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Enhancing geopolymer mortars: The role of surgical face masks in modifying mechanical and thermal properties

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Abstract

The primary aim of this study is to examine how expanded surgical face masks (SFMs) affect the mechanical properties, thermal conductivity, thermal insulation, and microstructure of geopolymer mortars. In the experimental phase, SFMs were used after removing the inner nose wires and ear loops, then cut into 5 mm × 5 mm pieces. These SFMs were added to various mixtures at different weight percentages (0%, 2%, 4%, and 6%), along with palm oil clinker (POC) and alkali activator. The mechanical properties of the mixtures, such as compressive strength, bulk density, and water absorption, underwent evaluation through testing. Moreover, thermal conductivity and thermal insulation measurements were carried out to gauge the effect of SFMs on this property. Microstructural analysis of the mixtures was conducted using scanning electron microscopy SEM to examine the impact of SFMs on mortar microstructure. The test results indicated that geopolymer mortar containing 2% SFM achieved a compressive strength of 67.3 ksc at 28 days, with an alkaline to fly ash ratio of 0.8 and POC to fly ash ratio of 3. The geopolymer mortars with POC containing SFMs had a bulk density ranging from 1,233 to 1533 kg/m^3 at 28 days. Notably, the use of SFMs resulted in a substantial enhancement in thermal conductivity and thermal insulation. Additionally, a strong correlation was found between thermal conductivity and bulk density, suggesting a potential relationship between these properties.

Keywords: Surgical face mask, Thermal conductivity, Thermal insulation, Mortar, Geopolymer

1. Introduction

The rapid increase in the world population has led to a greater need for construction materials, especially concrete blocks and bricks. This rise, projected to be 3,198.3 billion units by 2031, was estimated at 2,088.6 billion units in 2022 [1]. However, this increasing demand has worsened environmental issues. Traditional materials such as Ordinary Portland Cement (OPC), stone, sand, and mud contribute to environmental degradation through the extraction and manufacturing processes. Dealing with these challenges necessitates innovative and sustainable solutions. Studies investigating alternative construction materials have drawn increasing attention, demonstrating the potential use of waste materials from different industries as binders or aggregates [2-4]. Geopolymer materials have emerged as a promising option among these alternatives. Geopolymers provide a sustainable alternative to traditional materials, utilizing waste resources and minimizing environmental impact. They are created by activating industrial by-products or waste materials with alkali, offering numerous benefits over OPC-based materials. Importantly, they decrease carbon emissions and energy use in production, help preserve natural resources, and provide excellent durability. Furthermore, the flexibility of geopolymer materials enables the use of different waste streams as raw materials, promoting circular economy principles. Through the use of alkali activator solutions, geopolymerization transforms waste materials into durable construction components like blocks and bricks, aiding sustainable development goals. In view of these challenges, geopolymers have been extensively researched for their potential to solve environmental problems while meeting the requirements of the construction industry. Hamcumpai et al. [5] investigated steel fiber reinforced fly ash (FA) geopolymer concrete using recycled granite waste (GW) and rice husk ash (RHA). Their results demonstrated that the addition of RHA at 1% by weight of the binder resulted in improved mechanical properties in steel fiber reinforced geopolymer concrete FA. Specifically, compressive strength increased by 25% and flexural strength improved by 70% when combined with hooked steel fibers. This indicates that the combination of RHA and steel fibers contributes significantly to the strength and durability of the concrete mixture. In addition, the environmental impact and cost-effectiveness of FA geopolymer concrete with steel fiber reinforcement were also evaluated as part of this investigation. The results indicate that the use of 1% RHA and 0.5% steel fibers is a suitable balance and increases the environmental strength by 15 compared to plain geopolymer concrete, making it a viable option for sustainable construction practices.

The widespread use of personal protective masks, such as surgical face masks, N95 masks, and KF94 masks, has played a crucial role in reducing the spread of COVID-19 globally. However, the increased use of masks has led to a surge in demand, creating hazardous waste [6]. As a result, the environmental impact of disposable masks is worrying. Many end up littering streets, polluting

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water sources, or filling landfills [7]. In 2020, mask consumption reached alarming levels, especially in densely populated areas. Asia uses an estimated 1.875 billion face masks daily, followed by Europe with 445 million and Africa with 411 million, totaling about 3.378 billion masks worldwide [8]. Although there may have been a recent decline in usage, the environmental impact of this extensive consumption continues. The main problem is that single-use masks are mostly made of plastic. Plastic takes hundreds of years to break down in the environment, posing a long-term threat to ecosystems and wildlife [9]. Urgent action is needed to tackle the environmental impact of disposable face masks.

In developing countries, the civil and infrastructure sectors heavily rely on aggregates, leading to increased environmental degradation due to the depletion of natural resources and greenhouse gas emissions. To mitigate these adverse effects, there has been a growing emphasis on recycling and reusing construction and demolition waste in civil engineering projects [10]. The waste from construction, factories, and electrical power plants can be used as aggregate for concrete, such as crumb rubber [11], recycled plastic [12, 13], coarse bottom ash [14], recycled concrete aggregate [15-17], reclaimed asphalt [18-20], palm kernel shell [21-23], and palm oil clinker [24-26]. Palm oil clinker (POC) is agro-waste produced and accumulated as biomass at power plants in southern Thailand. Generally, POC waste is sent to landfills, resulting in an environmental problem. The lightweight characteristics of POC have attracted significant interest from researchers, particularly regarding its potential application as a replacement for sand and stone aggregates in construction materials. This innovative approach aims to enhance material sustainability and reduce reliance on traditional resources. Geopolymer mortars can use POC for the replacement of normal sand to achieve lower bulk density. Darvish et al. [27] showed that geopolymer mortars can be prepared using POC aggregate. A bulk density reduction of about 17% was achieved using POC as sand in geopolymer mortar. Salari et al. [28] showed that using 100% POC produced low compressive strength in lightweight concrete, resulting in a 90-day compressive strength of 26.7 MPa and a bulk density of 1,500 kg/m^3. Additionally, researchers have explored the incorporation of surgical face masks into concrete mixtures to enhance certain properties. Thoudam et al. [29] found that adding surgical face masks to alkali-activated bricks reduced density and increased water absorption. Similarly, Kilmartin-Lynch et al. [30] observed improved compressive strength in concrete with polypropylene fibers from surgical face masks. Durmus et al. [31] demonstrated a slight increase in compressive strength with the addition of surgical face masks to self-compacting high-strength concrete. Meanwhile, Win et al. [32] investigated surgical face masks (SFMs) as polypropylene fiber in mortar. The study found that incorporating polypropylene fibers from SFMs significantly enhanced the mechanical properties of cement mortar. Notably, the compressive, direct tensile, and flexural strengths improved, with optimum performance observed at 0.15% SFM, which outperformed other mortar mixtures. In pavement materials, studies have shown that waste surgical face masks can enhance the unconfined compression of the base and sub-base materials [7]. However, excessive use of surgical face masks may reduce the unconfined compressive strength of pavement materials. While several researchers have focused on the physical and mechanical properties of materials containing surgical face masks, the current study aims to investigate the thermal properties of geopolymers with palm oil clinkers for geopolymer thermal blocks. The low-density characteristic of POC makes it a suitable material for incorporation into concrete block mixtures. This study evaluates the thermal conductivity and insulation of geopolymer mortars and blocks, in addition to traditional parameters such as compressive strength, bulk density, and water absorption. By examining the thermal properties of geopolymer thermal blocks, this study seeks to contribute to the sustainable development of construction materials and to mitigate environmental impacts associated with traditional construction practices.

As mentioned above, the use of surgical face masks increased during the COVID-19 pandemic, which has led to a significant increase in the amount of waste, mainly due to the plastic composition of most masks. This accumulation poses a significant environmental problem as it takes centuries for the plastic to decompose, thus impacting ecosystems. Repurposing surgical face mask waste as a construction material offers an innovative strategy to help alleviate this issue. In this study, the researchers investigated the potential of using surgical face masks as a partial substitute for sand in a geopolymer mortar made from fly ash and palm oil waste with the aim of developing a sustainable and environmentally friendly building material. This approach not only addressed the environmental issues associated with non-biodegradable surgical face mask waste but was also in line with the principles of sustainable construction by reducing the reliance on natural resources and lowering carbon emissions by reducing OPC consumption.

2. Materials and methods

2.1 Research methodology

To elucidate the methodology employed in this study, a detailed and comprehensive flowchart is provided, as illustrated in Figure 1. The methodology comprises several decisive steps that are intended to ensure systematic implementation of the research objectives. This research involves multiple stages, beginning with material preparation for the experiment, determining the geopolymer mortar mixture composition, followed by casting, demolding, curing the specimens, and testing the samples. The data gathered from these experimental activities are subsequently analyzed to convey the conclusions. The workflow of this research is depicted in Figure 1.

2.2 Materials

Fly ash (FA) from the Mae Moh power plant in Lampang province, Thailand, is essential in many industries. The particle size distribution of FA was analyzed using a Malvern Mastersizer instrument, and the results are presented in Figure 2. In addition, the chemical composition of the fly ash was also evaluated via X-ray fluorescence (XRF) analysis, as summarized in Table 1. The summation of silica oxide (SiO_2), alumina oxide (Al_2O_3), and iron oxide (Fe_2O_3) was 77.66% which could be divided as 45.27%, 23.00%, and 9.39% for SiO_2, Al_2O_3, and 23.00%, respectively. The calcium oxide (CaO) was less than 18% which could be classified as class F according to ASTM C618 [33].

The alkaline activator was prepared with sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) (industrial grade with 99% purity). The chemical composition of sodium silicate is shown as 29.45 wt% SiO_2, 14.85 wt% Na_2O, and 55.70 wt% H_2O. The alkaline activator solution was prepared with a ratio of 1:2.5 by mixing NaOH with Na_2SiO_3.

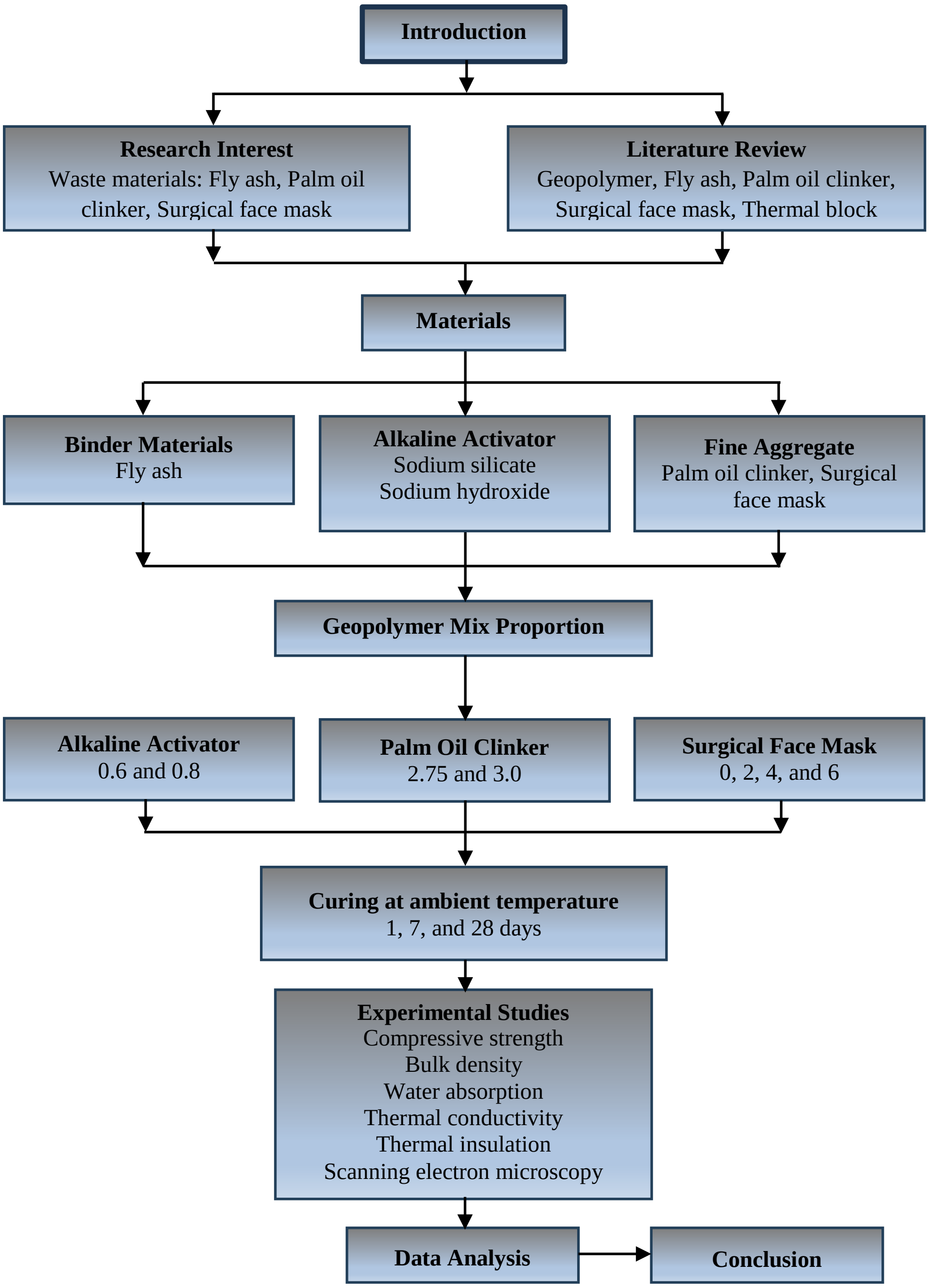

Figure 1 Flowchart of the research methodology

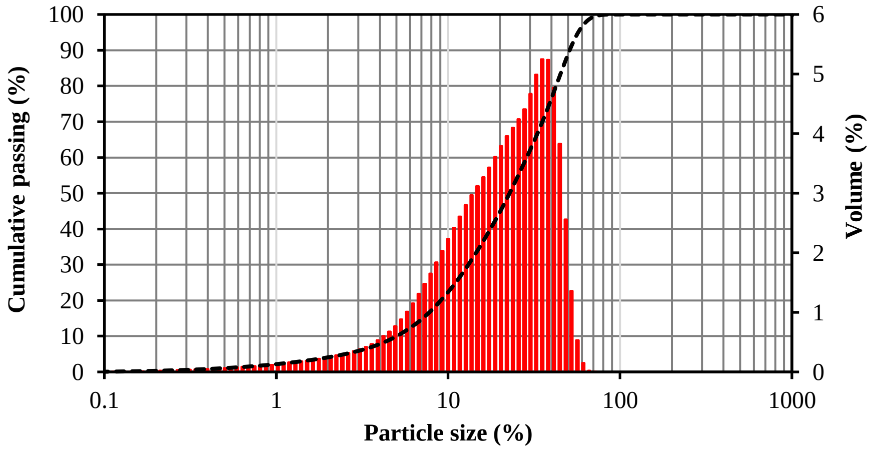

Figure 2 Particle size distribution of FA

Table 1 Chemical composition of FA

Oxides	Fly ash (%)
SiO_2	45.27
Al_2O_3	23.00
Fe_2O_3	9.39
CaO	12.47
MgO	1.70
Na_2O	1.03
K_2O	2.31
SO_3	2.73
Other	3.18

Palm oil clinker (POC) is derived as a byproduct from electric power plants during the processing of waste palm oil, which includes palm kernel shells, empty fruit bunches, and mesocarp fiber, following the extraction of palm oil from palm fruits (Figure 3a). In the laboratory, the POC undergoes crushing and sieving to achieve a particle size below 4.75 mm using sieve No. 4 (Figure 3b). Characterized by its porous nature, lightweight composition, and high water absorption (as detailed in Table 2), POC exhibits a lower bulk density, rendering it suitable for application in making lightweight concrete blocks and concrete paving blocks. The physical properties of POC are outlined in Table 2, while the particle size distribution is depicted in Figure 4.

The surgical face masks (SFM) used in the mixtures were cut to a square shape. SFMs used against the COVID-19 epidemic have 3 layers. The waste SFMs were kept in an oven at 70 ºC for 6 hours to ensure decontamination [34]. Xiang et al. [35] found that subjecting N95 respirators and surgical face masks to dry heat at both 60 °C and 70 °C for 1 hour successfully eradicated six species of respiratory bacteria and one fungal species, as well as inactivating the H1N1 indicator virus. Moreover, after undergoing 70 °C heat treatment for 1, 2, and 3 hours, there were no observable alterations in the shape and components of the respirators and face masks. To prepare the SFMs, start by removing the ear loops. Next, use scissors to cut the mask into a square with dimensions of 5 × 5 cm. The water absorption of the SFMs was determined in accordance with the standard test method ASTM C128-15. As shown in Table 2, the measured value was 5.91%. The micrographs of the outer layer of the SFMs which can be seen in Figure 5a show a non-smooth surface and a larger diameter of fibers compared to the inner layer. The surface micrographs of the inner layer in Figure 5b reveal a smooth surface texture with thin fibers.

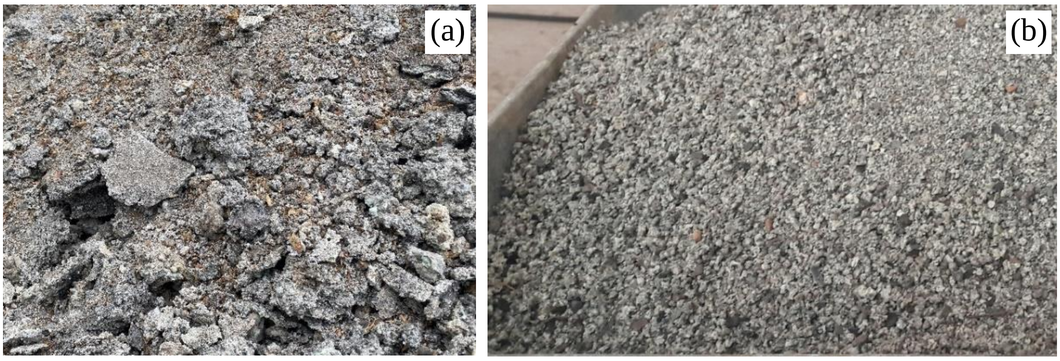

Figure 3 Physical properties of POC: (a) original POC, and (b) after crushing and sieving

Table 2 Physical properties of POC and SFM

Properties	POC	SFM
Bulk specific gravity (SSD)	1.89	0.36
Water absorption (%)	5.20	5.91
Loose bulk density (kg/m^3)	675	-
Compact bulk density (kg/m^3)	730	-

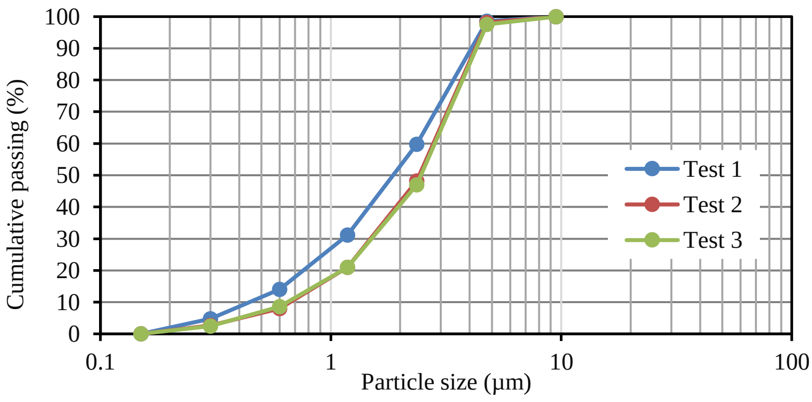

Figure 4 Particle size distribution of POC

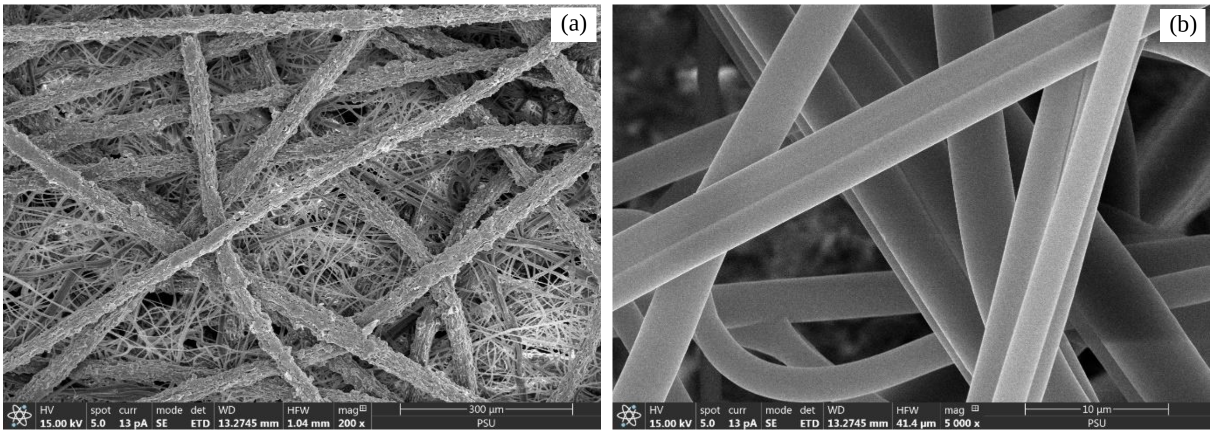

Figure 5 SEM micrographs of the surgical face mask: (a) outer layer and (b) inner layer

2.3 Sample preparation

This study investigates the properties of geopolymer mortars by examining the effects of different ratios of alkaline activators, aggregate, and surgical face masks (SFMs). Fourteen mixtures were prepared, varying the SFM content at ratios of 0%, 2%, 4%, and 6% by weight of aggregate. The mix proportions of the geopolymer mortars were defined by alkaline to fly ash (FA) ratios of 0.6 and 0.8, POC to FA ratios of 2.75 and 3.0, and a sodium silicate to sodium hydroxide ratio of 2.5:1 by weight. These mix proportions are outlined in Table 3. The preparation of geopolymer mortars involved three main steps. Firstly, POC, SFM, and FA were hand-mixed for approximately 3 minutes to ensure the uniform distribution of materials. Secondly, sodium hydroxide, sodium silicate, and water were combined to form a homogeneous alkaline activator solution. Finally, the alkaline activator was added to the solid materials from the first step and mixed for about 5 minutes until a homogeneous slurry was obtained (refer to Figure 6). The process of mixing the mortar was challenging because the mixture exhibited a dry texture. This dryness resulted from the high water absorption capacity of POC and SFM. The problem was especially pronounced in mixtures with a high proportion of face masks.

After mixing, the fresh geopolymer mortar was poured into 50 × 50 × 50 mm molds and allowed to set and harden for subsequent testing. The curing process involved maintaining the samples at room temperature (30±2 ºC) for 24 hours. Subsequently, the geopolymer mortars were demolded and stored at room temperature for further testing at intervals of 1, 7, and 28 days for compressive strength, and 28 days for thermal conductivity and water absorption.

Table 3 Mix proportion of geopolymer mortars with 100 g FA

Symbol	FA	POC	SFM		Alkaline	Water
	(g)	(g)	(g)	(%)	(g)	(g)
2-A6W5	100	275	0	0	60	50
2-M4A6W5	100	269.5	5.5	2	60	50
2-M6A6W5	100	264	11	4	60	50
2-A8W7	100	275	0	0	80	70
2-M2A8W7	100	269.5	5.5	2	80	70
2-M4A8W7	100	264	11	4	80	70
2-M6A8W7	100	258.5	16.5	6	80	70
3-A6W7	100	300	0	0	60	70
3-M4A6W7	100	294	6	2	60	70
3-M6A6W5	100	288	12	4	60	70
3-A8W7	100	300	0	0	80	70
3-M2A8W7	100	294	6	2	80	70
3-M4A8W7	100	288	12	4	80	70
3-M6A8W7	100	282	18	6	80	70

2.4 Test method

Geopolymer mortars were prepared as cubic specimens measuring 50 × 50 × 50 mm to determine their compressive strength at 1, 7, and 28 days. Following casting, the samples remained in their molds for 24 hours at an average room temperature of 30±2 ºC before being demolded and kept at room temperature until testing. Compressive strength testing was conducted using a universal testing machine (UTM) in accordance with ASTM C109/C109M-16a [36]. Compressive strength tests were conducted on three samples at each curing time.

The bulk density of the geopolymer was measured after curing at room temperature for 28 days. This was calculated by dividing the mass of the three samples by the volume of each sample (mass/volume).

The water absorption test evaluates the change in mass of a saturated sample during water absorption. In this study, the specimens were kept at room temperature (30±2 ºC) for 28 days. Subsequently, the geopolymer samples were immersed in water, and after 24 hours, the samples were removed and weight measurements were recorded after surface drying. The calculation of water absorption utilized the formula provided below (Equation 1).

$$W_{ab}\ (\%) = \left(\frac{W_{SS} - W_{28}}{W_{28}}\right) \times 100 \quad (1)$$

Water absorption (W_{ab}) is determined by Formula (1), where Wss represents the weight of the saturated surface of the sample (in grams), and W_{28} is the weight of the sample at 28 days (in grams).

Thermal conductivity of the 50 × 50 × 50 mm^3 samples was measured using a portable heat transfer analyzer (Isomet 2114) and tested with a direct measuring instrument using a surface probe (see Figure 7). The thermal conductivity of the geopolymer mortars was measured at 28 days curing at ambient temperature, and three specimens were tested for each of the mix proportions.

To evaluate the thermal insulation capabilities, a sample with dimensions of 7 × 19 × 39 cm, which matches the size of commercially available concrete blocks, is utilized. The test is performed within a foam chamber, as illustrated in Figure 8. Five temperature sensors are strategically installed at specific positions, also shown in Figure 8, to monitor the temperature variations at each location throughout a total duration of 5 hours. This setup allows for precise measurement of the temperature changes occurring over time in each sensor location. The thermal insulation of the block made use of one sample.

Scanning electron microscopy (SEM) was conducted on small scraps of geopolymer mortars from the compressive strength test at 28 days. A JIMS-5800 LV model scanning electron microscope was used to investigate the microstructure matrix and fibers of the surgical face masks in the samples.

Figure 6 Step mixtures of geopolymer mortars: (a) prepare the mixture, (b) mixing, and (c) geopolymer mortars

Figure 7 Thermal conductivity test of the geopolymer mortar

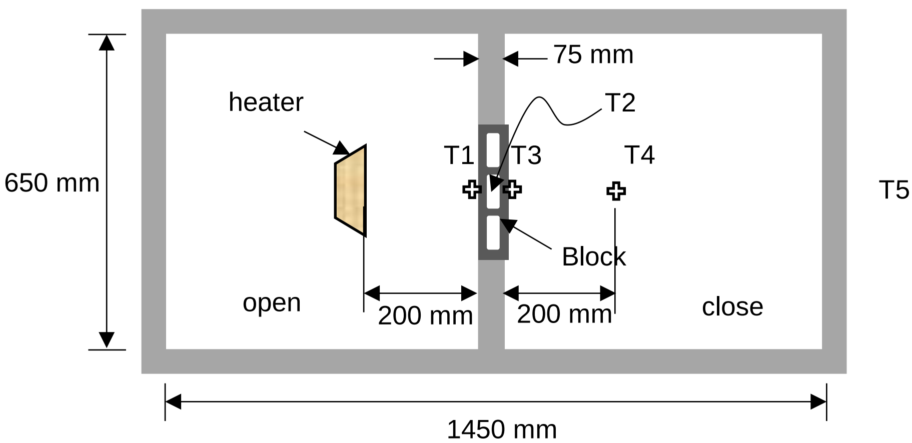

Figure 8 Diagram illustrating the arrangement of temperature sensors and the setup for testing the thermal insulation of concrete blocks

3. Results and discussion

3.1 Compressive strength

Figure 9 shows the compressive strength values of the geopolymer mortar samples after 28 days. These samples vary in FA-to-POC fine aggregate ratios, FA-to-alkali activators, and SFM content. Results were compared to a control sample without SFM. Compressive strength consistently decreased as SFM content increased under all conditions. This suggests that adding SFM to the geopolymer matrix reduces its compression resistance. Possible reasons for this include SFM's ineffective adhesion to the geopolymer paste and the reported debonding of fibers from the alkali-activated matrix due to the smooth surface of the polypropylene fibers, as noted by [37]. Lower bulk density and higher water absorption due to increased SFM content may also decrease compressive strength. Amin et al. [38] demonstrated that an increase in the percentage of SFM leads to a reduction in compressive strength, primarily due to the formation of additional pores. This reduction in compressive strength can be attributed to the higher void content (i.e., increased porosity) in the mortar mix, which results from the reduced workability of SFM-modified mortar. The void content was observed to increase with higher SFM content. Furthermore, the decrease in the strength of SFM mortar may also be attributed to the inadequate bonding between the SFM particles and the hardened cement matrix [39].

In comparison to the sample without SFM, the compressive strength of the specimen containing 2% and 4% SFM decreased significantly by 54.1% and 78.4%, respectively, as depicted in Figure 9a. This reduction can be attributed to the low liquid content in the geopolymer mortar system, characterized by an FA-to-alkali activators ratio of 0.6 and water-to-FA ratio of 0.5. Geopolymer mortars containing SFM tend to absorb water from the alkali solution, resulting in a dry geopolymer matrix. Furthermore, when utilizing an FA-to-alkali activators ratio of 0.8 and water-to-FA ratio of 0.7 for the geopolymer paste, the compressive strengths of the specimens containing 2%, 4%, and 6% SFM decreased by 36.8%, 44.9%, and 47.5%, respectively, as illustrated in Figure 9b. These findings indicate that the presence of SFM adversely affects the compressive strength of geopolymer mortars across different mixing ratios. Interestingly, specimens containing SFM exhibited slightly different compressive strength values at all curing ages, with the lowest values observed in comparison to all mixtures. This suggests that the use of a large quantity of POC may lead to significant water absorption, resulting in a dry texture of the geopolymer mortar. This aligns with findings from a previous analytical study [40], which reported that compressive strength tends to decrease at higher POC volumes due to the resulting high porosity and large pores within the matrix.

The 3-M2A8W7 sample demonstrated higher compressive strength than all geopolymer samples containing SFM, with values of 65.6 ksc and 67.3 ksc at 7 and 28 days, respectively. This was lower than the compressive strength of 3-A8W7 (without SFM), which measured 15.1 ksc and 23.8 ksc, respectively. Achieving maximum compressive strength in samples mixed with SFM suggests that the alkali solutions and liquid consistency in the system are well-suited for both reaction and consistency. This finding aligns with a study by Win et al. [32], which reported a decrease in compressive strength in specimens mixed with SFM. It is noteworthy that in this study SFMs were used in regulated sizes of 5 mm × 5 mm. Using SFMs in sheet form is considered unfavorable, resulting in a negative compressive strength value. Moreover, incorporating a high volume of POC may hinder the geopolymer paste from fully coating the POC surface. This incomplete coating reduces the material's adhesion ability, which directly contributes to a decline in compressive strength. However, Thoudam et al. [29] reported that SFMs were ground using a dry process. The SFMs contain shredded and fibrous mask particles. When mixed in the preparation of alkali-activated bricks, the mean compressive strength of specimens after ambient curing shows an improvement in the strength of the bricks with the addition of SFMs.

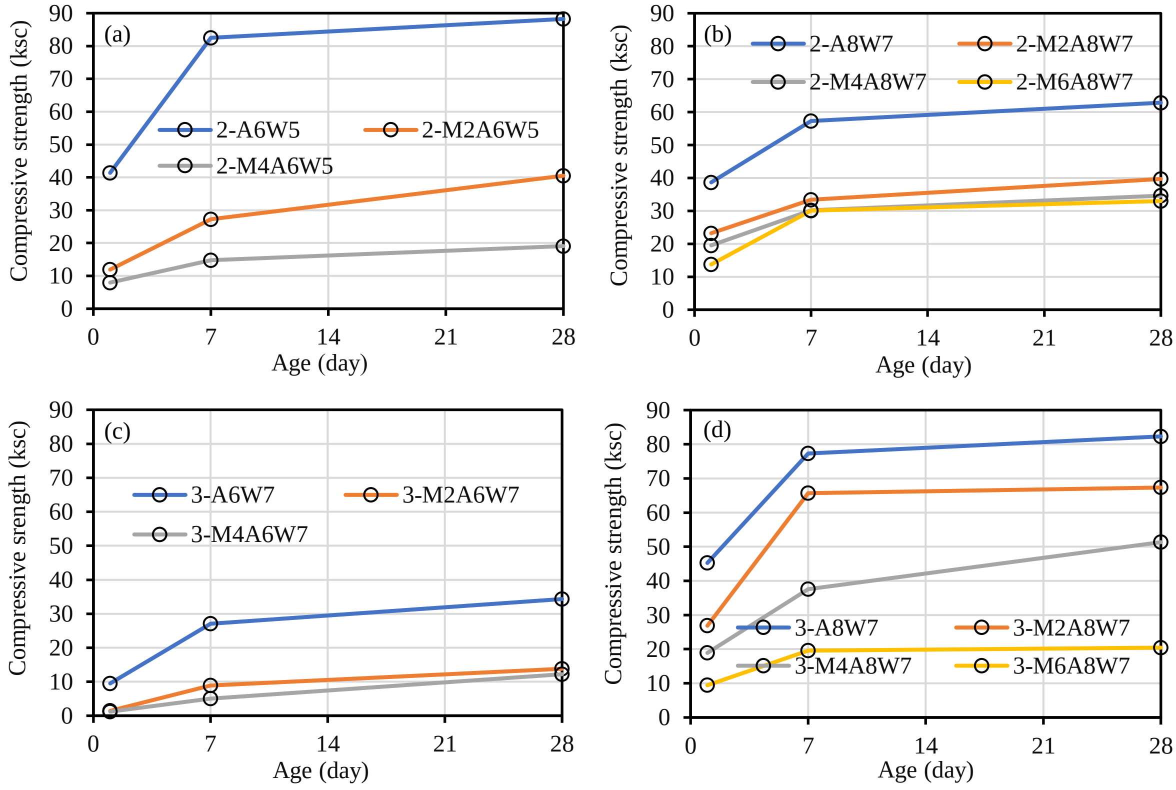

Figure 9 Compressive strength of geopolymer mortars: (a) POC=2.75, AK=0.6, W/B=0.5, (b) POC=2.75, AK=0.8, W/B=0.7, (c) POC=3.0, AK=0.6, W/B=0.7, and (d) POC=3.0, AK=0.8, W/B=0.7

3.2 Bulk density

After 28 days of curing at ambient temperature, testing was conducted to determine the bulk density of geopolymer mortars containing expanded surgical face masks (SFMs) at 0%, 2%, 4%, and 6% by weight of palm oil clinker (POC). The results, depicted in Figure 10, illustrate a clear trend: an increase in SFM content leads to a reduction in the bulk density of geopolymer mortars. This effect can be attributed to the low specific gravity of SM particles. These findings align with previous investigations by Win et al. [32] and Thoudam et al. [29], which also observed a decrease in bulk density with the inclusion of SFM. The bulk density of the geopolymer mortars ranged from 1,233 to 1,533 kg/m³, reflecting the low bulk density characteristic of POC. Notably, samples prepared with 4% SFM exhibited lower liquid content in the system, resulting in reduced bulk density compared to other mixtures (see Figures 10a and 10c). Overall, these results highlight the impact of SFM content on the bulk density of geopolymer mortars, emphasizing the importance of careful consideration when incorporating SFM into such materials. Further research in this area could provide valuable insights into optimizing the composition and properties of geopolymer-based systems.

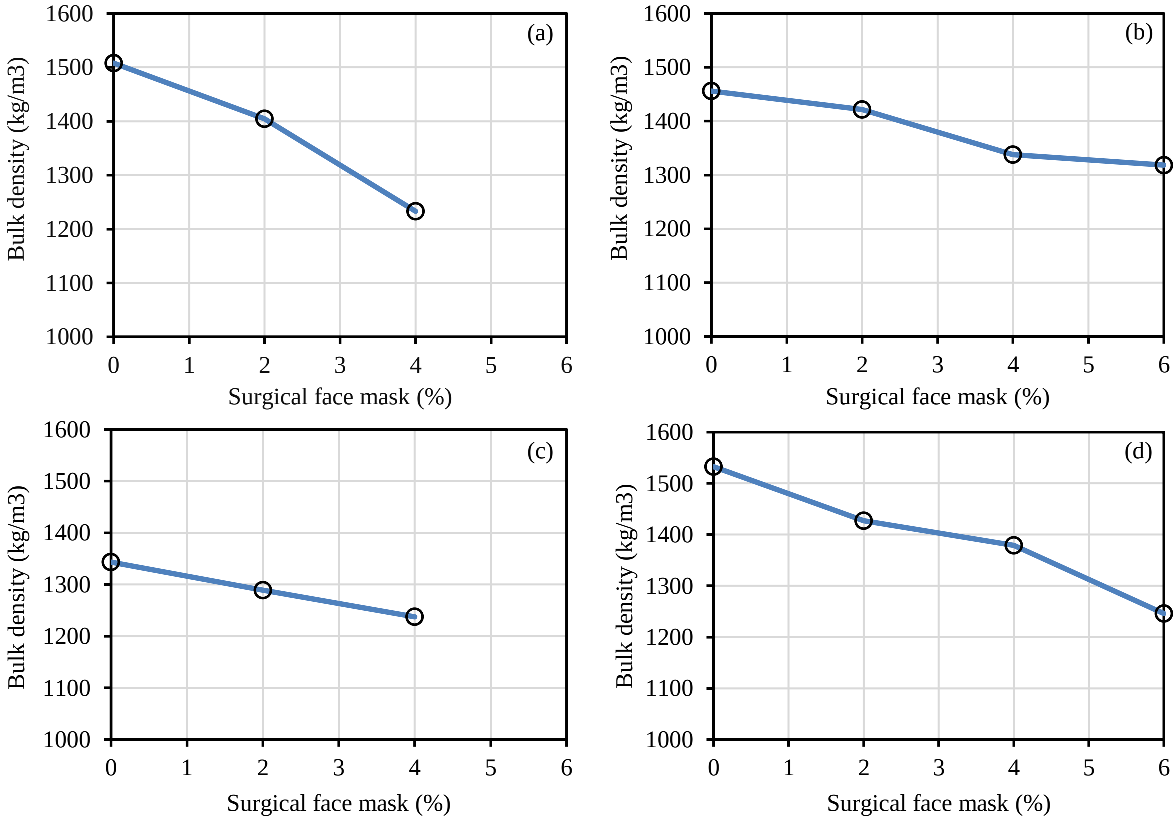

Figure 10 Bulk density of geopolymer mortars at 28 days: (a) POC=2.75, AK=0.6, W/B=0.5, (b) POC=2.75, AK=0.8, W/B=0.7, (c) POC=3.0, AK=0.6, W/B=0.7, and (d) POC=3.0, AK=0.8, W/B=0.7

3.3 Water absorption

3.3.1 Effect of masks

The water absorption test results for all mixtures are depicted in Figures 11a-11d. Observations revealed that the 1-hour water absorption values varied depending on the POC ratio and alkali activator ratio used in the mixtures. Specifically, for samples with a 2.75 POC ratio and an alkali activator ratio of 0.6, the 1-hour water absorption ranged from 3.73% to 12.5%, while for those with a 3.00 POC ratio, it ranged from 8.2% to 12.6%. Similarly, samples prepared with an alkali activator ratio of 0.8 exhibited water absorption ranging from 5.4% to 7.9% for 2.75 POC and from 7.7% to 9.6% for 3.00 POC. Furthermore, soaking geopolymer samples in water for durations ranging from 1 to 24 hours had a negligible effect on water absorption. However, all samples exhibited an increase in water absorption with higher SM content in the mixtures. For instance, as illustrated in Figures 11a and 11c, the apparent water absorption of the mixtures notably increased with higher SM content. Specifically, the water absorption increased by 127.88% for the reference mixture (2-A6W5) with a 2% SFM content and by 259.25% with a 4% SFM content after 24 hours of submersion. Similarly, the inclusion of SFM in alkali-activated bricks led to increased water absorption as the SFM content increased. This increase in water absorption and pore percentage can be attributed to the void spaces created by the presence of SFM in the bricks [29]. Additionally, previous research by [32] confirmed that cement mortars exhibited increased water absorption with higher concentrations of surgical face masks. Finally, it is worth noting that the samples were investigated for the volume of permeable voids to further understand their water absorption characteristics.

It was observed that the mixes using an alkali activator ratio of 0.8 exhibited slightly different values for water absorption compared to the sample without SFM (0%) and those containing the SFM (2-6%). Conversely, geopolymer mortars using an alkali activator ratio of 0.6 demonstrated more significant differences in water absorption values. For instance, as depicted in Figure 11a, the mixes containing the SFM (0-4%) exhibited water absorption values of 3.73%, 8.50%, and 13.40%, respectively, after being submerged in water for 24 hours. This indicates a notable increase in water absorption as the SFM content in the mixture rises, which was particularly evident in the lower alkali activator ratio conditions. Mixtures with low alkaline content exhibit high water absorption due to the limited amount of water contributed by sodium silicate, which reduces the total water available in the system. As a result, the geopolymer develops a dry structure, thereby increasing its water absorption capacity.

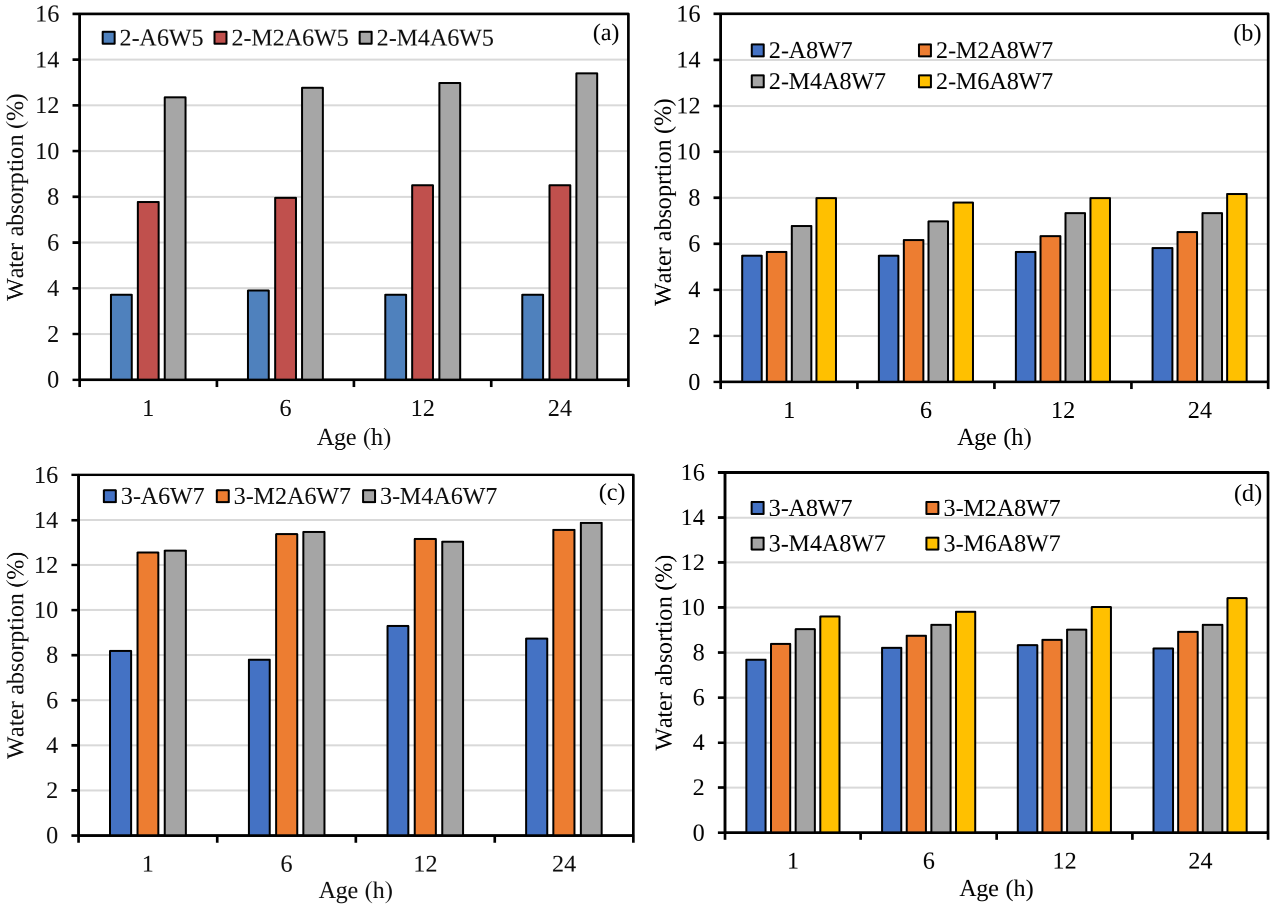

Figure 11 Water absorption of geopolymer mortars: (a) POC=2.75, AK=0.6, W/B=0.5, (b) POC=2.75, AK=0.8, W/B=0.7, (c) POC=3.0, AK=0.6, W/B=0.7, and (d) POC=3.0, AK=0.8, W/B=0.7

3.3.2 Effect of POC

The effect of fly ash to POC ratio and the replacement of POC fine aggregate by SM on water absorption is depicted in Figure 10, with further discussion provided in Section 3.3.1. Notably, Figure 12 illustrates that geopolymer mortars with a fly ash to POC ratio of 1:2.75 exhibited lower water absorption across all mixtures when SFM was replaced at 2-6%. However, as the fly ash to POC ratio increased, there was a corresponding increase in water absorption. This trend can be attributed to the higher volume of fly ash mixed into the geopolymer mortars. Conversely, samples with a ratio of 1:3 demonstrated higher water absorption, with the POC fine aggregate playing a significant role in this increase due to its pore structure [41]. These findings align with similar observations reported by Abutaha et al. [42], where an increase in water absorption was directly associated with a higher volume of POC, leading to an increase in voids within the geopolymer matrix.

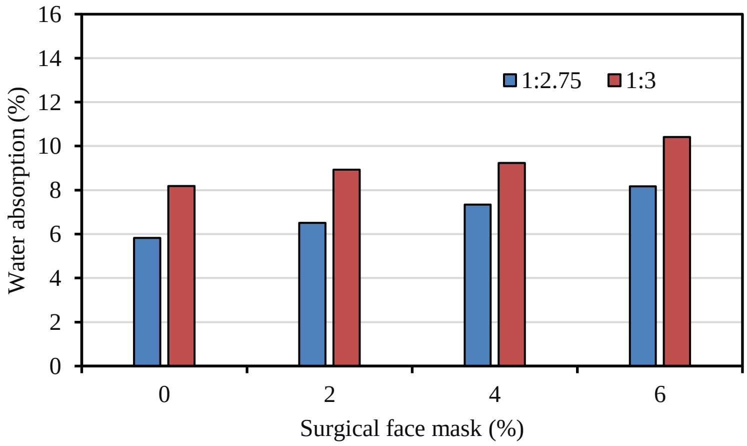

Figure 12 Water absorption of geopolymer mortars with different POC levels

3.3.3 Effect of alkaline activator

The water absorption of 28-day geopolymer mortars, considering the effect of the alkali solution to binder (fly ash) ratio, is illustrated in Figure 13. For geopolymer samples without SFMs, marginal differences in water absorption were observed for alkali solution to binder ratios of 0.6 and 0.8. However, when mortar samples partially replaced POC fine aggregate with SM, geopolymer samples containing 2% and 4% SM with an alkali solution to binder ratio of 0.6 exhibited significantly higher water absorption compared to those with a ratio of 0.8. The disparity in water absorption can be attributed to the lower water content in the geopolymer matrix at a 0.6 ratio, necessitating additional water when SFMs were incorporated. Furthermore, the higher volume of POC fine aggregate containing SFM, due to the lower specific gravity of SFM compared to POC, further increased the water demand of the geopolymer system, particularly in comparison to samples with an alkali solution to binder ratio of 0.8.

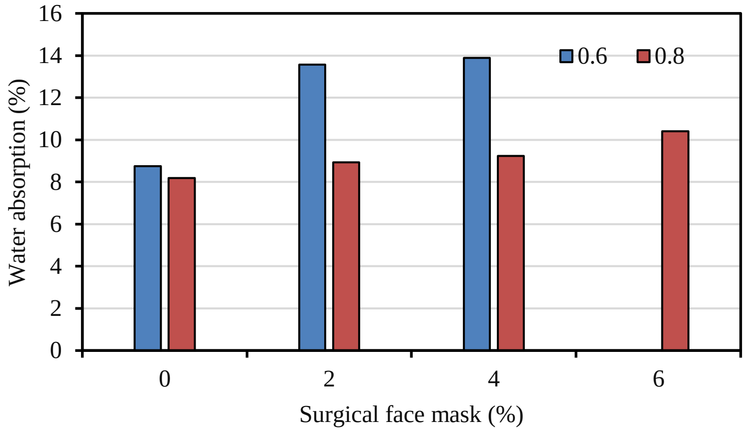

Figure 13 Water absorption of geopolymer mortars with different AK levels

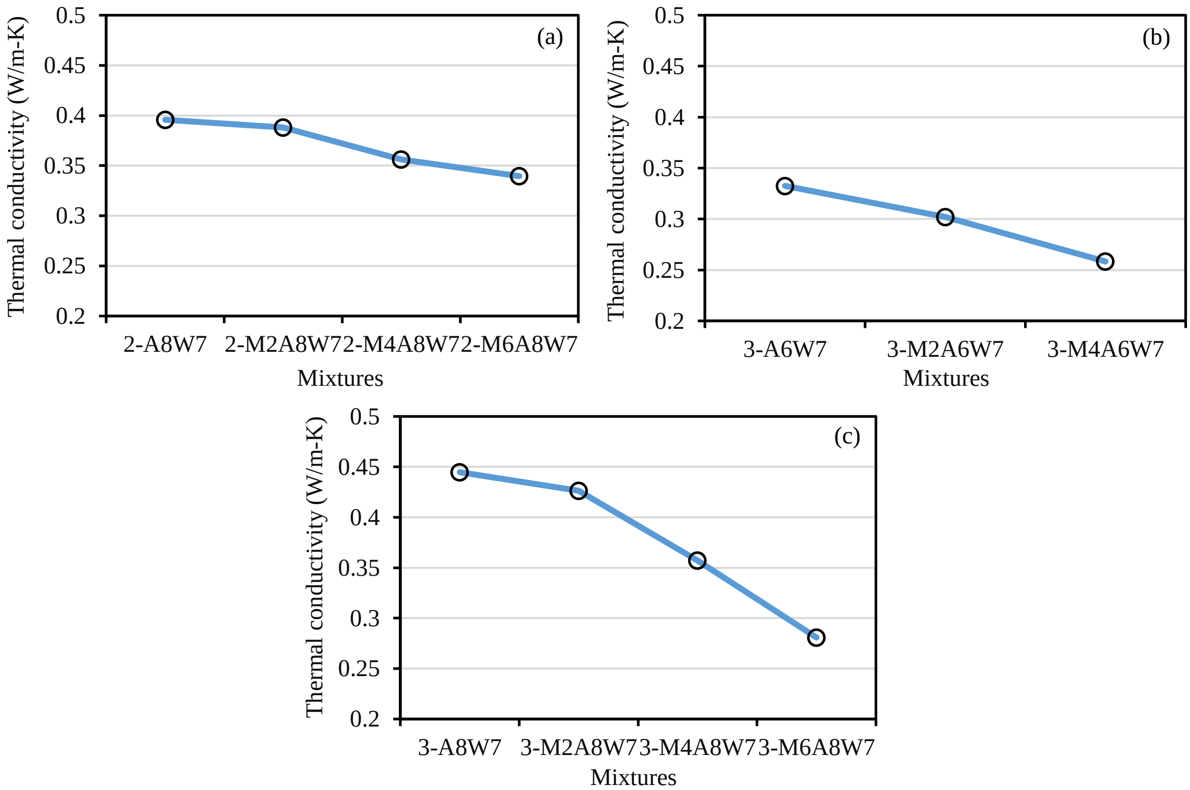

Figure 14 Thermal conductivity of geopolymer mortars: (a) POC=2.75, AK=0.8, W/B=0.7, (b) POC=3.0, AK=0.6, W/B=0.7, and (c) POC=3.0, AK=0.8, W/B=0.7

3.4 Thermal conductivity

Thermal conductivity measures the quantity of heat transmitted through a unit thickness in a direction perpendicular to a surface of unit area. In the context of geopolymer mortar samples utilizing FA and POC fine aggregate containing SFM, thermal conductivity plays a crucial role in determining the insulation properties, as depicted in Figure 14. The addition of SFM leads to a decrease in thermal conductivity. This is because SFMs are characterized by their low thermal conductivity, measured at 0.049 W/m·K. [43]. Furthermore, the presence of a dry geopolymer matrix contributes to the reduction in thermal conductivity of the specimens. The observed decreases in bulk density, compressive strength, and thermal conductivity may be attributed to the higher porous volume in the matrix, particularly evident in the interfacial transition zone between SFM and the geopolymer paste and POC fine aggregate. This aligns with findings from previous studies [44-46], which indicated that samples with lower density exhibited lower conductivity. Similarly, in the realm of lightweight aggregate concrete, it is well-established that thermal conductivity generally decreases as porosity increases [47].

The investigation into thermal conductivity values in geopolymer mortars with partial replacement of POC fine aggregate by SFM revealed notable insights. In Figure 14a, the thermal conductivity values ranged from 0.34 W/m-K (2-M6A8W7) to 0.39 W/m-K (2-A8W7). Similarly, in Figure 14b, values ranged from 0.26 W/m-K (3-M4A6W7) to 0.33 W/m-K (3-A6W7), while in Figure 14c, they varied from 0.28 W/m-K (3-M6A8W7) to 0.44 W/m-K (3-A8W7). These findings offer valuable insights into the thermal behavior of geopolymer mortars under different conditions. To contextualize these results, it is informative to compare them with those reported by Liu et al. [48] for fly ash-based geopolymers with oil palm shell aggregate. The thermal conductivity values obtained in this study are comparable to those reported by Liu et al. [48] ranging from 0.47 to 0.58 W/m-K. This suggests that the utilization of SFM as a partial replacement for POC fine aggregate has a discernible impact on the thermal conductivity of geopolymer mortars.

3.5 Relationships between thermal conductivity and bulk density

Comparing the thermal conductivity of geopolymer mortars containing SFM to those without SFM reveals the potential of SFM as a material for enhancing energy efficiency in building applications. This comparison is pivotal in understanding the impact of SFM on the thermal properties of geopolymer mortars, contributing to the development of more sustainable building materials. In Figure 15, the relationship between thermal conductivity and bulk density is depicted, demonstrating a strong correlation between these two parameters. It is noteworthy that the samples exhibited a linear relationship between bulk density and thermal conductivity, indicating the influence of material density on heat transfer characteristics. This finding aligns with research by Akçaözoğlu et al. [49], who attributed low bulk density in samples to high content of waste plastic (such as PET) in the geopolymer matrix, consequently reducing the rate of heat transfer through the specimen. Furthermore, it is essential to recognize that thermal conductivity and bulk density are closely related to compressive strength [45, 49, 50]. The observed decrease in thermal conductivity and bulk density with a reduction in compressive strength underscores the intricate interplay between these properties in geopolymer materials. These characteristics, coupled with the material's ability to be cast into various shapes, position lightweight geopolymers as highly suitable materials for use in building blocks, offering both thermal efficiency and structural integrity.

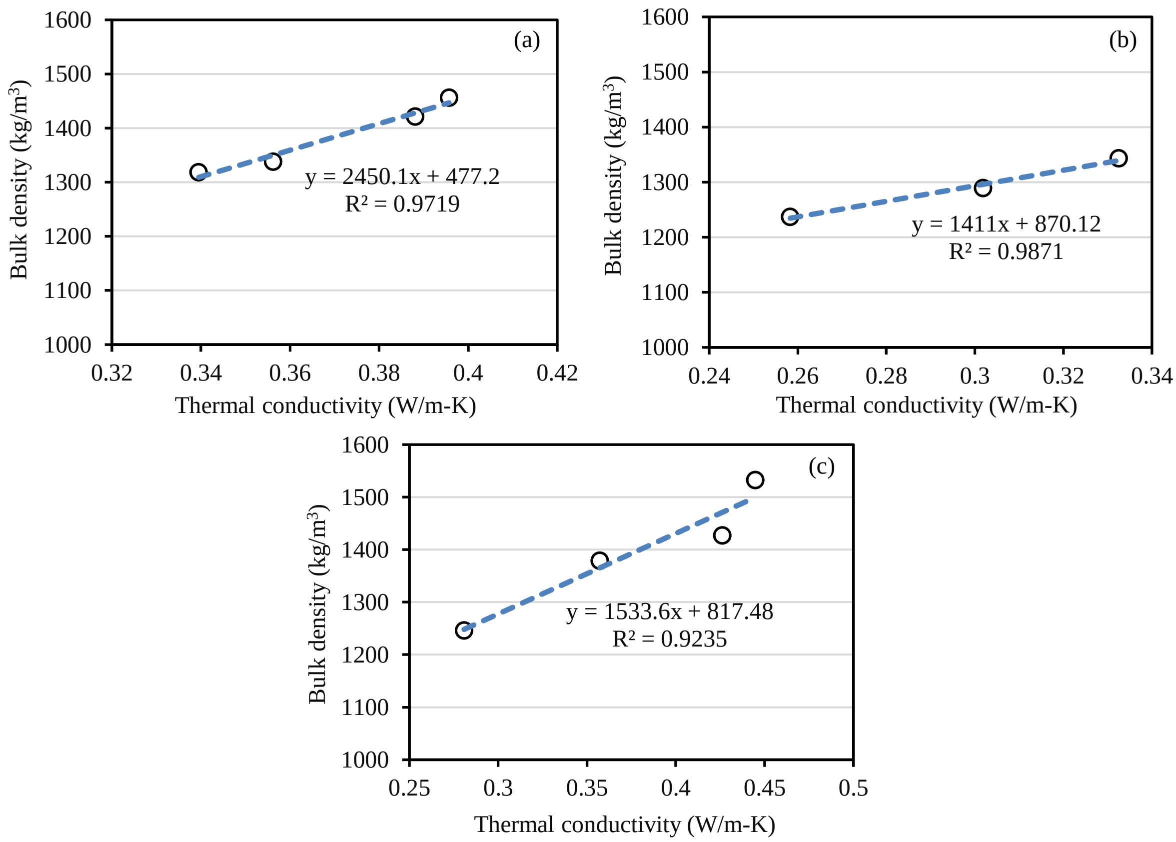

Figure 15 Relationship of bulk density and thermal conductivity: (a) POC=2.75, AK=0.8, W/B=0.7, (b) POC=3.0, AK=0.6, W/B=0.7, and (c) POC=3.0, AK=0.8, W/B=0.7

3.6 Thermal properties of blocks

The thermal insulation performance of concrete blocks was tested using samples of the same size as those available commercially, measuring 7 × 19 × 39 cm with three air cavities. The results of these tests are illustrated in Figure 16. Observing the temperature distribution curve of commercial blocks and geopolymer blocks, shown in Figure 16a, it was evident that upon applying heat to the block surface at T1 (the side exposed to the heat source), there was a rapid temperature increase during the first hour. This increase slowed down gradually over the subsequent two hours. This behavior indicates that both commercial blocks and geopolymer blocks accumulate heat right from the first hour of exposure.

When analyzing the temperature difference between the heated surface (T1) and the opposing surface (T3) of the block, it was found that commercial blocks displayed a narrower temperature range compared to geopolymer blocks incorporating palm oil clinker aggregate. This finding highlights that palm oil clinker aggregate, characterized by its numerous pores, significantly enhances thermal insulation compared to traditional blocks, which utilize dense crushed stone aggregate which lacks pores and consequently allows heat to transfer more readily. Studies conducted by Singh et al. [51] have shown that increasing pore volume within a sample reduces its thermal conductivity.

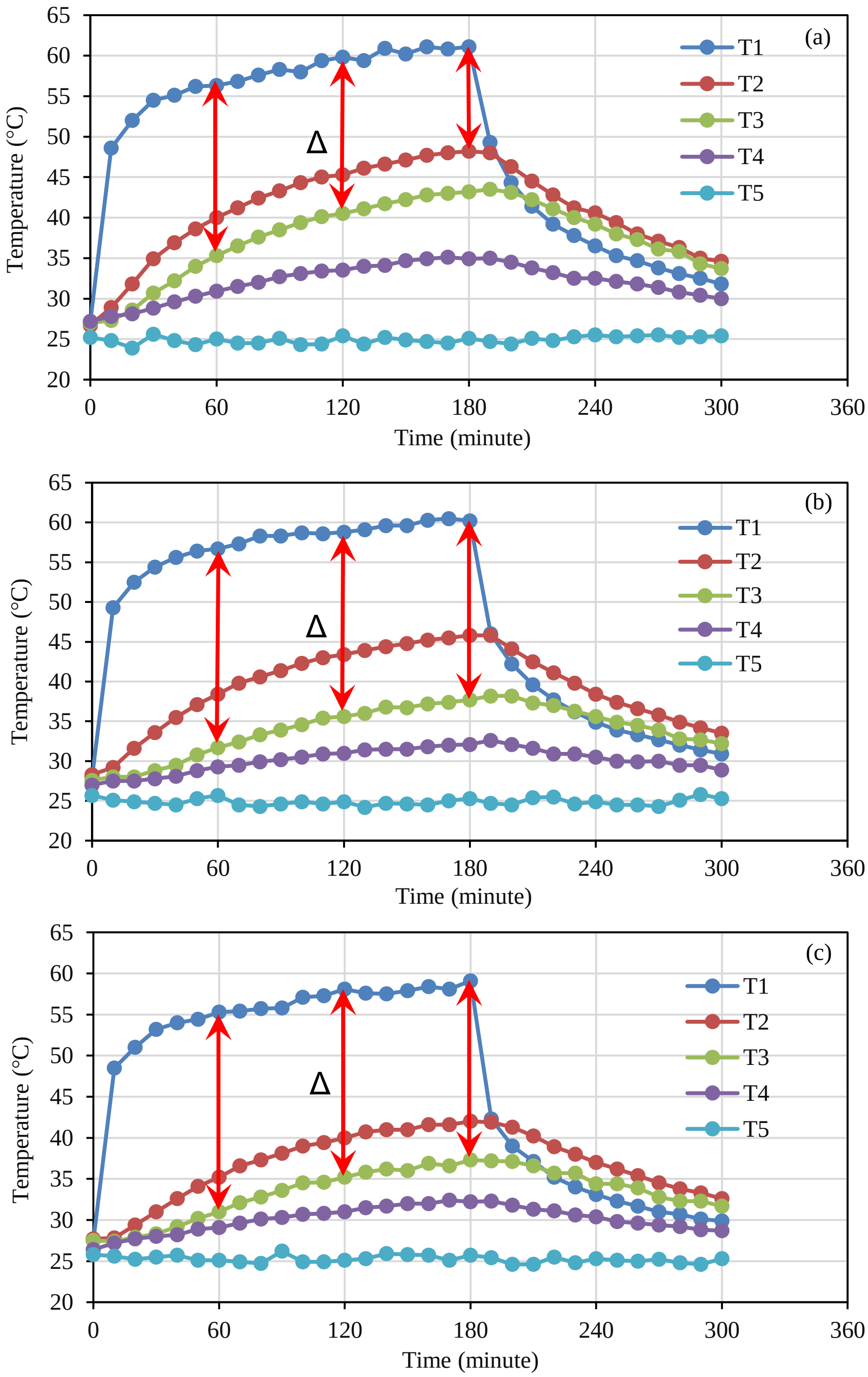

Figure 16 Temperature distribution curves of blocks: (a) commercial block, (b) 3-A8W7 block, and (c) 3-M2A8W7 block

Figure 17 provides a comparative analysis of the thermal insulation properties between commercial blocks and geopolymer blocks incorporating palm oil clinker aggregate. In traditional blocks, after approximately 100 minutes of heat exposure, the reduction in the percentage of heat at the heated surface (T1) relative to the opposite surface (T3) suggests that commercial blocks have notably inferior thermal insulation performance compared to geopolymer blocks containing palm oil clinker aggregate. Interestingly, when comparing the performance within geopolymer blocks made with palm oil clinker aggregate, it was observed that the addition of surgical face mask material slightly enhanced the thermal insulation properties. This study thus highlights that the high porosity of palm oil clinker aggregate plays a substantial role in enhancing thermal insulation, whereas the addition of surgical face mask material has only a minimal effect.

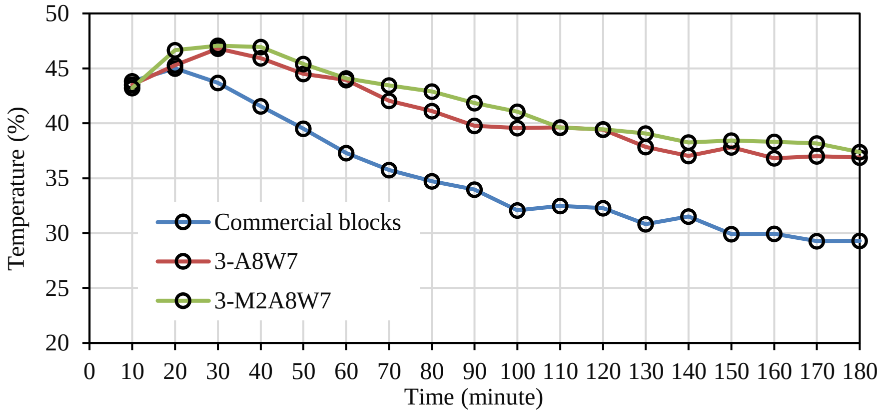

Figure 17 Comparison of the temperature of blocks at positions T1 and T3

Geopolymer mortar incorporating used surgical face masks, made from non-biodegradable polypropylene, offers a sustainable waste management solution by reducing landfill waste and lowering the demand for virgin materials. This innovative approach addresses the surge in mask disposal caused by the COVID-19 pandemic while significantly reducing the carbon footprint compared to traditional cement-based mortar. Studies indicate that adding masks can enhance properties such as thermal performance. Furthermore, geopolymer mortars are environmentally friendly at the end of their life cycle, as they do not release significant greenhouse gases or toxic substances during demolition. By stabilizing plastic waste within the mortar, the risk of microplastic pollution is also minimized. However, a comprehensive life cycle analysis is necessary to fully assess the environmental and technical trade-offs of this solution.

3.7 SEM images

The microstructure of geopolymer samples was analyzed using SEM to assess the impact of SFM content, as depicted in Figure 18. The sample containing 2% SFM (3-M2A8W7) exhibited a non-homogeneous structure with small pores. Unlike the geopolymer without SFM (3-A8W7), which showed a lower presence of unreacted raw materials, the sample with 2% SFM had many flakes. The presence of SFM fibers in the matrix led to a porous structure, likely contributing to the decline in compressive strength of the fiber-reinforced geopolymer mortars, as evident in Figure 18d. Additionally, there was no adhesion between geopolymer paste and SFMs in geopolymers containing SFM, attributable to the smooth surface of the fibers. This lack of adhesion resulted in a non-homogeneous geopolymer matrix, further affecting compressive strength. The high water absorption of SFMs might inhibit the growth of geopolymerization products, as SFMs absorb water in the geopolymer matrix, resulting in a suboptimal reaction. Win et al. [32] reported that an increase in SFMs leads to higher water absorption and a reduction in compressive strength.

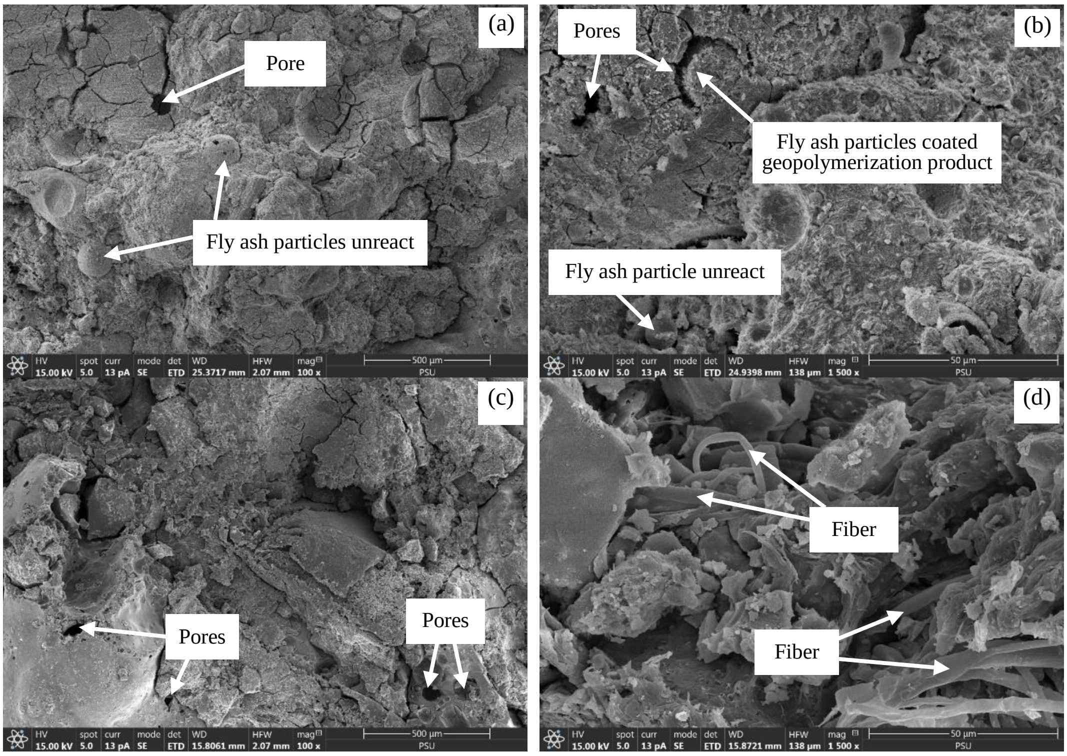

Figure 18 SEM images of geopolymer mortars: (a) 100x 3-A8W7 (b) 1500x 3-A8W7 (c) 100x 3-M2A8W7 and (d) 1500x 3-M2A8W7

4. Conclusions

This preliminary research focuses on the incorporation of SFMs in geopolymer mortars. It presents a series of tests to investigate the effects of SFMs with partial replacement in POC on the mechanical properties, thermal conductivity, and microstructure of geopolymer mortars. The experiments led to the following conclusions:

- In the series of geopolymer mortar samples incorporating SFM, the mixture with SFM 2% demonstrated the highest compressive strength, reaching 67.3 ksc. This maximum strength was observed at the mixing ratio of 3-M2A8W7.
- In summary, the density of geopolymer mortar at 28 days lay within the range of 1,233 to 1,533 kg/m^3. The geopolymer mortar had a low bulk density of 1,427 kg/m^3 with a compressive strength of 67.3 ksc (3-M2A8W7). The mixture provided the highest compressive strength with the use of SFM content.
- Water absorption increased with an increase in SFM in the geopolymer matrix. The water absorption values of geopolymer mortars using an FA to POC ratio of 3 were higher than those of geopolymer mortars using an FA to POC ratio of 2.75 by weight, when immersed in water for 24 h, which had water absorption ranging from 25-40%. This was observed when the samples had higher alkali activators (0.8).
- The thermal conductivity of geopolymer mortars decreased with increasing SFM content, with 3-M2A8W7 (0.43 W/m-K) showing a 2.3% reduction and 3-M6A8W7 (0.28 W/m-K) a 36.7% reduction compared to samples without SFM. However, mortars with 6% SFM are unsuitable for thermal block applications due to insufficient compressive strength.
- The thermal resistance of samples 3-A8W7 and 3-M2A8W7 at 180 minutes demonstrates superior performance compared to conventional concrete blocks, with improvements of 7.6% and 8.1%, respectively.

The test results on geopolymer mortars incorporating palm oil clinker aggregate and surgical face masks reveal that although the compressive strength is not particularly high, the material possesses a low density and excellent thermal insulation properties. Notably, the aggregate comprises entirely waste materials, such as palm oil clinker from biomass power plants and used surgical face masks. Utilizing these waste materials not only enhances the thermal performance of the mortar but also contributes significantly to waste reduction by recycling materials that would otherwise be discarded.

This study explored the partial replacement of palm oil clinker aggregate with face masks, cut into dimensions of 5 × 5 cm. The high water absorption of both materials posed challenges during the mixing process. Consequently, the geopolymer mortar exhibited a dry consistency, leading to reduced compressive strength. Additionally, the inclusion of large quantities of face masks had a pronounced negative impact on compressive strength. This effect can be attributed to the lightweight nature of face masks, which results in a substantial volumetric proportion within the mixture. Future investigations should focus on minimizing the quantity of face masks used and reducing their size to enhance compatibility and performance in the composite material.

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6. References

[1] Transparency Market Research. Concrete Block and Brick Manufacturing market [Internet]. 2024 [cited 2024 Aug 15]. Available from: https://www.transparencymarketresearch.com/concrete-block-brick-manufacturing.html.

[2] Arunkumar K, Muthukannan M, Suresh Kumar A, Chithambar Ganesh A, Kanniga Devi R. Hybrid fibre reinforced eco-friendly geopolymer concrete made with waste wood ash: A mechanical characterization study. Eng Appl Sci Res. 2022;49(2):235-47.

[3] Somna R, Saowapun T, Somna K, Chindaprasirt P. Rice husk ash and fly ash geopolymer hollow block based on NaOH activated. Case Stud Constr Mater. 2022;16:e01092.

[4] Mahdi SN, Babu R DV, Hossiney N, Abdulla MMAB. Strength and durability properties of geopolymer paver blocks made with fly ash and brick kiln rice husk ash. Case Stud Constr Mater. 2022;16:e00800.

[5] Hamcumpai K, Nuaklong P, Chindasiriphan P, Jongvivatsakul P, Tangaramvong S, Di Sarno L, et al. High-strength steel fibre-reinforced geopolymer concrete utilising recycled granite waste and rice husk ash. Constr Build Mater. 2024;433:136693.

[6] Klemeš JJ, Fan YV, Tan RR, Jiang P. Minimising the present and future plastic waste, energy and environmental footprints related to COVID-19. Renew Sustain Energy Rev. 2020;127:109883.

[7] Saberian M, Li J, Kilmartin-Lynch S, Boroujeni M. Repurposing of COVID-19 single-use face masks for pavements base/subbase. Sci Total Environ. 2021;769:145527.

[8] Benson NU, Bassey DE, Palanisami T. COVID pollution: impact of COVID-19 pandemic on global plastic waste footprint. Heliyon. 2021;7(2):e06343.

[9] Dhawan R, Bisht BMS, Kumar R, Kumari S, Dhawan SK. Recycling of plastic waste into tiles with reduced flammability and improved tensile strength. Process Saf Environ Prot. 2019;124:299-307.

[10] Lei B, Li W, Tang Z, Tam VWY, Sun Z. Durability of recycled aggregate concrete under coupling mechanical loading and freeze-thaw cycle in salt-solution. Constr Build Mater. 2018;163:840-9.

[11] Iqbal HW, Hamcumpai K, Nuaklong P, Jongvivatsakul P, Likitlersuang S, Pothisiri T, et al. Enhancing fire resistance in geopolymer concrete containing crumb rubber with graphene nanoplatelets. Constr Build Mater. 2024;426:136115.

[12] Haruna S, Jongvivatsakul P, Hamcumpai K, Iqbal HW, Nuaklong P, Likitlersuang S, et al. Multiscale investigation of the impact of recycled plastic aggregate as a fine aggregate replacement on one-part alkali-activated mortar performance. J Build Eng. 2024;86:108768.

[13] Haruna S, Jongvivatsakul P, Kunamisarut A, Iwanami M, Likitlersuang S. Optimizing mechanical properties of one-part alkali-activated mortar with recycled plastic and graphene nanoplatelets using response surface methodology. Constr Build Mater. 2024;450:138701.

[14] Chindasiriphan P, Meenyut B, Orasutthikul S, Jongvivatsakul P, Tangchirapat W. Influences of high-volume coal bottom ash as cement and fine aggregate replacements on strength and heat evolution of eco-friendly high-strength concrete. J Build Eng. 2023;65:105791.

[15] Tabsh SW, Abdelfatah AS. Influence of recycled concrete aggregates on strength properties of concrete. Constr Build Mater. 2009;23(2):1163-7.
[16] Pizoń J, Gołaszewski J, Alwaeli M, Szwan P. Properties of concrete with recycled concrete aggregate containing metallurgical sludge waste. Materials. 2020;13(6):1448.
[17] Kumar G, Mishra SS. Effect of recycled concrete aggregate on mechanical, physical and durability properties of GGBS–fly ash-based geopolymer concrete. Innov Infrastruct Solut. 2022;7:237.
[18] Hassan KE, Brooks JJ, Erdman M. The use of reclaimed asphalt pavement (RAP) aggregates in concrete. Waste Manag Ser. 2000;1:121-8.
[19] Rahman SS, Khattak MJ. Feasibility of reclaimed asphalt pavement geopolymer concrete as a pavement construction material. Int J Pavement Res Technol. 2023;16:888-907.
[20] Linek M, Bacharz M, Piotrowska P. Surface cement concrete with reclaimed asphalt. Materials. 2023;16(7):2791.
[21] Kupaei RH, Alengaram UJ, Jumaat MZB, Nikraz H. Mix design for fly ash based oil palm shell geopolymer lightweight concrete. Constr Build Mater. 2013;43:490-6.
[22] Maghfouri M, Shafigh P, Aslam M. Optimum oil palm shell content as coarse aggregate in concrete based on mechanical and durability properties. Adv Mater Sci Eng. 2018;2018(1):4271497.
[23] Azunna SU. Compressive strength of concrete with palm kernel shell as a partial replacement for coarse aggregate. SN Appl Sci. 2019;1:342.
[24] Hawa A. Strength and microstructural of geopolymer mortar from palm oil ash containing alumina powder with palm oil clinker aggregate. Eng Appl Sci Res. 2022;49(6):731-43.
[25] Hamada HM, Al-Attar AA, Tayeh B, Yahaya FBM. Optimizing the concrete strength of lightweight concrete containing nano palm oil fuel ash and palm oil clinker using response surface method. Case Stud Constr Mater. 2022;16:e01061.
[26] Hawa A, Salaemae P, Abdulmatin A, Ongwuttiwat K, Prachasaree W. Properties of palm oil ash geopolymer containing alumina powder and field Para rubber latex. Civ Eng J. 2023;9(5):1271-88.
[27] Darvish P, Alengaram UJ, Poh YS, Ibrahim S, Yusoff S. Performance evaluation of palm oil clinkersand as replacement for conventional sand in geopolymer mortar. Constr Build Mater. 2020;258:120352.
[28] Salari F, Alengaram UJ, Alnahhal AM, Ibrahim ZB, Yusoff S, Ibrahim MSI, et al. Promulgation of sustainable palm oil clinker sand in the development of structural and non-structural lightweight foamed concrete. Struct Concr. 2023;24(3):3952-68.
[29] Thoudam K, Hossiney, N, Kumar SL, Aex J, Bhalkikar A, Fathima A. Assessing performance of alkali-activated bricks incorporated with processed surgical masks. J Mater Res Technol. 2023;25:6432-45.
[30] Kilmartin-Lynch S, Saberian M, Li J, Roychand R, Zhang G. Preliminary evaluation of the feasibility of using polypropylene fibers from COVID-19 single-use face masks to improve the mechanical properties of concrete. J Clean Prod. 2021;296:126460.
[31] Durmus G, Çelik DN, Demircan RK, Kaplan G. Effect of waste COVID-19 face masks on self-compacting high-strength mortars exposed to elevated temperature. Ain Shams Eng J. 2023;14(8):102058.
[32] Win TT, Jongvivatsakul P, Jirawattanasomkul T, Prasittisopin L, Likitlersuang S. Use of polypropylene fibers extracted from recycled surgical face masks in cement mortar. Constr Build Mater. 2023;391:131845.
[33] ASTM. ASTM C618-22: standard specification for coal fly ash and raw or calcined natural Pozzolan for use in concrete. West Conshohocken: ASTM International; 2022.
[34] Faculty of Medicine Ramathibodi Hospital, Mahidol University. Disinfection of N95 masks and surgical masks with HEAT and UV-C [Internet]. 2020 [cited 2024 Aug 15]. Available from: https://www.rama.mahidol.ac.th/ramacloud/s/yQRm3wl WmKFZKJX. (In Thai)
[35] Xiang Y, Song Q, Gu W. Decontamination of surgical face masks and N95 respirators by dry heat pasteurization for one hour at 70°C. Am J Infect Control. 2020;48(8):880-2.
[36] ASTM. ASTM C109/C109M-16a: standard test method for compressive strength of hydraulic cement mortars (using 2-in. or [50-mm] cube specimens). West Conshohocken: ASTM International; 2016.
[37] Bellum RR. Influence of steel and PP fibers on mechanical and microstructural properties of fly ash-GGBFS based geopolymer composites. Ceram Int. 2022;48(5):6808-18.
[38] Amin F, Javed MF, Ahmad I, Asad O, Khan N, Khan AB, et al. Utilization of discarded face masks in combination with recycled concrete aggregate and silica fume for sustainable civil construction projects. Sci Rep. 2024;14:449.
[39] Miah MJ, Pei J, Kim H, Sharma R, Jang JG, Ahn J. Property assessment of an eco-friendly mortar reinforced with recycled mask fiber derived from COVID-19 single-use face masks. J Build Eng. 2023;66:105885.
[40] Saeli M, Senff L, Tobaldi DM, Seabra MP, Labrincha JA. Novel biomass fly ash-based geopolymeric mortars using lime slaker grits as aggregate for applications in construction: influence of granulometry and binder/aggregate ratio. Constr Build Mater. 2019;227:116643.
[41] Ahmmad R, Alengaram UJ, Jumaat MZ, Sulong NHR, Yusuf MO, Rehman MA. Feasibility study on the use of high volume palm oil clinker waste in environmental friendly lightweight concrete. Constr Build Mater. 2017;135:94-103.
[42] Abutaha F, Razak HA, Ibrahim HA. Effect of coating palm oil clinker aggregate on the engineering properties of normal grade concrete. Coatings. 2017;7(10):175.
[43] Lee KP, Yip J, Kan CW, Chiou JC, Yung KF. Reusable face masks as alternative for disposable medical masks: factors that affect their wear-comfort. Int J Environ Res Public Health. 2020;17(18):6623.
[44] Ng SC, Low KS. Thermal conductivity of newspaper sandwiched aerated lightweight concrete panel. Energy Build. 2010;42(12):2452-6.
[45] Sengul O, Azizi S, Karaosmanoglu F, Tasdemir MA. Effect of expanded perlite on the mechanical properties and thermal conductivity of lightweight concrete. Energy Build. 2011;43(2-3):671-6.
[46] Saygili A, Baykal G. A new method for improving the thermal insulation properties of fly ash. Energy Build. 2011;43(11):3236-42.
[47] Khusshefari WH, Demirboğa R, Farhan KZ. Assessment of factors impacting thermal conductivity of cementitious composites—a review. Clean Mater. 2022;5:100127.
[48] Liu MYJ, Alengaram UJ, Juaat MZ, Mo KH. Evaluation of thermal conductivity, mechanical and transport properties of lightweight aggregate foamed geopolymer concrete. Energy Build. 2014;72:238-45.

[49] Akçaözoğlu S, Akçaözoğlu K, Atiş CD. Thermal conductivity, compressive strength and ultrasonic wave velocity of cementitious composite containing waste PET lightweight aggregate (WPLA). Comp B Eng. 2013;45(1):721-6.
[50] Albayrak M, Yörükoğlu A, Karahan S, Atlıhan S, Yılmaz Aruntaş H, Girgin I. Influence of zeolite additive on properties of autoclaved aerated concrete. Build Environ. 2007;42(9):3161-5.
[51] Singh RJ, Raut A, Murmu AL, Jameel M. Influence of glass powder incorporated foamed geopolymer blocks on thermal and energy analysis of building envelope. J Build Eng. 2021;43:102520.