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SUSTAINABLE MORTAR INCORPORATING MUNICIPAL SOLID WASTE INCINERATION FLY ASH AND BOTTOM ASH

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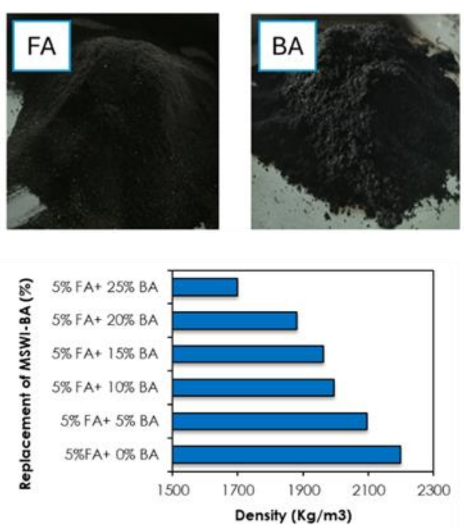
Graphical abstract



Abstract

The Pulau Pangkor plant is one of five small-scale incinerators in different locations in Malaysia. Due to the influence of waste components on the physical and chemical properties of resulting municipal solid waste incineration ash, fly ash (MSWI-FA) and bottom ash (MSWI-BA), the ash of each plant needs to be studied separately. Therefore, this study aims to investigate the effect of using Pulau Pangkor MSWI-FA as a supplementary cementitious material and MSWI-BA as a partial replacement for fine aggregate on mortar performance. Several experiments were conducted to evaluate the material properties, as well as the properties of fresh and hardened mortars, using 5-20% MSWI-FA and 5-25% MSWI-BA replacement ratios. The inclusion of MSWI-FA increased mortar flow by up to 16%, whereas the addition of 25% MSWI-BA reduced flow by up to 76% relative to the control mix. Replacing cement with MSWI-FA reduced compressive strength by 6%–26% across the range of replacement levels, due to MSWI-FA's lack of pozzolanic properties. The results also indicated that lower ash density significantly reduced the resulting mortar density by up to 23%. The higher water absorption of MSWIA also increased the mortar's absorbency; the effect of MSWI-BA was higher. In conclusion, this work provides important insights into the future applications of MSWIA in contexts requiring lightweight, highly absorbent additives with low compressive strength.

Keywords: Construction materials, MSWI, bottom ash, fly ash, water absorption, compressive strength

1.0 INTRODUCTION

The construction industry substantially contributes to global warming and resource depletion [1]. Approximately 40-50% of the worldwide greenhouse gas emissions originate from these operations [2]. With increased economic growth, the need for construction and urbanization increased, potentially boosting global cement demand by about 12–23% above 2020 levels by 2050 [3]. In addition, the exhaustion of natural resources and the high cost of the mining process, especially the aggregate usually obtained by riverbeds of the local river, thus becoming the global trend towards searching for alternative materials [4].
Along with the accelerated urbanization process and the improvement of living standards of the population, modern society, which is dominated by consumption, produces large amounts of different types of waste every year, especially municipal solid waste [5], [6]. To protect the environment, numerous initiatives are being implemented to recycle these types of solid waste and utilize them to produce sustainable construction materials [7], [8]. Most industrialized nations are increasingly turning to incineration as a waste treatment technology due to its ability to significantly reduce the initial waste's volume and bulk [9], [10]. For instance, five small-scale rotary kiln incinerators were built at five popular tourist destinations in Malaysia: Pulau Langkawi, Cameron Highlands, Pulau Labuan, Pulau Pangkor, and Pulau Tioman [11]. From the incineration work, two types of MSWIA are generated, which are MSWI-BA and MSWI-FA. To dispose of this waste ash, many researchers have conducted studies on using MSWI-FA as a

cement substitute, and MSWI-BA as a substitute for fine aggregates.

After the MSW has been burned out, MSWI-BA is discharged from the bottom of the combustion process, accounting for approximately 80% of the MSW by quantity [12]. The second by-product of incineration is MSWI-FA, which is recovered through emissions control equipment. It accounts for about 5-20% of the overall amount of burned waste [13]. The utilization of these by-products and waste in building applications is an intriguing option for the industry.

Many investigations looked at the characteristics of mixtures made with a specified quantity of MSWIA [14], [15]. According to Lv et al. [16], using MSWI-FA was led to improve the concrete pore structure and compressive strength. Lu et al. [17] discovered that MSWI-BA may serve as a partial substitute for fine particles in concrete, resulting in enhanced compressive strength. Another study by Joseph et al. [18] indicated that MSWI-BA is usually considered a non-hazardous material. As a result, it is viable to utilize it in a variety of applications, such as road base material. These alternative materials are additives that contribute to making building mixtures more environmentally friendly.

On the other hand, the supply of MSWI-FA, an important supplementary cement material (SCMs) used, has been curtailed as a result of the shutdown of thermal power plants. This prompts researchers to continue extensive research for using MSWI-FA as SCMs. The physical and chemical properties of MSWIA cannot be stabilized since they are dependent on a variety of parameters .However, very few studies have combined the effects of MSWI-FA and MSWI-BA on the engineering properties of mortar. Therefore, this study aims to investigate the chemical and physical characterization of MSW-FA and MSWI-BA, as well as the fresh and mechanical properties of the mortar containing MSWIA. Thus, the use of MSWIA as an alternative to cement and fine aggregates in the mortar and concrete industry contributes to their proper disposal and maintains the sustainability of natural resources.

2.0 METHODOLOGY

MSWI-FA and MSWI-BA were collected from Pulau Pangkor, Malaysia, as seen in Figure 1. Ordinary Portland Cement (OPC) corresponding to ASTM C150 Type I from a single source was used throughout the experimental work. As a fine aggregate, natural river sand having particles smaller than 4.75 mm was used.

The collected MSWI-FA was used in its raw condition, while MSWI-BA and sand were prepared in a saturated surface-dry (SSD) condition to maintain the integrity of the water-cement ratio. Tap water was utilized in research for mixing, thereby curing, and for other applications.

The present study calculated mortar mix ratios based on the volume of the components due to the low bulk density of MSWI-FA and MSWI-BA. The ratio of cement to fine aggregates in all mortar mix designs was 1:3. A constant water-binder ratio of 0.6 was used for all mixes. A cube size (50 x 50 x 50 mm) was used to create the mortar specimens (Figure 2, a).

In the first stage, MSWI-FA was used to replace cement at 5%, 10%, 15%, and 20%. The replacement ratio that produced the highest compressive strength (5% MSWI-FA) was selected for the second stage. In this stage, MSWI-BA replaced sand at 5%, 10%, 15%, 20%, and 25%, while keeping the MSWI-FA content at 5%. To streamline the presentation of the results and discussion, each combination is designated with the following identifiers: (BA=MSWI-BA), (FA=MSWI-FA). The mix proportions for all mortar mixtures are presented in Table 1.

Fresh mortar workability was evaluated using the ASTM C1437 flow table test. For hardened properties, the compressive strength test was performed in accordance with ASTM C109. Figure 2,c shows the compressive strength testing machine. The hard density test was calculated by utilizing a measuring scale to determine the weight of the cube (Figure 2,b). Meanwhile, the Ultrasonic pulse velocity (UPV) was measured according to ASTM C597 to assess internal quality. Figure 2,d depicts the UPV test on mortar as well as the testing equipment. The water absorption test was carried out in accordance with BS 1881: Part 122 (2011). The average of three specimens was used as the test result for each replacement level. All mortar specimens were water-cured at 20 ± 2 °C until the designated testing ages.

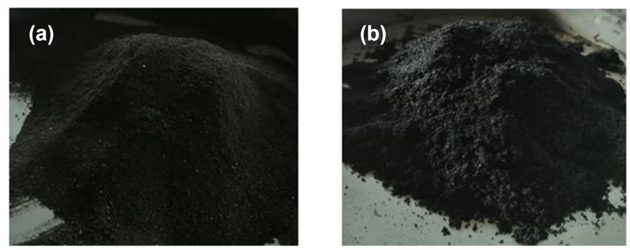


Figure 1 Samples of (a) MSWI-FA and (b) MSWI-BA

Table 1 The designs mix proportion for trial mix and design mix (kg per cubic meter of mortar)

Specimens ID	OPC	MSWI-FA	Sand	MSWI-BA	Water
OPC	500	0	1500	0	300
5FA	475	13	1500	0	300
10FA	450	27	1500	0	300
15FA	425	40	1500	0	300
20FA	400	54	1500	0	300
5FA+5BA	475	13	1425	29	300
5FA+10BA	475	13	1350	58	300
5FA+15BA	475	13	1275	87	300
5FA+20BA	475	13	1200	116	300
5FA+25BA	475	13	1125	145	300

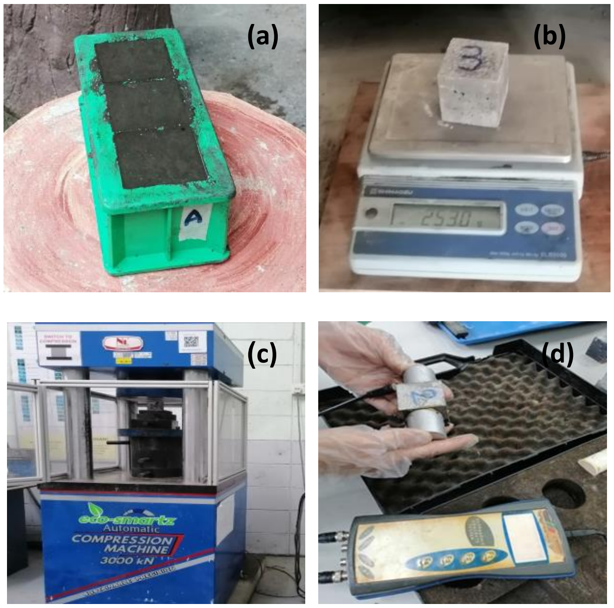


Figure 2 (a) Casted specimens, (b) Measuring scale, (c) Compressive strength machine, (d) UPV equipment

3.0 RESULTS AND DISCUSSION

3.1 Materials Characterization

Figure 3 shows that the grading curve of MSWI-BA falls outside the standard limit, indicating a coarser particle distribution compared to natural sand.

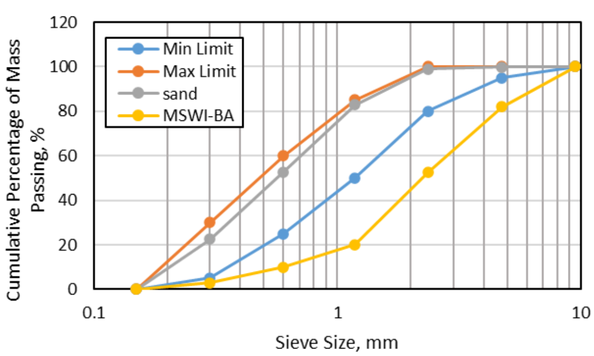


Figure 3 Grading of sand and MSWI-BA

Table 2 shows the physical properties of OPC, sand, and MSWIA. The table indicates that the densities of MSWI-FA and MSWI-BA were lower than those of OPC and sand. Therefore, adding them reduced the density of the mortar. There was a 75% passage rate for MSWI-FA via a 45 µm wet sieve. This value is acceptable because it is more than the permissible limit, which is ≥ 34%, as satisfied by ASTM C618. The 7-day strength activity index of MSWI-FA was 59%. While it was 63% for 28 days. The values are not acceptable because they are below the allowable limits of 75% based on ASTM C311. Hence, MSWI-FA does not exhibit sufficient pozzolanic activity and primarily functions as a filler in the mortar mix. Besides, the water absorption of MSWI-BA (31.7%) was considerably higher than that of natural sand (2.9%). It can be attributed to its highly porous microstructure, the presence of unburnt organic residues, and the irregular and cracked particle surfaces formed during the incineration process; these characteristics increase the internal pore volume and surface area, leading to substantially greater water retention.

The chemical composition has been examined using X-ray Fluorescence (XRF), as presented in Table 3. The total proportion of silica, aluminium, and iron was less than 70% and, therefore, could not be classified as pozzolan as stated in ASTM C618.

Table 2 The physical characterizations of materials

Properties	OPC	MSWI-FA	Sand	MSWI-BA
Colour	Grey	Black	Yellow	Black
Bulk density (kg/m^3)	920	496	1320	512
% Passing through 45 µm wet sieve	98	75	-	-
Strength activity index : 7 days (%)	100	61	-	-
28 days (%)	100	65	-	-
Water absorption at 24 hours (%)	-	-	2.9	31.7

Table 3 The chemical characterizations of materials

Parameters	OPC (%)	MSWI-FA (%)
Calcium, CaO	68.3	45.3
Silica, SiO_2	16.4	8.5
Aluminum, Al_2O_3	4.2	4.5
Iron, Fe_2O_3	3.5	3.2
Potassium, K_2O	0.2	3.0
Magnesium, MgO	2.4	2.1
Manganese, MnO	-	0.1
Sulphur, SO_3	4.4	2.5

3.2 Workability

The flowability of the mortar is influenced by the proportions of MSWI-FA and MSWI-BA, as shown in Figures 4 and 5. An increase in MSWI-FA content improves workability because MSWI-FA exhibits lower pozzolanic reactivity than OPC. When a portion of the cement is replaced with MSWI-FA, fewer early hydration reactions occur, resulting in less mixing water being consumed for wetting and hydration. As a result, more free water remains available to lubricate the particles in the mixture, thereby enhancing the mortar's overall flowability. This reduction is attributed to the coarser and more angular morphology of MSWI-BA compared with natural sand, which lowers packing density and increases internal friction during mixing. Consequently, the mortar requires more free water to retain the same consistency, even when MSWI-BA is used in saturated surface-dry (SSD) conditions. As the proportion of

MSWI-BA increases, the mortar becomes progressively stiffer and exhibits lower flowability due to the reduced fine particle content and the mechanical interlocking of the angular MSWI-BA particles. Similar behaviour associated with MSWI-FA and MSWI-BA incorporation was reported by Irshidat et al. [19].

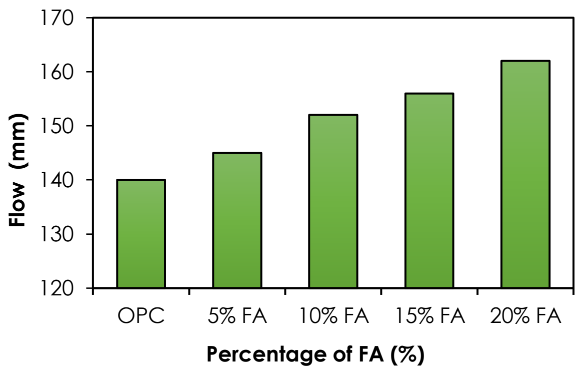


Figure 4 Effect of MSWI-FA addition on flowability

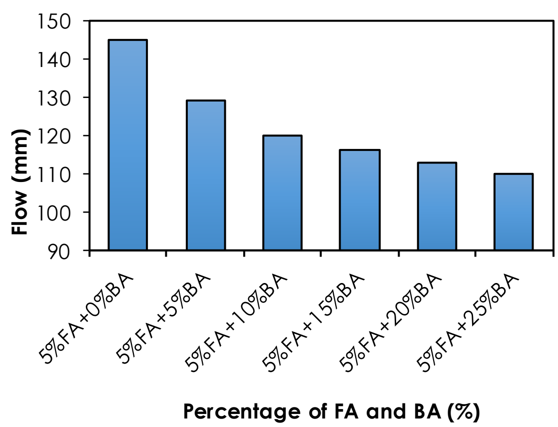


Figure 5 Effect of MSWI-BA addition on flowability

3.3 Density

Mortars containing MSWI-FA have been found to provide a lighter density than OPC mortar (Figure 6). This is due to the low density of MSWI-FA molecules. Thus, the higher the percentage of cement replacement with MSWI-FA, the lighter the resulting mortar. On the other hand, the densities of the mix comprising 5%, 10%, 15%, 20%, and 25% of sand substituted by BA are 2095, 1995, 1961, 1880, and 1700 kg/m³, respectively, which corresponds to 5%, 9%, 11%, 15% and 23% reduction. Densities of mixtures after 28 days of curing are shown in Figure 7. MSWI-BA (512 kg/m³) has a lesser density than sand (1320 kg/m³). Consequently, when MSWI-BA is used as a partial substitute for sand in mortars, the density is expected to decrease as the BA percentages in mixtures rise. Caprai et al. [20] observed a similar phenomenon.

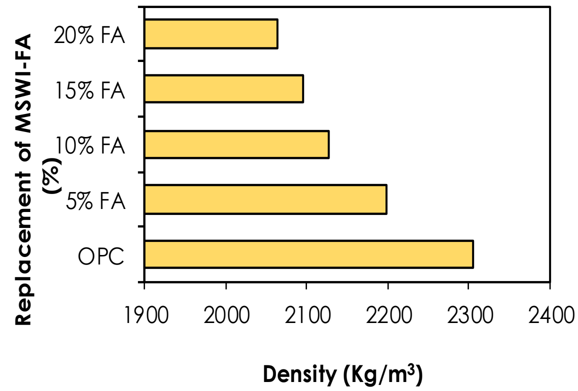


Figure 6 Density of mortar containing MSWI-FA

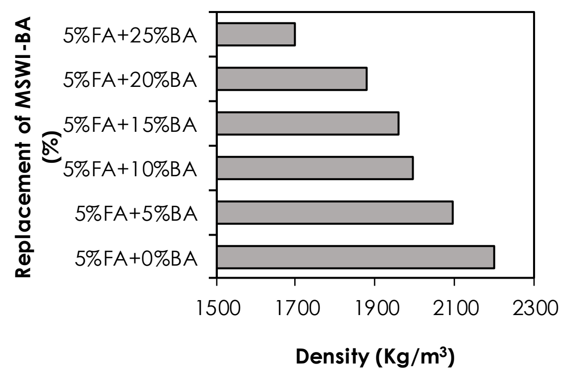


Figure 7 Density of mortar containing MSWI-BA

Meanwhile, this reduction in density correlates with a decline in compressive strength, as the lighter MSWIA particles contribute less to the load-bearing capacity of the mortar [21]. The linear correlation between density and compressive strength of MSWIA mortar can be seen in Figure 8. The coefficient of determination, R^2, was 97.4 %, which shows a good prediction of the relationship.

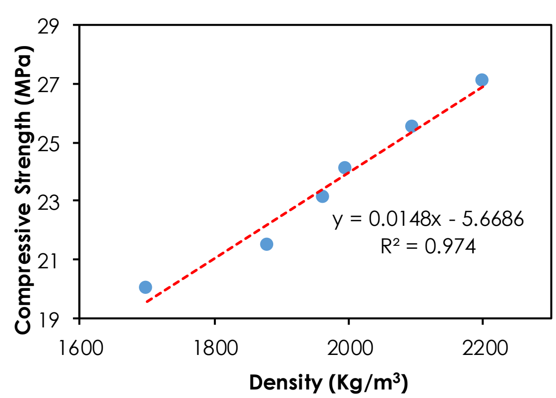


Figure 8 The relationship between density and compressive strength of MSWIA mortar

3.4 Compressive Strength

For the properties of mortar in the hardened state, all mortar samples with MSWI-FA content showed a decrease in compressive strength as more MSWI-FA was added, as shown in Figure 9, consistent with the limited pozzolanic activity indicated by the ash's low strength activity index in Table 2. As cement is progressively replaced by raw MSWI-FA, fewer C–S–H and other hydration products form, leading to a more porous matrix and a weaker interfacial transition zone. Therefore, the mix with 5% MSWI-FA, retaining about 87% of the control compressive strength, can be considered an acceptable compromise between mechanical performance and waste utilization, whereas higher replacement levels result in excessive strength loss. A similar trend has been reported by Li et al. [22], who found that the use of untreated MSWI-FA as a SCM in mortar reduces compressive strength due to its low reactivity and dilution of clinker phases. Ghazalia et al. [23] reported that increasing MSWI-FA content leads to higher total porosity and lower strength in mortar or concrete matrices.

On the other hand, compressive strength generally decreases as MSWI-BA is replaced with sand compared to OPC mortar regardless of the curing period, as stated in Figure 10. Replacing sand with 5%, 10%, 15%, 20%, and 25% MSWI-BA resulted in strength reductions of 6%, 11%, 15%, 21%, and 26%, respectively, which is consistent with the trend reported by Caprai et al. [24]. This reduction can be attributed primarily to the highly porous nature of MSWI-BA. Although MSWI-BA was used in the SSD condition, its internal pore structure still promotes the formation of a less compact mortar matrix and weakens the interfacial transition zone, leading to lower strength development [25]. In addition, MSWI-BA particles are coarse, less dense and more irregular than natural sand, which further increases the number of voids and disrupts particle packing within the matrix. These combined factors reduce compactness and hinder efficient load transfer, ultimately resulting in a noticeable decrease in compressive strength as the MSWI-BA replacement level increases.

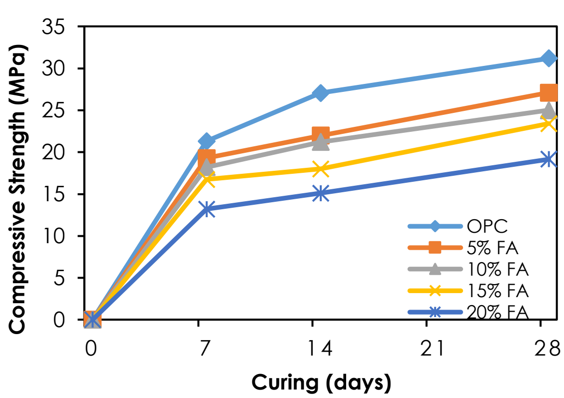


Figure 9 Effect of adding MSWI-FA on compressive strength of OPC mortar

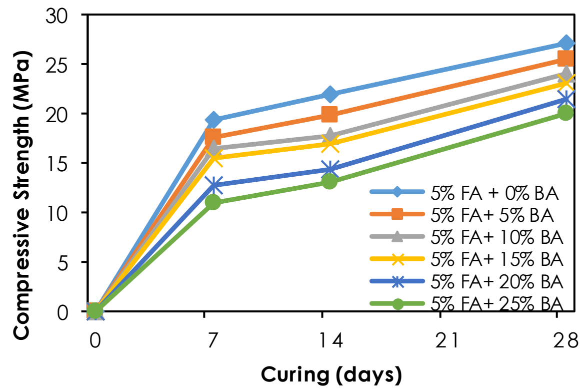


Figure 10 Impact of adding MSWI-BA on the compressive strength of MSWI-FA mortar

3.5 Water Absorption

Figure 11 and Figure 12 show the effect of using MSWIA on mortar water absorption. The mortar's water absorption marginally increased once the cement was replaced with MSWI-FA due to its low pozzolanic activity compared to traditional supplementary cementitious materials. This low reactivity results in fewer hydration products, which are crucial for filling voids; thus, higher water absorption occurs. Furthermore, there is a steady increase in water absorption with MSWI-BA content. The data indicate that water absorption after 7 days significantly exceeded that after 28 days. This occurs because water is required for the curing process. Subsequently, the shape and dimensions of the pores diminish as they get saturated with hydration-calcium silica hydrates. The increase in water absorption percentage with 25% replacement of sand with MSWI-BA was five times compared to MSWI-BA-free mortar due to the rise in MSWI-BA absorption itself, and this was similar to the result observed by Ghanem et al. [24] and Taherlou et al. [26]. However, this could be related to the increased surface area of BA due to the angular molecular form of the MSWI-BA surface, which leads to enhanced water absorption. Additionally, the MSWI-BA utilized in this research was water-absorbent due to its surrounding dust, which has been shown to absorb extra water.

The water absorption value and the compressive strength of MSWIA mortar have a strong linear correlation, as shown in Figure 13. The coefficient of determination (R^2) value of 98.3% showed a good prediction of the relationship. The elevated water absorption capacity of MSWIA mortar necessitated the incorporation of more water to get the requisite workability (the water-to-cement ratio was 0.6). This results in increased porosity after evaporation, in addition to the incomplete pozzolanic reactions, thereby reducing its compressive strength.

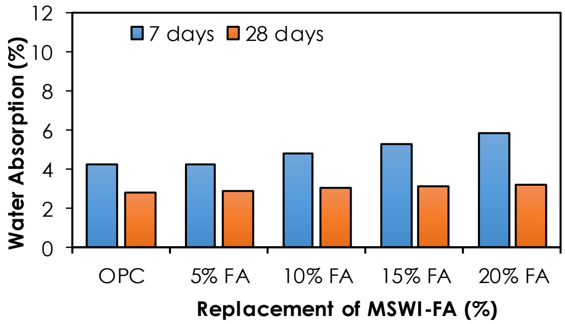


Figure 11 Effect of MSWI-FA on the water absorption of mortar

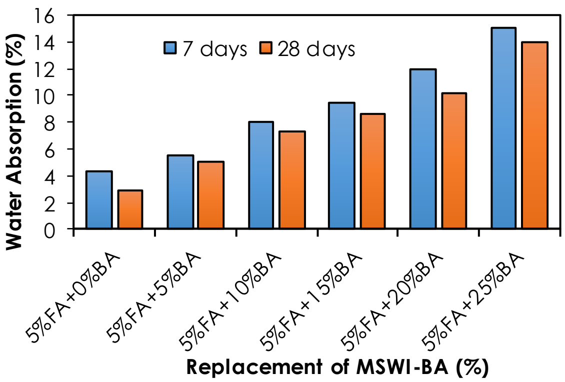


Figure 12 Effect of MSWI-BA on the water absorption of mortar

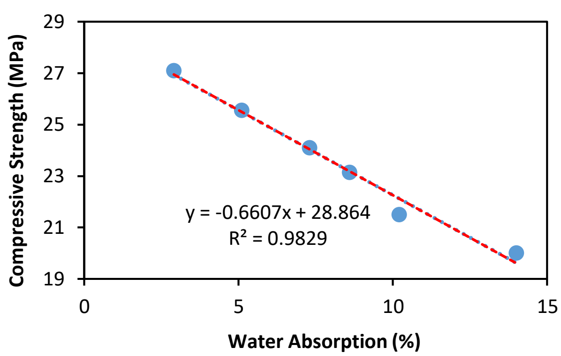


Figure 13 The relationship between water absorption and compressive strength of MSWIA mortar

3.6 UPV

For mortars containing MSWI-FA and MSWI-BA, all UPV values of MSWI-BA's mixtures fall within 3000-3500 m/s. This indicates doubtful mortar quality due to the high MSWI-BA adsorption capacity, which results in void formation that causes lower UPV values. The linear relationship between UPV and compressive strength of mortar was shown in Figure 14. The correlation was determined using cube mortar values of UPV from 3788 m/s to 3020 m/s and the compressive strength from 31.2 MPa to 20.01 MPa, respectively. The coefficient of determination, R^2, was 99.4%, which represents good confidence in the relationship. It was found that the compressive strength of mortar decreased when UPV values decreased.

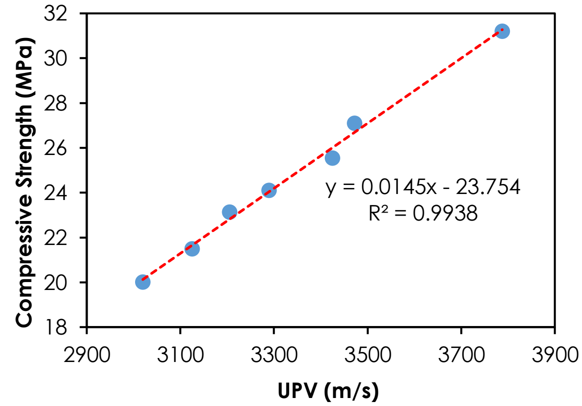


Figure 14 Relationship between UPV and compressive strength of MSWIA mortar

4.0 CONCLUSION

The aim of this study was to evaluate MSWI-FA and MSWI-BA from Pulau Pangkor, Malaysia, as viable components for construction materials. The conclusions are drawn as follows:

1) From the results of physical and chemical properties, this study found limitations in the use of raw MSWI-FA as an OPC substitute due to its low content of pozzolanic components. However, it can be used in small quantities to improve workability. On the other hand, MSWI-BA should be treated before being used in construction owing to its elevated water absorption relative to natural aggregate.
2) In the fresh state of the mortar, the flow rate increased as the proportion of MSWI-FA that was replaced with cement increased. While a clear decrease in the mortar flow rate was observed with increasing MSWI-BA sand replacement ratio. It is suggested to use it in SSD condition or add a superplasticizer as an admixture to increase workability.
3) Replacing 5% MSWI-FA with cement and 5-25% MSWI-BA with sand led to a change in the compressive strength, density, and UPV values of the mortar in an inverse proportion as the replacement ratios increased. While the absorption rates were steadily increasing.

Therefore, this study provides valuable insights into the potential use of MSWIA in situations where lightweight or highly absorbent admixtures are required, such as pavements. At the same time, further investigation is needed into the potential for strength enhancement when superplasticizers are added as well as the effect of aggressive environments.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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