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Physico-mechanical and thermal performances of eco-friendly fired clay bricks incorporating palm oil fuel ash

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ABSTRACT

This study investigated the use of palm oil fuel ash (POFA), a by-product of burning solid waste from palm oil production, as a clay replacement in brick manufacturing. Clay was thus replaced with 5%, 10%, 15%, and 20% POFA by weight in bricks produced in a local factory to study the feasibility of large-scale manufacturing. The physico-mechanical properties of these bricks (linear shrinkage, weight per unit area, compressive strength, and apparent porosity) were compared with those of conventional bricks without POFA. The thermal performances of the bricks were assessed by measuring the difference in temperature between their top and bottom surfaces during exposure to direct sunlight. The results of this study indicate that replacing clay with POFA reduced the linear shrinkage of the bricks. Furthermore, the weight per unit area and compressive strength of bricks containing higher replacement percentages of POFA decreased due to their increasingly porous structure. Replacing clay with up 10% POFA still met the minimum compressive strength criteria of the Indonesian Industrial Standard for non-load-bearing wall materials (i.e., 2.5 N/mm^2). Furthermore, 10% POFA bricks provided better thermal performance, exhibiting a temperature difference of about 6 °C compared to 2.5 °C for conventional bricks without POFA. Therefore, using 10% POFA as a clay replacement in large-scale brick production can address POFA disposal problems, reduce clay consumption, and decrease energy demand for indoor cooling, yielding a more environmentally friendly clay brick.

1. Introduction

In recent years, production of bricks has increased considerably in many developing countries such as Indonesia. For reasons of speed and economy, bricks are increasingly preferred as building materials. However, this increases the need to make the buildings more environmentally friendly. Bricks are typically produced using conventional methods that consume enormous amounts of clay material, approximately 3.13 billion m^3 of clay soil per year [1]. Many researchers have therefore focused on the development of brick material technology using waste by-products to reduce the consumption of natural soil clay. Moreover, this approach promises to overcome the waste management issues caused by such by-products and reduce the degradation of natural environment resulting from soil clay extraction, thereby leading to more sustainable brick production [2,3]. Fly ash, quarry residues, rice husk ash (RHA), and sugarcane bagasse ash (SBA) have all accordingly been introduced as alternatives to clay in brick production [4–10].

The physical properties of clay bricks are affected by the raw material properties, manufacturing methods, and firing temperatures. A high firing temperature causes the quartz in clay to soften and develops bonds between clay particles after cooling. Additives are often as fluxing agents to help increase the development of bonds between clay particles at lower firing temperatures [4]. Comparing the compressive strengths of bricks fired at temperatures of 800 °C, 900 °C, and 1000 °C, the highest compressive strength was obtained at a firing temperature of 1000 °C when fly ash was added to the clay brick mixture (0–100 wt.% clay) [5]. Clay replacement with 50–60% of quarry residues and firing at 1000–1100 °C yielded a compressive strength that was 1.5 times higher than that of conventional bricks [6]. The addition of RHA or SBA to clay mixtures reduced the brick density according to the waste content, resulting in bricks that were lighter than conventional bricks [7–10]. The increased apparent porosity in bricks containing RHA or SBA has been identified as the main reason for the observed reduction in brick density [10].

The consumption of electrical energy produced by non-renewable fuels increases CO_2 emissions, which promotes global warming. As 40% of the energy consumed by a building is used for heating and cooling purposes, and 12% is consumed by the building walls alone [11, 12],

Abbreviations: POFA, palm oil fuel ash; RHA, rice husk ash; SBA, sugarcane bagasse ash; XRF, X-ray fluorescence; XRD, X-ray diffraction; SEM, scanning electron microscopy; ASTM, American Society for Testing and Materials; LOI, loss of ignition.

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using microporous bricks as a wall material can improve the thermal performance of walls and reduce the energy demand for cooling, leading to more energy-efficient buildings [13]. Waste materials can be used as additives to develop micropores in bricks, thereby improving their thermal performance [12]. Indeed, several waste materials have been used to prepare microporous bricks, including ceramic sludge [14], recycled paper waste [12], pumice [15], RHA [8], and SBA [4]. The use of bricks with 4% RHA added to a clay brick mixture showed a 6 °C indoor temperature reduction compared to the use of conventional bricks [8]. Similarly, bricks with 40% ceramic sludge exhibited an indoor/outdoor temperature difference of 10.1 °C compared to a difference of only 4.2 °C when using conventional bricks [14].

Palm oil fuel ash (POFA) is a waste material produced by the burning of the solid waste from palm oil production (e.g., palm kernel shells, mesocarp fibers, and empty fruit brunches) as a boiler fuel to generate electricity in palm oil mills or power plants. As much as 5% of the burned solid waste material is converted into POFA [16]. This POFA is mostly disposed of in open fields due to its low nutritional value. This disposal method creates environmental problems and leads to health issues, including lung diseases [17]. Indonesia is the largest producer of palm oil, accounting for 49.39% of global production [18]; consequently, Indonesian palm oil industries are currently facing a significant challenge in disposing of POFA. Therefore, using POFA waste as a raw material in brick production can offer a solution to the POFA disposal problem, reduce clay consumption, and produce environmentally friendly clay bricks.

Though POFA is a pozzolanic material that is commonly used to improve the strength and durability of concrete, only a few studies in the literature have discussed the use of POFA in fired clay brick production. Kadir et al. [19] studied the effects of clay replacement with different palm oil waste materials (i.e., POFA, palm kernel shells, palm fibers, and empty fruit bunches) on the technological properties of fired clay bricks. Clay replacement with 1–10% of palm oil waste adversely affected the strength and durability of the bricks, but lightweight bricks with lower thermal conductivity were obtained. Similar results were also reported by other researchers [20,21], who determined that the density and compressive strength of clay bricks decreased and water absorption increased with increasing POFA content due to increased porosity.

Most previous studies have produced POFA brick specimens under a controlled firing temperature in the laboratory on a small scale. However, conventional bricks are typically produced on a large scale using a brick kiln. As different production methods may affect brick properties [10,14] this study investigated the feasibility of POFA as a clay replacement in large-scale brick production. The clay was therefore replaced by 5%, 10%, 15%, and 20% POFA, and the effect of these replacement percentages on the physico-mechanical and thermal performances of the resulting bricks were compared with those of conventional bricks without POFA. In addition, for the first time, the thermal performances of POFA bricks were evaluated under direct sun exposure. The results of this study provide significant data for various stakeholders such as the brick industry, which can advantageously utilize waste materials, as well as industries that produce waste POFA, thus enabling the production of environmentally friendly and economically beneficial bricks.

2. Experimental procedures

2.1. Materials

The clay used in this study was obtained from a local kiln brick manufacturer in Makassar, Indonesia. The POFA was supplied by the local palm oil industry. Table 1 lists the chemical compounds of the raw materials obtained by X-ray fluorescence analysis. The clay contained 62.39% of SiO_2 as its major component, and other oxides such as Al_2O_3 (14.28%), Fe_2O_3 (9.02%), CaO (7.96%), and K_2O (4.88%). Note that the SiO_2 content of the clay used in this study was slightly higher than

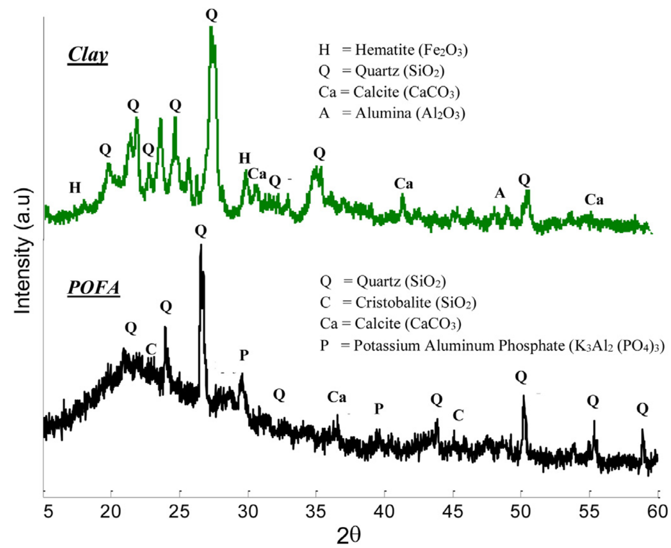

Fig. 1. XRD patterns of clay and POFA.

that of commonly used clays (50–60%) in the brick industry [22]; a higher content of SiO_2 will decrease the brick porosity and increase the risk of brick cracking during the cooling process after firing [8]. Clay containing 10–20% Al_2O_3 is commonly used for brick making [22]; in this study, the Al_2O_3 content of the clay met this specified range. In addition, the F_2O_3 content of the clay was less than 10%, which is the recommended value for preventing the formation of efflorescence on bricks [22]. Similar to the clay, the POFA used in this study also contained a large amount of SiO_2 (72.04%) along with CaO (8.99%), K_2O (6.53%), P_2O_5 (4.84%), and Fe_2O_3 (2.13%). The fluxing agent content (Fe_2O_3, K_2O, MgO, CaO, and Na_2O) in the POFA was lower than that in the clay, which can increase the brick porosity after the firing process [10]. In addition, the loss on ignition (LOI) of the POFA was higher than that of the clay, indicating the presence of organic matter in the ash. Fig. 1 shows the clay and POFA X-ray diffraction (XRD) patterns. Quartz was the main clay component, followed by hematite, calcite, and alumina. The POFA was also dominated by quartz, followed by traces of cristobalite, calcite, and potassium aluminum phosphate. Fig. 2 provides scanning electron microscopy (SEM) images of the clay and POFA used in this study. The POFA particles had a porous structure by nature, which can increase the water required to achieve the appropriate brick mixture consistency for casting.

Fig. 3 shows the particle size distribution of the clay and POFA used in this study, determined by sieve analyses performed in accordance with ASTM C325 [23] and ASTM C136 [24], respectively. The clay material was finer than the POFA, containing 86.8% silt and clay and approximately 13% sand. In contrast, only approximately 66.39% of the POFA particles passed sieving at 0.25 mm. This is important as the raw material gradation has been observed to affect the brick porosity after firing [25]. In addition, the specific gravities of the POFA and clay were determined in accordance with ASTM D854 [26]. The specific gravity of the POFA (1.92) was smaller than that of clay (2.36), indicating that lighter bricks can be obtained by replacing clay with POFA.

2.2. Sample manufacturing

The brick specimens were manufactured following the typical procedure used in the local brick industry. The POFA proportions added to the brick mixture were based on the replacement of clay weight (Table 2). First, clay and POFA were manually dry-mixed until the mixture became homogeneous. Thereafter, water was added to the mixture, followed by additional mixing to obtain a uniformly distributed mixture suitable for making bricks. Subsequently, the clay mixture was placed

Table 1
Chemical compounds of clay and POFA.

Component (%)	SiO_2	Al_2O_3	CaO	Fe_2O_3	K_2O	TiO_2	P_2O_5	MnO	LOI
Clay	62.39	14.28	7.96	9.02	4.88	1.03	–	0.23	9.94
POFA	72.04	3.29	8.99	2.13	6.53	0.10	4.84	0.41	12.05

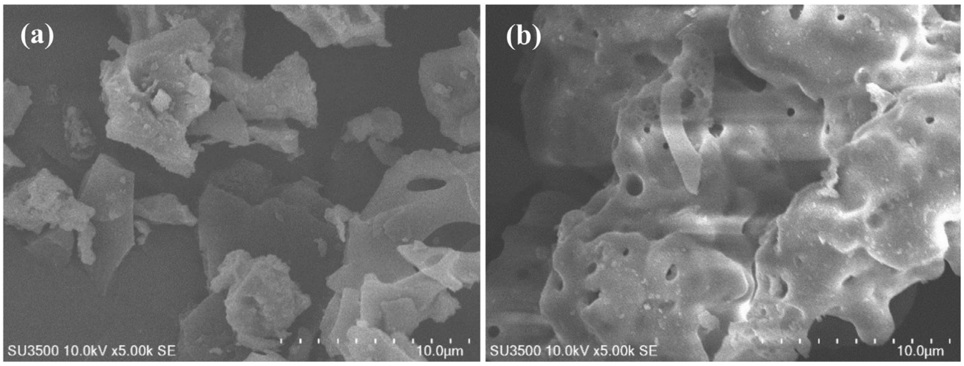

Fig. 2. SEM images of the raw (a) clay and (b) POFA.

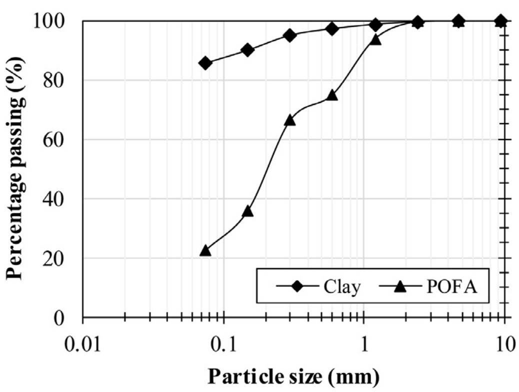

Fig. 3. Particle size distribution of clay and POFA.

Table 2
Brick specimen mixing proportions.

Mix ID	Clay (g)	POFA (g)	Water (g)
0% POFA	1000	0	153
5% POFA	950	50	159
10% POFA	900	100	161
15% POFA	850	150	169
20% POFA	800	200	172

into 200 × 100 × 50 mm brick molds and then leveled and compacted manually until flat and solid. The bricks were then removed from the molds and dried for 8 days before being fired in a brick kiln at 850 °C for 3 days. After the firing process, the brick specimens were allowed to cool for 14 days before being transferred to the laboratory for further testing. A total of 100 brick specimens were prepared.

2.3. Measurement methods

The linear shrinkage of each brick specimen was determined by measuring the change in its length before and after the firing process as per ASTM C326 [27]. The unit weight and the compressive strength of each brick specimen was measured according to ASTM C67–07 [28]. The ASTM C20 [29] guidelines were followed to obtain the apparent porosity of the brick specimens. Five brick specimens of each type were used for each of these tests.

Thermal performance tests were performed from 08:00 to 14:00 on a sunny day in a manner similar to previous works [8,14], as shown in the experimental setup in Fig. 4. A polyester board was used to cover all sides of the bricks except their top surfaces (i.e., 200 × 100 mm), which were exposed to direct sunlight. Wood sawdust was used to fill the space between the bottom of each brick specimen and the polyester board to avoid trapping air beneath the brick. Digital thermometers were attached to the top and bottom of the exposed bricks to record the temperature changes during direct sunlight exposure. The temperature difference between the top and bottom of the bricks was then used to determine the thermal performance. The thermal performances of the bricks with POFA were compared to that of the conventional brick without POFA. Finally, SEM images were obtained to characterize the microstructures of the various brick specimens corresponding to their measured performance.

3. Results and discussion

3.1. Linear shrinkage

Brick shrinkage occurs as a result of the evaporation of water from inside the bricks during the firing process; hence, it is closely related to the firing temperature. Fig. 5 shows the effects of POFA content on the linear shrinkage of bricks. The addition of POFA clearly reduced the linear shrinkage of the bricks. The control bricks without POFA shrank 4.19%, whereas those with POFA shrank between 2.94 and 3.73%. The decrease in the shrinkage of bricks made with POFA was caused by their high content of silica, which is a non-plastic component and that behaves as a filler material to decrease the plasticity of the clay/POFA mixes. Indeed, a similar trend was observed by other researchers [9], who reported that the linear shrinkage of fired bricks decreased with increasing SBA content.

Suitable bricks generally have a linear shrinkage value less than 8% [30]. All clay bricks evaluated in this study exhibited linear shrinkage values less than 8%, indicating that the POFA can reduce linear shrinkage during the firing process. Visual inspection was conducted to evaluate the cracking due to shrinkage. It is worth noting that no cracks were observed on the brick surfaces after production, indicating that bricks containing POFA will not be easily broken when transported and handled.

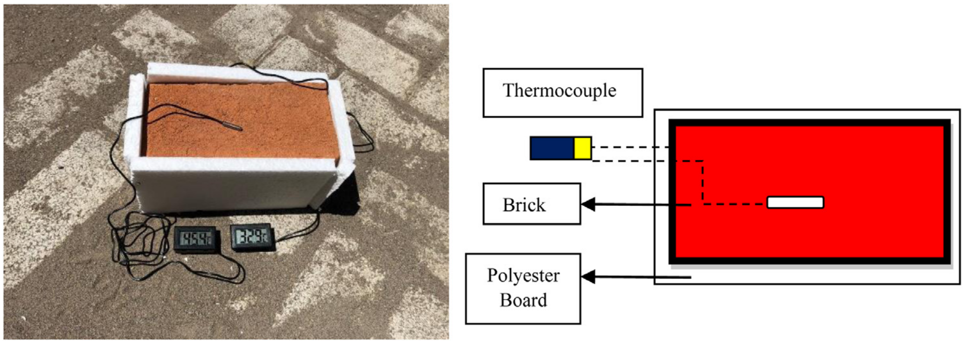

Fig. 4. Experimental setup to evaluate the thermal performance of brick specimens.

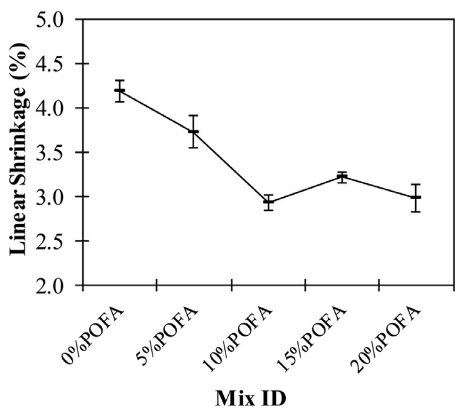

Fig. 5. Brick linear shrinkage.

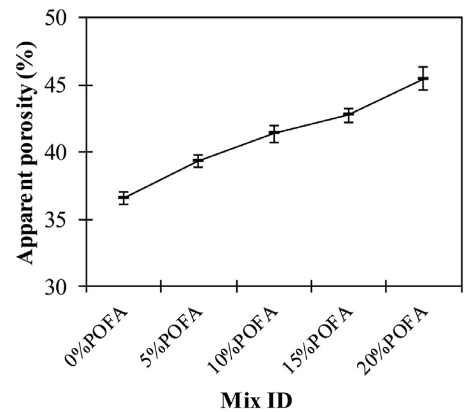

Fig. 7. Apparent porosity of brick specimens.

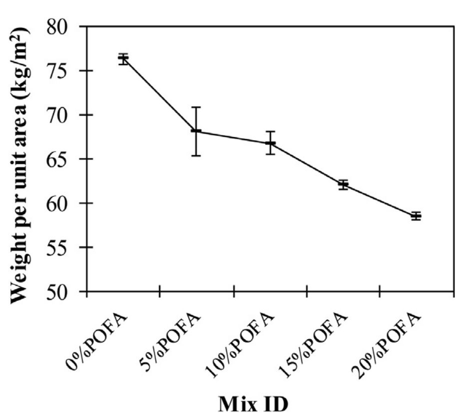

Fig. 6. Weight per unit area of brick specimens.

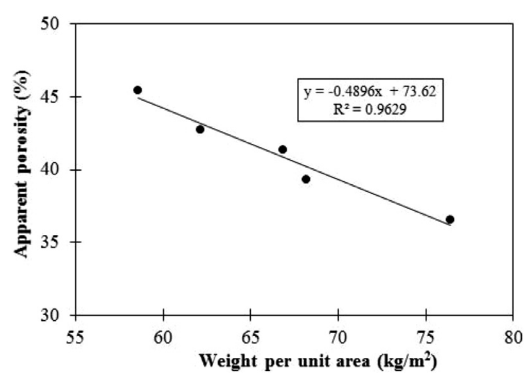

Fig. 8. Relationship between the apparent porosity and the weight per unit area of brick specimens.

3.2. Weight per unit area

Fig. 6 presents the effects of POFA percentage on the weight per unit area of the brick specimens, showing a reduced weight per unit area in bricks containing POFA. For instance, the bricks without POFA had a weight per unit area of 76.41 kg/m^2 that decreased by 10.76, 12.53, 18.68, and 23.34% for bricks containing 5, 10, 15, and 20% POFA, respectively. This result can be attributed to the increased porosity of the bricks with POFA and the lower specific gravity of POFA compared to clay. Previous studies [9,10] also found that the brick porosity increased when incorporating agricultural waste ash, producing lighter bricks. Lighter bricks can reduce the cost of construction by making it easier to transport them to the construction site, requiring less energy to lift them to the higher floors of multi-story buildings, and decreasing the dead load of the resulting structure.

3.3. Apparent porosity

Fig. 7 shows that the apparent porosity increased with increasing POFA content, and confirms the results in Fig. 6, indicating that the increasing porosity with increasing POFA content corresponded to a decreasing weight per unit area, as shown in Fig. 8. For example, an apparent porosity of 36.58% was observed for the bricks without POFA, whereas an apparent porosity of 45.46% was obtained for the brick specimens with 20% POFA. Note that the evaporation of water during the de-hydroxylation reaction of carbonate decomposition and the biomass residual combustion generally affect brick porosity [31]. In addition, the fluxing agent content in the raw material is an important factor when developing or reducing brick porosity.

During the firing process, a higher fluxing agent content will increase the liquid phase, resulting in a molten material that compresses the interspaces inside the bricks [10]. The fluxing agent content of the clay

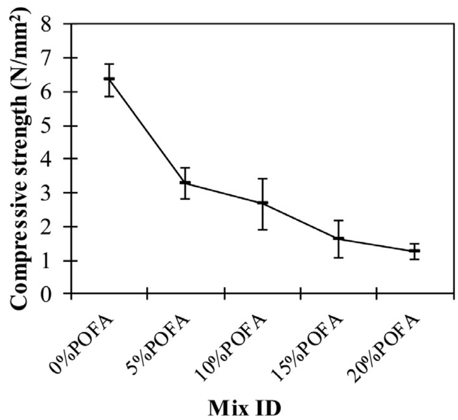

Fig. 9. Compressive strength of bricks.

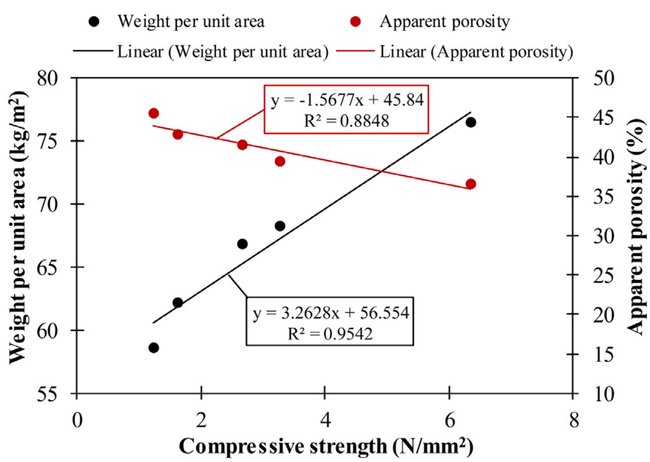

Fig. 10. Relationship between compressive strength, weight per unit area, and apparent porosity of the POFA brick specimens.

used in this study was higher than that of the POFA; therefore, the brick porosity increased with increasing POFA content. The increase in the porosity of bricks incorporating POFA will also lead to a higher water absorption capacity. These results are in line with the SEM images of the bricks and the relationship between porosity and weight per unit area (Fig. 8). Previous studies have reported similar results for bricks incorporating porous materials such as RHA and SBA [9,10,32].

3.4. Compressive strength

Fig. 9 shows the effect of POFA content on the compressive strength of the brick specimens. The compressive strength almost linearly decreased with increasing POFA content. The bricks without POFA exhibited a compressive strength of 6.44 N/mm^2, whereas those containing 5, 10, 15, and 20% POFA exhibited a 48.34, 58.13, 74.56, and 80.47% decrease in the compressive strength, respectively. The porosity, density, and pore size have been found to strongly influence the compressive strength of bricks [10,31]. Accordingly, Fig. 10 shows the linear relationship between the compressive strength, weight per unit area, and apparent porosity of the bricks according to POFA content. Similar results were also found in previous studies [10,32,33].

The organic matter decomposition and the high silica content in the raw materials used in this study clearly affected the porosity of the bricks and may induce flaws in the clay brick body [9]. In this work, the POFA had LOI of 12.05%, indicating that the considerable presence of organic matter in the ash likely affected the brick porosity. The silica content in the POFA was also ~50–60% greater than the preferred limit in clay [34]. Therefore, the higher amount of silica in POFA strongly affected the compressive strength of the bricks. Although the replacement of clay with any amount of POFA resulted in a decrease in the compressive strength, the replacement of clay with 10% POFA still achieved a compressive strength greater than 2.5 N/mm^2, satisfying the Indonesian Industrial Standard [35] for non-load bearing wall materials.

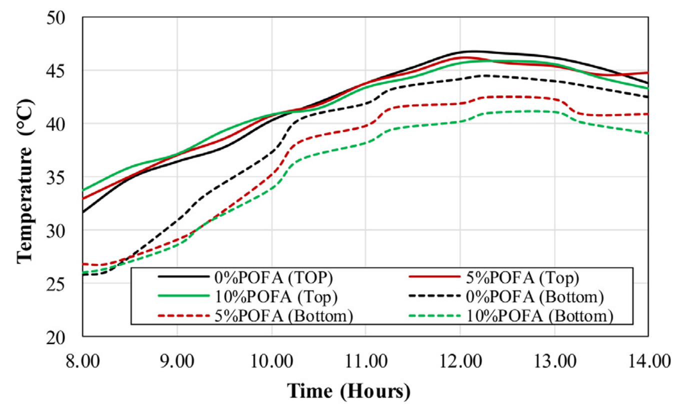

Fig. 11. Variation in the top and bottom surface temperatures of bricks exposed to direct sunlight over time.

3.5. Thermal performance

Based on the results of the compressive strength tests, only brick specimens containing 0, 5 and 10% POFA were selected for further study of thermal performance, as these specimens satisfied the Indonesian Industrial Standard [34] for non-load bearing wall materials. Fig. 11 shows the variations in the top and bottom surface temperatures of bricks with 0, 5, and 10% POFA over time. It can be observed that there was no significant difference in the temperature of the top surface of the brick specimens according to POFA content. However, the bottom surfaces of the brick specimens containing POFA exhibited lower temperatures than those of the brick specimens without POFA. For example, at 12:00, which was expected to have the highest temperature during the day, the temperatures of the bottom surface of the 0% POFA, 5% POFA, and 10% POFA bricks were 44.2, 41.9 and 40.2 °C, respectively. The differences between the top and bottom surfaces of the 5% POFA and 10% POFA bricks were approximately 3.8 and 5.6 °C, respectively, whereas that of the 0% POFA bricks was only 2.5 °C. This indicates that the replacement of clay with 10% POFA provided a better thermal performance than the use of only clay, along with a compressive strength within the permissible limits for wall materials.

The increased brick porosity with added POFA is the main reason for the observed improvement in thermal performance. Similar results were obtained by previous studies in which agricultural waste materials, such as RHA or SBA, were added to clay bricks to obtain improved thermal performance. Indeed, 29% and 31% reductions in thermal conductivity compared to conventional clay bricks were obtained when using 15% RHA or 15% SBA, respectively [4]. Furthermore, adding 4% RHA to a clay brick mixture resulted in a 6 °C reduction in the indoor temperature compared with the use of conventional bricks [14]. Using POFA bricks as a wall material would therefore reduce the energy demand for indoor cooling and help to improve the energy-efficiency of buildings.

3.6. Microstructures

The microstructures of the brick specimens containing POFA were characterized through SEM images. Fig. 12 shows the microstructure of a brick specimen without POFA (control) and with 10% POFA. A porous structure can be observed in both specimens; however, more visible pores can be found in the brick specimen containing 10% POFA due to the organic materials initially present in the POFA and released

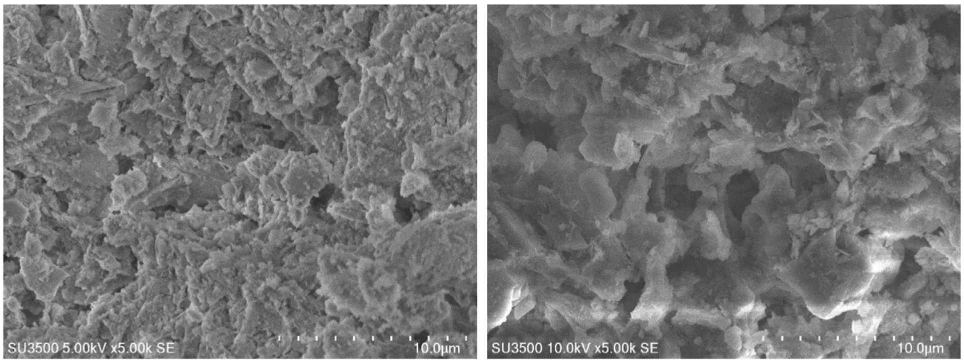

Fig. 12. SEM images of bricks with POFA contents of (a) 0% and (b) 10%.

in the form of carbon dioxide during firing. Consequently, this increased the porosity of the brick specimens containing POFA. These results are consistent with the results of the compressive strength, weight per unit area, apparent porosity, and thermal performance tests.

4. Conclusions

This study investigated the use of POFA, a by-product of burning the solid waste from palm oil production, as a clay replacement for large-scale brick production. The following conclusions can be drawn from the test results characterizing the brick properties according to POFA content:

(1) The replacement of clay with POFA in bricks resulted in a smaller linear shrinkage and weight per unit area. Bricks with a lower weight per unit area can reduce the cost of construction and the dead load of the structure they are used to construct.
(2) The compressive strength of the bricks decreased with increasing POFA content due to the resulting higher porosity. Up to 10% of the clay can be replaced with POFA when manufacturing bricks. A compressive strength of 2.66 N/mm^2 was obtained at this level of replacement, satisfying the Indonesia Industrial Standard for non-load bearing wall materials.
(3) In terms of thermal performance, the 10% POFA bricks yielded the highest temperature difference between top and bottom surfaces of about 5.6 °C, followed by 5% POFA and 0% POFA at about 3.8 °C and 2.5 °C, respectively. This improved temperature difference can help to reduce the energy demand for indoor cooling and improve the energy-efficiency of buildings when using POFA bricks as wall materials.

The findings of this study indicate that 10% replacement of clay with POFA offers an attractive approach for the large-scale production of lightweight bricks for use in non-load-bearing wall materials. The use of such bricks can therefore reduce the usage of natural clay resources in brick manufacturing, reduce the environmental impact of POFA disposal, and produce eco-friendly and sustainable building materials that result in lower energy consumption.

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Declaration of Competing Interest

There are no conflicts of interest to declare.

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