Research Article

Properties of Mortars Mixed with Polystyrene and Hemp Fiber Wastes

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Abstract
When polystyrene (PS) and hemp fiber waste were mixed into the sand aggregate, some physical-mechanical properties of mortar changed. The PS and hemp fiber were tested as partial replacements for sand in mortar with three designated percentages of 2.5, 5.0 and 10.0% by mass. The properties of mortar with PS were found to be better than that of the mortar with hemp fiber. The water absorption of mortar with PS was comparable with the reference mortar but lower than that of mortar with hemp fiber. The compressive strength of the mortar with PS was higher than that with hemp fiber whereas the tensile strength of the mortar with 2.5% PS and hemp fiber was comparable and was higher than that of the reference mortar. The thermal conductivity of a wall plastered by mortar containing PS decreased as the PS content was increased, whereas the thermal conductivity of a wall plastered by mortar containing hemp fiber increased as the hemp fiber content was increased. Thick crack was detected in the reference wall while hair line crack occurred from the wall plastered with PS and hemp fiber mortars. The results indicated that 10.0% PS could be used as a partial replacement for sand in mortar with an improvement in some of the properties of the mortar.

Keywords: Flammability, Fire behavior, Hemp fiber, Mortar, Physical and mechanical properties, Polystyrene, Thermal conductivity

1 Introduction

Hemp is a dicotyledonous plant from the order of Rosales with the family of Cannabaceae and genus Cannabis [1]. Hemp fiber is very strong compared with cotton, flax, and nettle [2]. Hemp fiber is one of the most popular of natural fiber, which has been supplied for textile industry and cloth factory. A demand of hemp fiber increases because of its toughness and softness. Its fiber is stronger than that of cotton and warmer than that of linen. Hemp fiber can absorb 100% moisture better compared with nylon [3]. Regarding to the environmental value of using plant materials, hemp materials benefit from the mechanical strength of the hemp fibers [1]. Hemp fiber is durable, lightweight, affordable to produce, water-proof, fire-proof, self-insulating, resistant to mold, moisture-proof, highly breathable, resistant to pests, and good heat resistance in wintertime and cool in summer. In addition, this material is ideal for resisting damage caused by earthquakes, floods, or other natural disasters [4]. Due to an increase demand of textile industry and cloth factory from hemp, there is large amount of hemp fiber waste that generated from the production line of the industry.

Agricultural waste fibers have a considerable potential in the composite material industry, because they are environmentally friendly, recyclable, low cost, and sustainable materials with high strength value [5]. For the field of construction, the most suitable for solving the problem of pollution and conservation of natural resources are the use of the agro-waste materials as the environmentally friendly construction materials, which are energy efficiency [5]. In addition, construction materials generated from different agricultural waste materials are relatively low cost and are more durable, lightweight, and environmentally friendly than traditional. Therefore, an application of by-products and agricultural wastes as raw materials is practical importance for developing an innovative, environmentally friendly, and sustainable products instead of the traditional building materials used today [5].

The agricultural wastes were tested for construction materials. For example, Sales and Lima [6] conducted mortars and concretes with sugarcane bagasse ash (SCBA) as sand replacement. The results found that the SCBA samples presented physical properties similar to those of natural sand. In addition, the mortars produced with SCBA in place of sand showed better mechanical results than the conventional mortar. For the experiment of Taha *et al.* [7], straw was used as a reinforcement fiber in plaster material for wall plaster. Three types of straw were used such as wheat straw, barley straw, and wood shavings. It was found that the thermal conductivity of materials decreased with increasing straw fiber content and decreased with increasing sand content. The straw fibers have greater effect on the change of thermal conductivity than the effect of sand. The plaster reinforced by barley straw fibres has the highest values of thermal insulation.

Plastic is one of those potential waste materials and there are three possible ways of including it in concrete and mortar [8]. The first one is as resin to produce polymer concrete and mortar after being depolymerised [9]. Secondly, plastic is as a binder after being melted with sand and clay [10]. Thirdly, plastic is as particles (e.g, fibres or pellets) as a replacement of fine or coarse aggregate [8].

For plastic waste, the recovery rate of plastic waste is low because of the low value of recycled plastic and the lack of technological support for its recovery. Most plastic waste is very stable and degrades very slowly in the environment either when disposed of as landfill or when it enters the ocean or atmosphere. If plastic waste is not disposed of properly, it causes environmental and economic problems. The large amounts of plastic waste now being produced are leading to food chain contamination, biodiversity breakdown, energy waste, and economic loss [11].

Plastic waste can be used in many civil engineering applications. For example, recycled plastic waste has been used as a partial replacement for sand in the aggregate that is required to improve the strength and durability of concrete in road and pavement construction or as an insulator or conduit in building construction [12], [13]. The incorporation of PET fibers significantly improve the flexural strength of mortars with a major improvement in mortar toughness. The maximum volume of PET fiber for a desired workability was 1.5% [14].

In mortars, the plastic fibers act uniformly distributed reinforcing mortars against the cracks development due to plastic shrinkage. In the hardened mortar, the uniform distribution of fibres inhibits the transformation of microcracks in macrocracks in order to avoid a potential for more serious problems. The fiber bridge remains the stability of macrocracks [14]. In addition, the waste polyethylene terephthalate (PET) lightweight aggregates (WPLA) was used as a fine aggregate in mortar. The flow value increased, while the compressive strength decreased proportionally to the addition of WPLA with elapsed time. The amount of water absorption by unit area was higher than for the control mortar when the WPLA content was either 40% or 60% [15]. Nevertheless, the experiment of Pereira de Oliveira and Castro-Gomes [14] found that PET fiber incorporation does not significantly change the magnitude of the mortar compressive strength.

The addition of polycarbonate (PC) and PET plastic waste aggregates as partial replacement of

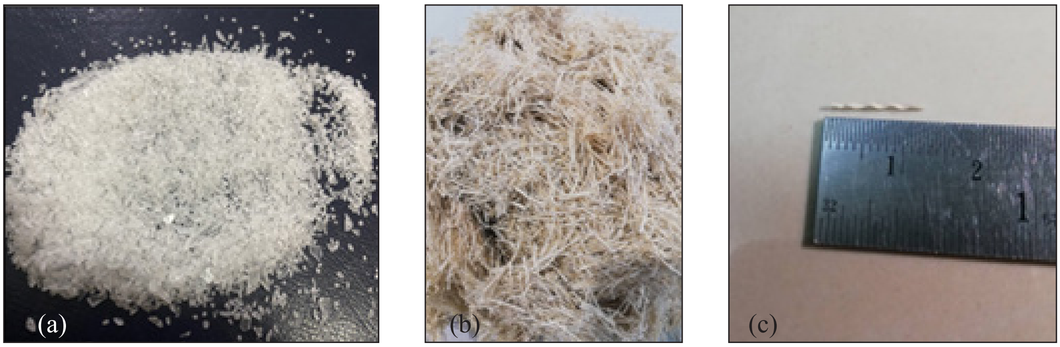


Figure 1: Plastic and agricultural wastes used in this study (a) PS (b) hemp fiber (c) 12 mm hemp fiber.

sand, contributes to reduce the specific weight of the cementitious material. The dry density values of waste plastic mixtures tend to decrease where 50% of sand (in volume) is replaced by PET and PC plastic aggregates. Therefore, this is useful in applications requiring lightweight materials. In addition, an increase plastic aggregates volume fraction results in an improvement in post-peak flexural strength [16].

The fibers addition in mortar allows a reduction and redistribution of cracks or even avoid them if the large fiber volume incorporates at the mortar mixtures. A better dispersion of fibers obtained by dry pre-mixing improves the flexural strength [17]. A remarkable was observed with increments of the toughness and of the residual strength when increasing the percentage of fibers and increasing the fiber length. The tensile strength and toughness of the nylon reinforced mortar increased comparing with the unreinforced material [18].

The advantages of using wastes are a reduction of virgin natural resources and the wastes are being disposed of in a safe, effective, and environmentally friendly manner. This advantage solution motivated an impressive volume of research and development to conduct worldwide on the use of recycled materials, particularly on recycled aggregates [15]. Therefore, the use of waste as material for construction has been considered as an ideal way for disposing of waste.

The aims of the present research were to study the physical-mechanical properties of mortar containing PS and hemp fiber wastes. The thermal conductivity and fire behavior of wall plastered with mortar-containing PS and hemp fiber wastes were also investigated.

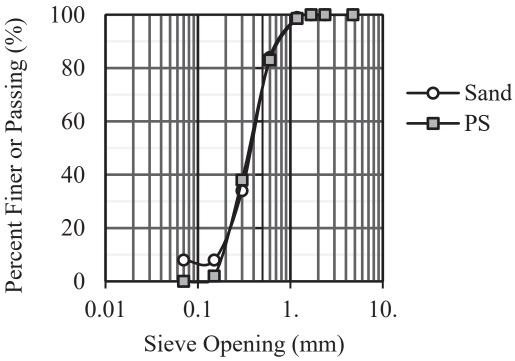


Figure 2: Particle size distribution.

2 Materials and Methods

2.1 *Materials*

The type I Portland cement used for a component of mortars had a density of 2.8 g/cm^3, normal consistency 2.6%, and specific gravity of 3.15. Polystyrene (PS) plastic waste used was obtained from Siampack Industry Co. Ltd. (Samut Prakan province, Thailand), and hemp fiber waste used was supported from hemp product of Ban Huai Sai community enterprise housewives (Chiang Mai, Thailand).

Before an experimental test, PS plastic waste was crushed into fine particles by machines [Figure 1(a)] and then examined by sieve analysis using a mechanical sieve shaker according to ASTM C136 [19] with mesh sizes of 4, 8, 16, 30, 50 and 100. The result of sieve test plots in Figure 2. The hemp fiber [Figure 1(b)] waste was cut into 12 mm of length [Figure 1(c)].

The PS plastic waste passed mesh size of 100 and hemp fiber waste of 12 mm were used to replace some proportion of sand in mortar composite at three designated percentages of 2.5, 5.0, and 10.0% by mass.

2.2 *Mixture proportioning and preparation of plastering mortar samples*

Samples of 50 mm cubes (50 × 50 × 50 mm) mortar were prepared consisting of 1 part of Portland cement type I mixed homogeneously with 2.75 parts of graded standard sand and then water was added. In order to obtain a constant consistency for the different proportions of PS plastic and hemp fiber added, the rate of mixing water to cement (W/C) was calculated for all batches to maintain a flow value in the range of 100 to 115% of base diameter of standard frustum. Samples of mortar were prepared with sand being replaced with PS plastic and hemp fiber at three designated percentages of 2.5, 5.0, and 10.0%. The different compositions of the mortars studied are shown in Table 1.

After preparation, the 50 mm cubes of mortar were kept in a humid chamber at a constant temperature of 23 ± 2°C for 24 h. After that, the mortar cubes were removed from the mold, and cured in a water tank at ambient conditions for 28 days. The mortar cubes were then tested for dry density, water absorption, compressive strength and tensile strength, and the arithmetic means of the values for 6 cubes were recorded.

2.3 *Test of physical properties of mortar samples*

Fresh mortars were tested for flow and hardened mortars were tested for water absorption and dry bulk density. For the flow test, the flow of a fresh mortar, representing its workability, was examined according to ASTM C230 [20]. For each mortar mix, the water requirement was recorded in terms of W/C ratio. The flow values for each mortar mix were kept constant in the range of 100 to 115% of base diameter of standard frustum. A mold for a sample was filled with two layers of fresh mortar with each layer being tamped 20 times. The mold was then removed and the mortar sample and the flow table were dropped immediately through a height of 12.7 mm for 25 times in 15 s.

The water absorption of the cubes was tested according to ASTM C642 [21], [22]. The 50 mm cube specimens with a curing age of 28 days were dried at a temperature of 110 ± 5°C for 24 h. When a constant weight was obtained, the cube specimens were cool down at least 4 h and then weighed. After that, the cube specimens were submerged in water for 24 h. The specimens were then removed from the water, wiped and weighed, and the size measured within 3 min.

The dry density of the mortar samples taken from the curing water basin were determined according to ASTM C642 [21], [23]. The weight and size of cubes were measured before being dried at 105 ± 5°C for 24 h. After oven-dry, the cube specimens were weighed.

2.4 *Test of mechanical properties of mortar samples*

The compressive strength of the mortar samples was tested according to ASTM C109 [24], [25]. For a curing period of 28 days, six cubes of size 50 mm were examined using a compressive strength testing machine and the values were recorded. The load on a cube was applied at a uniform rate of 1.4–3.5 kg/cm^2 per second. The compressive strength test was stopped after the load had decreased by 30% from its maximum value. The dissipated energy per cubic meter was determined for a sample from the area under the compressive stress versus strain curve.

Table 1: Mix proportions of the mortar blended plastic waste and physical properties of the mortar samples

Mortar	Cement (g)	Sand (g)	PS (g)	Hemp Fiber (g)	W/C Ratio	Water (dm^2)	Dry Density (g/cm^3)	Water Absorption (%)	Flow Value (mm)
Reference	500	1375.000	0	0	0.75	375	2.04 ± 0.09	1.98	101.18 ± 0.59
PSM2.5	500	1340.625	34.375	0	0.73	365	1.72 ± 0.05	2.23	103.04 ± 2.56
PSM5	500	1306.250	68.750	0	0.75	375	1.78 ± 0.03	2.05	103.49 ± 1.17
PSM10	500	1237.500	137.500	0	0.76	380	2.07 ± 0.05	1.88	105.03 ± 1.50
HEMPM2.5	500	1340.625	0	34.375	0.73	365	1.91 ± 0.06	10.91	102.67 ± 1.88
HEMPM5	500	1306.250	0	68.750	0.75	375	1.93 ± 0.05	11.10	102.12 ± 1.95
HEMPM10	500	1237.500	0	137.500	0.76	380	1.90 ± 0.04	11.34	101.52 ± 2.55

(a) (b)

Figure 3: (a) Wall construction from concrete block and (b) plastering by mortar samples.

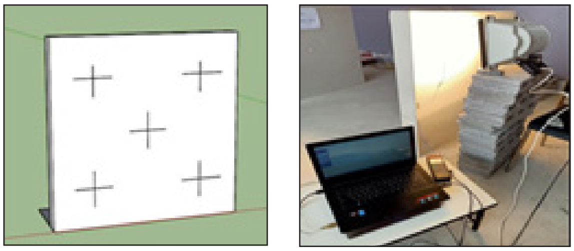
The tensile strength was examined according to ASTM C190 [26]. A dog bone shape of size 50 mm at a curing period of 28 days were examined using tensile test machine.

2.5 *Wall construction and plastering by mortar samples*

Three specimens of walls with thickness 7 cm and of size 1 × 1 m were created with concrete blocks (7 × 19 × 39 cm) as shown in Figure 3(a). In brief, 1.5–2.0 cm of mortar was laid along the string line. After that, the first concrete block was laid and taped slightly. Then, one end of the next concrete block was buttered up with mortar and abut it to the first concrete block. This step was repeated using string line as a guide. The wall specimen was built until 1 m of the height. After the three wall specimens were prepared. They were kept wet for curing at least 7 days to enhance the strength to a wall. Then, the two sides of each wall specimen were covered with mortar 1.5 cm thick [Figure 3(b)] in which a percentage of the sand aggregate was replaced with plastic waste and agricultural fiber wastes as described in Table 1. The wall specimens were then left for 28 days before the test.

2.6 *Heat properties of wall sample*

The test of heat transfer of wall specimen was modified from an experiment of Rasooli *et al.* [27]. After 28 days of wall plastering with mortar sample, five points for testing heat transfer of wall were designed and these points were marked on both two sides of wall [Figure 4(a)]. The first test point was a center of wall specimen and other four test points were a distance of 45 cm from the center on the diagonal.



(a) (b)

Figure 4: Thermal properties of wall sample. (a) Five test points design for (b) heat transfer testing.

Then, the sensor of two K-Type thermocouples (CERTER 306) were mounted on opposite sides of a wall at the same points on each side. The K-Type thermocouples was connected with the computer. The distance between the spotlight and a wall specimen was 30 cm and a fan was used as a natural wind to bring the heat from the spotlight to the wall. A 1,500 watt iodine spotlight was used as a heat source and calibration was carried out with an infra-red (IR) thermography camera.

For each of the five test points [Figure 4(a)], the spotlight was turned on for 15 min before the data loggers were turned on for measuring and recording temperatures. After 15 min, the temperatures of the two sides of the wall were measured and recorded every minute for 60 min and the spotlight was then turned off. The data loggers on the thermocouples measured the temperature every 1 min and the results were recorded on a computer. The temperatures of the two sides of the wall were then measured and recorded for a further 10 min [Figure 4(b)]. The differences in temperature between the two sides of the wall were used to calculate the heat transfer, thermal conductivity, thermal resistance, and heat transfer coefficient in the Equations (1)–(3) below,

$$K = \frac{QL}{A\Delta T} \tag{1}$$

$$R = \frac{L}{K} \tag{2}$$

$$U = \frac{1}{R} \tag{3}$$

Where, K is the thermal conductivity (W/m·K), Q is the amount of heat transferred through the wall (W),

Figure 5: Fire behavior testing.

L is the thickness of the wall (m); *A* is the area of the wall surface (m^2), ΔT is the difference in temperature (°K); *R* is the thermal resistance (m^2K/W); *U* is the heat transfer coefficient (W/m^2K).

2.7 *Fire behavior of wall sample*

The highest tensile strengths of the mortar blended with PS and hemp fiber were chosen to finish the walls for testing their heat properties and fire behavior. The area of circle with diameter 40 cm was used to investigate fire of wall plastered by mortar containing with PS and hemp fiber wastes. The point of testing was designed and plotted at a center of a circle. Then, the fire was sprayed using gas nozzle to the wall at a distance of 10 cm. A flammability of wall samples was examined at 1,000°C for 1 hr by a directly applied flame (Figure 5). The time for a flammability test was carried out according to NFPA255 [28].

3 Results and Discussion

3.1 *Physical properties of the mortar mixed with PS and hemp fiber*

The dry density of the mortar samples is shown in Table 1. The reference mortar had a dry density of 2.04 ± 0.09 g/cm^3. For the PS mortars, the dry densities increased as the proportion increased from 2.5% to 5.0% to 10%. For the hemp mortars, the dry densities of hemp mortars increased as the proportion of hemp increased from 2.5% up to 5.0%, but then decreased at a proportion of 10%. In comparison with the reference mortar, the dry densities of hemp mortars were lower at all percentages, whereas the dry densities of PS mortars were lower at 2.5% and 5.0% but slightly higher at 10%.

It can be seen that the water absorption of the hemp mortars was significantly higher than that of the reference mortar and that of the PS mortars. In addition, the water absorption of the hemp mortars increased as the percentage of hemp increased. In contrast with hemp mortars, it was found that the water absorption of PS mortars decreased as the percentage of PS increased. The water absorption of the mortar with 10% PS was the lowest and was lower than that of the reference. Even though the water absorption of the mortar with 10% PS was similar to that of the reference mortar, the flow value for the PS mortar was in the range of 100–115% of base diameter of standard frustum (Table 1).

3.2 *Mechanical properties of the mortar mixed with PS and hemp fiber*

The results of the compressive strength tests for the mortars with plastic and hemp fiber wastes are shown in Table 2. The compressive strength increased with increasing curing time. The results show clearly that the compressive strength of PS and hemp mortars increased approximately linearly as the percentage of PS and hemp in the aggregate increased. The compressive strength of PS mortar was higher than that of the reference mortar at all percentages. The maximum compressive strength of 399.69 ± 2.69 ksc was observed in the mortar with 10.0% PS after curing for 28 days and was 1.20 times higher than that of the reference mortar. For hemp mortar, mortar with 10% hemp was higher than that of the reference mortar. Polystyrene has a greater compressive strength than natural fiber. A decrease in adhesive strength between the surfaces of the plastic waste and cement [29]. Since the plastic waste is a hydrophobic material the hydration of the cement might have been restricted [30]. A drop in compressive strengths due to the addition of plastic aggregates can be attributed mainly to the poor bond between the matrix and plastic aggregates [16].

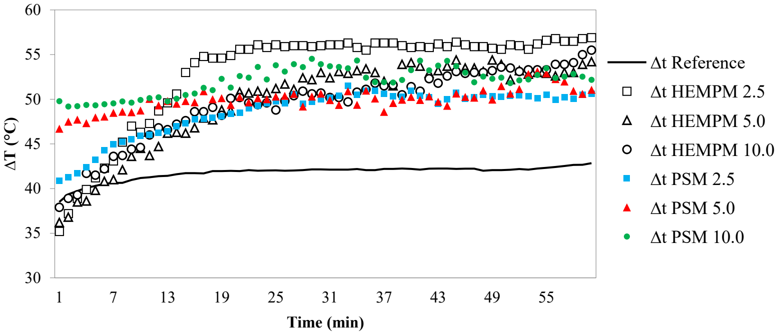


Figure 6: Different temperature profiles of wall.

Table 2: The strength of compressive and tensile among the reference mortar and mortar mixed with PS plastic and hemp fiber with curing time of 28 days

Samples	Compressive Strength (ksc)	Tensile Strength (ksc)
Reference	334.28 ± 2.47	48.10 ± 0.53
PSM2.5	339.20 ± 4.81	49.53 ± 0.40
PSM5	356.12 ± 7.10	44.23 ± 1.10
PSM10	399.69 ± 2.69	42.60 ± 1.14
HEMPM2.5	287.66 ± 3.22	49.17 ± 1.04
HEMPM5	336.62 ± 3.38	43.90 ± 1.15
HEMPM10	342.84 ± 4.67	29.03 ± 0.25

The tensile strength presents in Table 2. It can be seen that the tensile strength of both PS and hemp mortars decreased as the percentage of PS and hemp in the aggregate increased. However, the mortars with 2.5% PS and hemp were relatively higher than that of the reference mortar. The maximum tensile strength of 49.53 ± 0.40 ksc and 49.17 ± 1.04 ksc were found in the PS and hemp mortars, respectively (Table 2).

3.3 *Thermal properties of wall plastered with PS and hemp fiber*

The changes in temperature differences with time across walls plastered with the different mortars studied in this research are given in Figure 6. For the PS mortars, an increase in percentage of PS in the mortar increased the temperature difference profiles. For 5.0 and 10.0% PS, the temperature differences started at 46.7 and 49.78°C, respectively. At the final time, the average temperature differences of 2.5, 5.0, and 10.0% PS were 49.20 ± 2.68, 50.21 ± 1.29, and 52.26 ± 1.58°C, respectively.

In contrast, for the wall plastered with hemp mortar, the temperature differences of 2.5, 5.0, and 10.0% mortars started at 37.9, 36.7, and 38.32°C, respectively. The temperature then gradually increased up to 53°C. It was found that increased hemp content decreased the temperature differences with temperature differences of hemp 2.5, 5.0 and 10.0% mortars ranging up to 50.02 ± 5.67, 49.88 ± 5.06 and 49.38 ± 4.16°C, respectively.

It can be seen that the temperature differences across the reference wall were the lowest. The temperature difference started at 38.5°C and then gradually increased with time up to 42.84 ± 0.82°C. A different temperature of a referent wall ranged 41.97°C. An increased temperature differences indicate increased thermal resistance and reduced heat loss. The results show that the PS mortars are the best mortars for reducing heat loss. It noted that a lower temperature difference indicates a higher thermal conductivity and a higher heat loss.

The results for thermal conductivity of walls plastered with mortars containing PS and hemp fiber waste present in Table 3. As can be seen, the wall plastered with reference mortar had a thermal conductivity of 0.476 W/m·K while the mortars containing PS plastic and hemp fiber wastes all had lower values of the conductivity. In addition, as the percentage of PS increased the conductivity decreased, with the lowest thermal conductivity of a wall of 0.460 W/m·K occurring at 10.0% PS.

The low thermal conductivities of the PS mortars are due to the fact that PS has a lower conductivity than natural sand. It had been reported that PS had a possible use as insulation material for construction applications due to its physical property [13]. For hemp mortar, even though the lowest conductivity of a wall of 0.456 W/m·K occurring at 2.5% hemp, the thermal conductivity increased as the percentage hemp increased.

In the previous experiment, thermal conductivity (surface to surface) of wall from a normal hollow concrete block was in the range of 0.960 to 1.389 W/m·K [31] and 0.976 W/m·K [32] while the thermal conductivity value of the hollow reinforced precast concrete wall was 0.850 W/m K [33].

Thermal resistance (R) is the reciprocal of thermal conductance. The R-value is the measurement of resistance to heat flow through a thickness of material. From the results presented in Table 3, the thermal resistance of wall plastered with the reference mortar was 0.210 m^2K/W and the thermal resistance of wall plastered with the mortars containing PS plastic and hemp fiber wastes was relatively higher than that of the reference mortar. The resistance increasing as the percentage of PS increased. In contrast, the resistance decreasing as the percentage of hemp increased. This confirms that PS mortars can reduce heat loss by increasing the thermal resistance of walls.

Table 3: The comparison of thermal properties among the reference mortar and mortar mixed with PS plastic and hemp fiber

Mortar	Thermal Conductivity (W/m·K)	Thermal Resistance (m^2K/W)	Heat Rransfer Coefficient (W/m^2K)
Reference	0.476 ± 0.002	0.210 ± 0.001	4.763 ± 0.010
PSM2.5	0.464 ± 0.001	0.215 ± 0.001	4.641 ± 0.034
PSM5	0.464 ± 0.001	0.216 ± 0.001	4.635 ± 0.022
PSM10	0.460 ± 0.001	0.217 ± 0.001	4.600 ± 0.017
HEMPM2.5	0.456 ± 0.001	0.219 ± 0.004	4.557 ± 0.008
HEMPM5	0.460 ± 0.002	0.217 ± 0.001	4.605 ± 0.022
HEMPM10	0.462 ± 0.006	0.217 ± 0.001	4.617 ± 0.013

3.4 *Fire behavior of wall plastered with PS and hemp fiber*

Due to the highest tensile strength, the 2.5% PS and 2.5% hemp mortars were investigated their fire behavior compared with the reference mortar. Figure 7 shows the surface of wall specimens that were sprayed by gas nozzle at 1,000°C for 1 h. Hair line crack was observed from the wall specimens plastered with PS and hemp mortars while thick crack was found in the reference

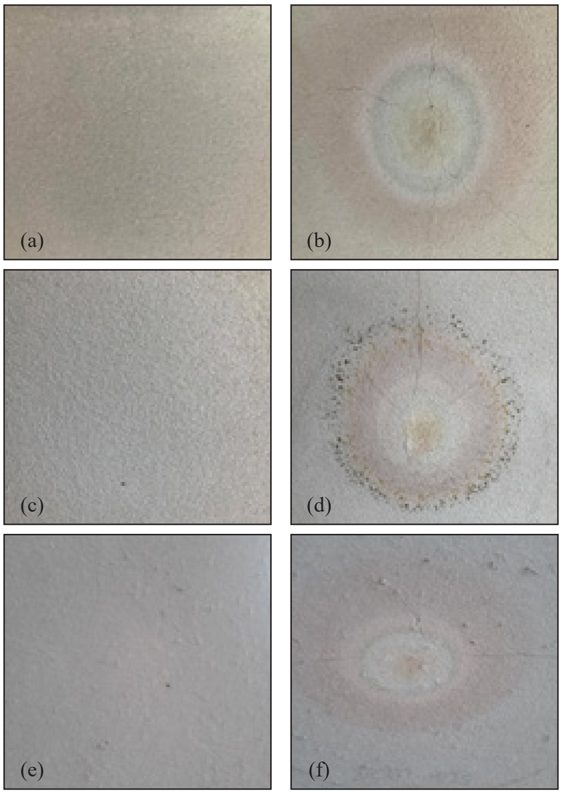


Figure 7: (a), (c) and (e) Surface of wall sample before testing; (b), (d) and (f) surface of wall after exposing with fire at 1,000°C for 1 h; (a) and (b) reference wall; (c) and (d) wall plastered with PS mortar; (e) and (f) wall plastered with hemp fiber mortar.

wall. When a combustible organic material is burnt it becomes a black soot, which represents carbon dioxide. A fine powder of carbon apparent blackness indicates the flammability. As can be seen, the black stain was appeared from the wall plastered with PS mortar more than that from a reference wall.

4 Conclusions

The results of the experiments reported in this paper show that mortar mixed with PS plastic waste can be used as a partial replacement for sand aggregate in mortar with the important properties of the mortar. The water absorption of mortars with PS plastic were found to be approximately the same as the sand reference mortar. The dry density of the mortar with 10.0% PS was also approximately the same as the reference mortar and higher than that of all mortar blended hemp fiber waste. The compressive strength of the mortar with 10.0%PS was 19.57% greater than that of the reference mortar and was also greater than that of the hemp fiber mortars. The thermal conductivities of walls plastered with the PS mortars were lower than that of the wall plastered with the reference mortar and the hemp fiber mortars. From the above results, PS waste has a good potential for improving the physical and mechanical properties of mortar and for developing ecological building materials by reducing the demand for natural sand and reducing the amount of plastic waste released into the environment.

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