g, respectively. Therefore, commercial development is highly promising.

Keywords: Natural fibre; Thermal conductivity; Compressive strength; Bulk density; Weight; Energy

1. Introduction

Energy has a significant influence in developing both industrial and business sector worldwide. At the present time, energy price trends to be high because of scarcity of energy source and in the meantime energy consumption is increasing continuously. Thailand is one of the countries facing such a problem. Therefore, it is important to find the way to reduce energy consumption and operating cost.

During the last decades, the use of fibres as an admixture either to complement or replace wood has grown exponentially due to mainly economic, environmental and political reasons. Various types of agriculture waste, after being processed, have been tested by blending with the other common compounds (soil, cement, sand and water) to make composite construction materials [1–10]. For instance, Ghavami et al. [2], investigated the application of sisal and coconut fibres in conjunction with three types of soil for the production of composite soil block reinforced with sisal and coconut fibres. One of the significant effects of the inclusion of natural fibres in the soil matrix was the prevention of shrinkage cracks due to the drying process. Youngquist [3], studied the options for using agricultural materials alone or in combination with wood to produce building components. They concluded that bagasses, cereal straw, and kenaf appear to have the most promise for composition panels. They are poorer in quality than those made of wood, but blending in small amounts (10–20%) of agricultural fibres was found to have no significant impact. Aggarwal [4] showed that bagasses can be used for the production of cement–bond composite materials for both internal and external applications in buildings. The tests undertaken by Coutts [5] showed that the bamboo fibre is a satisfactory fibre for incorporation into the cement matrix. Regarding soil, Walker [6] assessed the influence of soil characteristics and cement content on the physical properties of stabilized soil blocks. Both saturated strength and durability of cement stabilized

* Corresponding author. Tel.: +66-2-470-8625; fax: +66-2-427-9062.
E-mail address: joseph.khe@kmutt.ac.th (J. Khedari).
URLs: http://www.kmutt.ac.th/organization/bsrc, http://www.bsrc.net.

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soil blocks were improved by increasing cement and impaired by clay content. He concluded that the most ideal soils for cement soil block production should have a plasticity index between 5 and 15. Soils with a plasticity index above 20–25 are not suited to cement stabilization using manual presses, due to problems with excessive drying shrinkage, inadequate durability and low compressive strength. Reddy [7] studied the use of steam curing process and showed that it can lead to quick production of stabilized soil blocks. Salas et al. [8] investigated the characteristic of lightweight insulating concrete using rice husk in the natural state or treated with a 5% lime solution. Ramaswamy et al. [9] studied the behavior of concrete reinforced with jute, coir and bamboo fibres. The results show that vegetable fibres can be used with advantage in concrete in a manner similar to other fibres. The stability of these organic fibres in cement concrete appears to be good enough.

Although the results from this research on mechanical properties of fibre reinforcement are satisfying from the point of view of energy saving other properties, such as thermal conductivity, should also be taken into account.

In Thailand, a large amount of agriculture products are produced annually [11]. Some of these are shown in Table 1. The Building Scientific Research Center (BSRC) started research work on the use of natural fibres as an admixture on composite materials over four years ago. Thus, new lightweight composite concrete [1] and particleboards [12] were developed using young coconut (*Cocos nucifera*), durian peel (*Durio zibethinus*) and coconut coir. The manufactured specimens have good thermophysical properties and more especially, they have low thermal conductivity. Nowadays, there are some on-going studies on the durability and long-term performance of these materials so that commercial development might start.

On the other hand, research undertaken by the Thailand Institute of Scientific and Technological Research (TISTR) [13] has helped to produce commercial soil–cement blocks made by CINVA-Ram hand press and create a niche market of about 200–500 residential houses of 200 m^3 volume approximately per year. In fact, despite its reddish beautiful color and simplicity of construction it has two main disadvantages that are heavy weight and high thermal conductivity, about 5.60 kg/piece and 1.4823 W/m K, respectively (block dimension: $0.125\times0.25\times0.1$ m), Fig. 1.

Fig. 1. The shape of commercial soil–cement blocks ($0.125\times0.25\times0.1$ m).

In this study, the idea is to use agricultural waste to manufacture soil–cement block with lower thermal conductivity so as to reduce heat transfer into building in order to provide cooler indoor space or to decrease the energy consumption of building facilities such as air-conditioners.

2. Materials and experimental methodology

2.1. Raw materials

The raw materials used are as follows:

(i) *Portland cement*. An ordinary portland cement made by the Thai Petrochemical Industry (TPI) brand, Type I which complies with ASTM C 150–89 was used.
(ii) *Lateritic soil*. Actually, in Thailand lateritic soils are widely available (more especially in the north-eastern and northern regions of the country). In the experiments, the lateritic soil from Ratchaburi province (100 km west of Bangkok) was used. The soil was screened through mesh having openings of 2.38 mm. The chemical and physical properties of the soil are shown in Tables 2 and 3.
(iii) *Sand*. Local natural river sand that passes ASTM sieve number 8 (2.38 mm) was used. The sand did

Table 1
Thai agriculture production in 1994–1998 [11]

Type of agriculture	Productivity (10^3 tons/year)				
	1994	1995	1996	1997	1998
Coconut	1435	1413	1419	1386	1372
Rice	21,111	22,016	22,332	23,580	23,608
Sugar cane	50,597	50,597	57,974	58,977	50,332
Jute	116	105	99	90	45

Table 2
Chemical properties of the lateritic soil in Thailand [14]

Properties	% by weight
Ferric oxide (Fe_2O_3)	1.5–3.0
Aluminum oxide (Al_2O_3)	8–12
Silicon dioxide (SiO_2)	75–85
Calcium oxide (CaO_2) + other material	1.5–3.5
Loss on ignition	<5

Table 3
Physical properties of the lateritic soil in Thailand [14]

Properties	
Color	Often red
Specific gravity	2.58–2.66
Plasticity index	Non-plastic
Maximum dry density	1700–2200 kg/m^3
Optimum moisture content	10–20% by weight
Dry shrinkage	2–8% by weight
Fire shrinkage	2.5–10% by weight
Particle size	<2.87 mm

Table 4
Chemical composition of coconut coir [12]

Chemical composition	Unit (%)
Water solubles	5.25
Pectin and related compounds	3.00
Hemi-cellulose	0.25
Lignin	45.84
Cellulose	43.44
Ash	2.22

not contain any organic substances which can be harmful to the cement hydration. The size of sand was about 0.7 ± 0.145 mm.

(iv) *Mixing water*. The main water supply of the province was used.

(v) *Fibre*. Coconut coir were taken from a local market in Bangkok, passed to sieve number 8 (2.38 mm diameter) and sun-dried. The chemical properties of the coconut coir are shown in Table 4. The coir is golden brown with a thermal conductivity of 0.078 W/m K [12].

2.2. Preliminary analysis

The commercialized soil–cement blocks, here referred to as reference soil–cement block, have a composition ratio of soil–cement–sand of 6:1:1 by volume, respectively. The use of volume rather than weight is due to simplicity of the manufacturing process and saving in time. The corresponding mixing mass ratio of the reference sample is 27.6:4.0:4.2 kg. Unfortunately, no technical data on the commercial soil–cement blocks are available as most producers are small rural home companies. As the use of fibres would require more cement to be added to the mixture in order to maintain its solidity, which in turn will affect the color of the blocks, a preliminary study was conducted prior to the main investigation in order to identify the maximum cement ratio that would not affect the color of the blocks. As a result it was concluded that the maximum volume ratio of cement that would not change the color of the block is 1.5. A higher cement ratio gives a dark grey color which would certainly not satisfy potential customers.

2.3. Samples details and manufacture

In this study, 18 different mix ratios (soil:cement: sand:fibre) were considered as shown in Table 5. For each ratio, five specimens were manufactured. The nominal block size is standard: $125 \times 250 \times 100$ mm.

The production of fibre-based soil–cement block can be subdivided into the following steps:

(i) Weigh soil, cement, sand and fibre samples according to the desired ratio, following Table 5, then mix the four components and add water and mix well. The amount of water is about 2.5–3.0 l per 5 blocks. To determine the exact amount of water, a simple test by squeezing a ball of soil–cement mixture by hand is performed. If the ball can be broken in half without crumbling the mixture, that means it has the right water content.

Table 5
Mix details of fibre-based soil–cement block

Sample code	Volume ratio mixture Soil:Cement:Sand:Fibre[a]
Sp00:Reference (commercial)	6:1:1 (no fibre)
Sp01	6:1:1:0.4
Sp02	6:1:1:0.6
Sp03	6:1:1:0.8
Sp04	5:1:2:0.4
Sp05	5:1:2:0.6
Sp06	5:1:2:0.8
Sp07	5.75:1.25:1:0.4
Sp08	5.75:1.25:1:0.6
Sp09	5.75:1.25:1:0.8
Sp10	4.75:1.25:2:0.4
Sp11	4.75:1.25:2:0.6
Sp12	4.75:1.25:2:0.8
Sp13	5.5:1.5:1:0.4
Sp14	5.5:1.5:1:0.6
Sp15	5.5:1.5:1:0.8
Sp16	4.5:1.5:2:0.4
Sp17	4.5:1.5:2:0.6
Sp18	4.5:1.5:2:0.8

Note: 1 volume ratio of soil = 4.6 kg, 1 volume ratio of cement = 4.0 kg, 1 volume ratio of sand = 4.2 kg.
Weighing was carried out using an electronic balance with a precision of 0.01 kg.
[a] Fibre ratio is in kg (corresponding to 10%, 15% and 20% of reference cement volume).

(ii) Compress specimen using CINVA-Ram hand press under certain amount of pressure (about 1.0 M N/m^2). Then remove mold and leave specimen to be air cured for 24 h and water cured for 28 days.

3. Results and discussion

Table 6 presents the average properties of the five specimens of the different samples considered in this study. The composite specimens were tested based on the following testing standards:

(i) *bulk density*: performed according to ASTM C 134-94,
(ii) *thermal conductivity*: testing according to JIS R 2618,
(iii) *compressive strength*: measured according to ASTM C 140-96b.

3.1. Effect of fibre content on bulk density

The effect of change in coconut fibre content on bulk density is shown in Fig. 2. In general, the increase in the quantity of coconut coir in the coconut/soil–cement mix decreases the weight of the specimens. The replacement of soil–cement (dense materials) by coconut coir (light material) resulted in an increase of the total volume of mix even after compaction at 1.0 M N/m^2 pressure. This increase in volume of the compacted mix resulted in a decrease in weight and density of the specimens.

The specimens Sp10–Sp18 (ratio 4.5:1.25:2) have more or less the same weight. This is probably due to the low soil ratio and high sand ratio which can help to create voids that give the mixture a lightweight, minimizing, therefore, the effect of coconut coir on density.

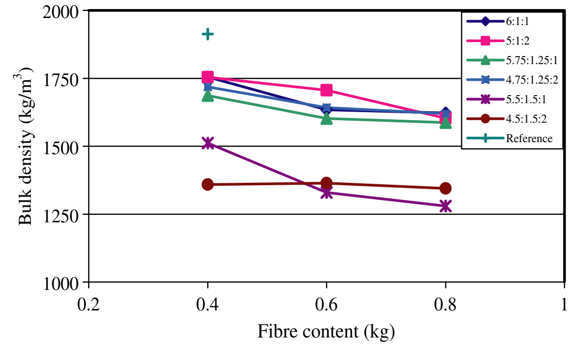

Fig. 2. Average sample bulk density vs. fibre content for the different mixture ratios.

3.2. Effect of fibre content on compressive strength

Relationship between compressive strength and fibre content is shown in Fig. 3. The result, for all mixing ratios, is a small reduction in compressive strength with increase in fibre content. This decrease can be explained as follows. The development of strength properties in fibre/soil–cement mix mostly depends on the formation of fibre–matrix, matrix–matrix and fibre–fibre bonds. The bonding can be affected by dimensions, surface conditions and number of fibres present in a given volume of material. Therefore, the increase in coconut fibres content resulted in a decrease in bond strength of the specimens, leading to a lower compressive strength.

Fig. 4 shows the relationship between the average compressive strength and bulk density for the different

Table 6
Average measured properties of the different fibre-soil–cement blocks[a]

Code	Mass (kg)	Bulk density (kg/m^3)	Compressive strength (MPa)	Thermal conductivity (W/m K)
Reference	5.60 ± 0.07	1913.17 ± 27.65	8.34 ± 0.80	1.4823
Sp01	5.17 ± 0.06	1754.94 ± 11.44	5.79 ± 0.76	0.9702
Sp02	5.10 ± 0.08	1634.15 ± 21.90	5.20 ± 0.31	0.9411
Sp03	5.06 ± 0.11	1622.29 ± 16.73	4.70 ± 0.38	0.8789
Sp04	5.21 ± 0.08	1754.27 ± 22.92	5.09 ± 0.40	0.9815
Sp05	5.05 ± 0.10	1706.00 ± 10.48	4.50 ± 0.16	0.8179
Sp06	4.85 ± 0.11	1603.45 ± 5.81	3.90 ± 0.14	0.7651
Sp07	5.14 ± 0.08	1686.37 ± 26.83	5.03 ± 0.59	0.7213
Sp08	4.99 ± 0.09	1602.15 ± 14.99	4.17 ± 0.41	0.6980
Sp09	4.85 ± 0.01	1586.77 ± 7.92	3.88 ± 0.34	0.6510
Sp10	5.11 ± 0.10	1718.07 ± 10.79	4.58 ± 0.33	0.7318
Sp11	5.00 ± 0.08	1642.45 ± 3.42	3.81 ± 0.04	0.7253
Sp12	4.92 ± 0.10	1620.05 ± 8.29	3.05 ± 0.08	0.7187
Sp13	5.09 ± 0.09	1508.60 ± 9.81	2.29 ± 0.32	–
Sp14	4.87 ± 0.05	1443.39 ± 10.28	1.98 ± 0.07	–
Sp15	4.76 ± 0.06	1410.79 ± 6.02	1.91 ± 0.15	–
Sp16	4.62 ± 0.09	1368.67 ± 31.66	1.67 ± 0.12	–
Sp17	4.60 ± 0.07	1364.38 ± 23.19	1.58 ± 0.06	–
Sp18	4.59 ± 0.05	1344.60 ± 8.56	1.50 ± 0.08	–

[a] These properties are the average of the five specimens for each mix ratio.

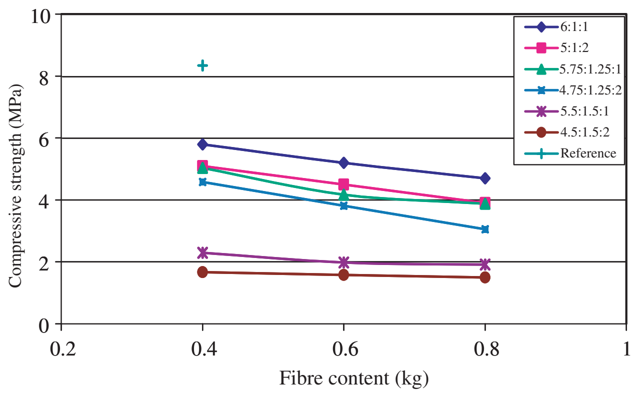

Fig. 3. Influence of fibre content on compressive strength.

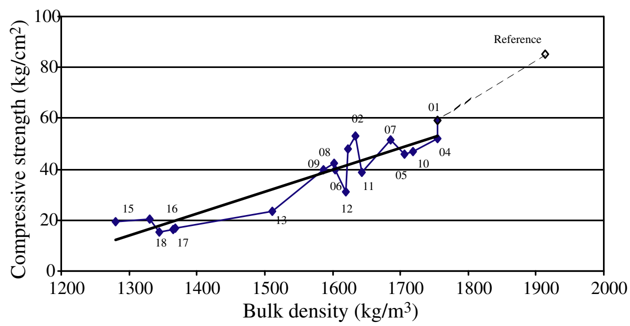

Fig. 4. Average compressive strength vs. bulk density. (The numbers indicate the samples code.)

fibre-based soil–cement blocks. The addition of light coconut coir to the mix creates voids leads to decrease in density. As a result, the compressive strength of specimen decreases accordingly. For a given mixing ratio, the higher the coconut ratio, the lower the compressive strength.

Also, it could be observed that the high compressive strength is obtained with the samples (Sp1–Sp3), where the mixing ratio of soil:cement:sand was the same as that of the reference sample (6:1:1), which is evident.

3.3. Effect of soil:cement:sand ratio on compressive strength

It is obvious that with a limited number of specimens, a separate analysis of the effect of each constituent is quite difficult and more especially when the manufacturing process is hand-made. However qualitative conclusions could be formulated. They are summarized here below:

1. Decreasing the soil ratio was found to impact the compressive strength of specimens significantly. Thus, with a constant sand ratio, for example samples code: Sp1–Sp3, Sp7–Sp9 and Sp13–Sp15, the lowest compressive strengths are obtained with the lowest soil ratio and when the cement ratio was high (Sp13–Sp15).
2. The effect of sand on compressive strength is also significant. However it always has to be analysed together with the soil:cement ratio. Thus, with low cement ratio (samples 4–6), the compressive strength is still important. When increasing the cement ratio and decreasing the soil ratio, a low compressive strength was obtained, due to the low mixing quality. In fact, at such ratio (samples 13–18), the block became brittle and crumbled during handling.

To conclude this section, a comparison to standard requirement is made. For instance, the compressive strength of specimens based on ASTM C 129 Standard for non-load-bearing concrete masonry units should be higher than 25 kg/cm^2. Accordingly, the manufactured specimens code 1–12 definitely pass the requirement for non-load-bearing walls. The other samples (code 13–18) which have lower compressive strength could not be manufactured commercially and further analysis is no longer necessary.

3.4. Effect of fibre content on thermal conductivity of samples

The effect of coconut fibre content on thermal conductivity is shown in Fig. 5. As expected, the thermal conductivity decreased when the quantity of fibre content increased. The relation between thermal conductivity and bulk density is shown in Fig. 6. Despite the small range of variation of the density of the specimens and the variation of mixture, it is well demonstrated that the new soil–cement block manufactured with coconut fibre coir has a relatively low thermal conductivity varying between 0.6 and 1 W/m K. This corresponds to a decrease of about 50% of the thermal conductivity of the reference specimen that is extremely satisfying.

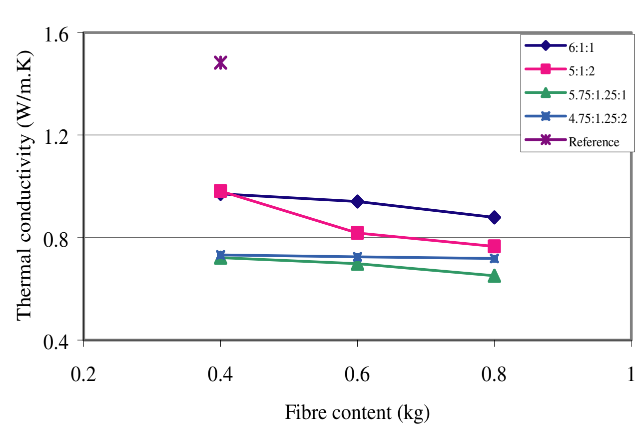

Fig. 5. Effect of fibre content on thermal conductivity.

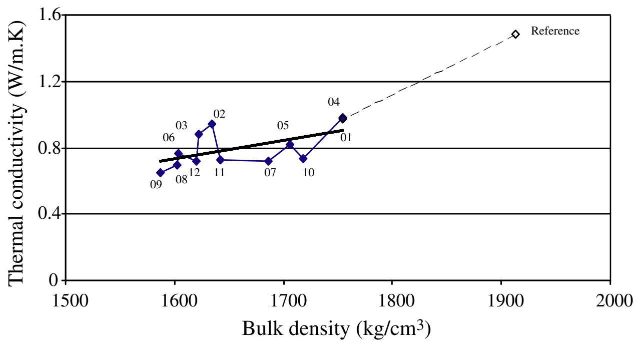

Fig. 6. Thermal conductivity vs. bulk density for specimens code (1–12).

4. Conclusions

Various mixture ratios were considered and five samples per specimen were fabricated using local hand-made manufacturing process widely used in the country. To maintain the block's natural beautiful color, a preliminary study was conducted to determine the maximum percentage of cement that could be used without leading to a significant color change. It was concluded that the use of coconut fibre as an admixture can reduce the thermal conductivity and yield a lighter block. The optimum volume ratio of soil:cement:sand and fibre weight (kg) is 5.75:1.25:2 and 0.8 kg coconut coir. The average specimen properties are as follows: thermal conductivity of 0.6510 W/m K, compressive strength of 3.88 MPa, mass of 4.85 kg and bulk density of 1586.77 kg/m^3. When compared to commercial soil–cement block, the corresponding decreases of thermal conductivity and mass are fairly significant, 54% and 750 g, respectively. As a compromise between economic constraints and block properties, different mixing ratio could be used. For instance, the optimum block (referenced as sample 9) costs about USA $0.11/block. It is 3.5% and 7.2% higher than that of the samples referenced 8 and 7, respectively (the mixing ratio is 5.75:1.25:1 and 0.6 kg coconut coir for sample 8 and 5.75:1.25:1 and 0.4 kg coconut coir for sample 7). The corresponding thermal conductivity of samples 8 and 7 are 7.2% and 10.8% higher than the optimum one, respectively. However they are still much lower than the commercial product in the local market, therefore they could be interesting options for commercial production.

The main features of coconut coir soil–cement block are the following:

1. The low thermal conductivity of blocks will help to prevent heat transfer into building and consequently to save energy.
2. Because of their low compressive strength, they could only be used to build non-load bearing concrete masonry units (2.45 MPa) as they could not support loads from floors and roof.
3. The weight of coconut coir soil–cement is lower than commercial soil–cement block by about 13%. Hence, they are also convenient to deliver.

Today, commercial development seems to be highly promising. However, investigation on the long-term performance and the life time of the coconut coir soil–cement block should be done prior commercialization. BSRC has already set up a plan to investigate the durability of fibre-based soil–cement blocks.

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