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Research Article

A COMPARATIVE STUDY ON THE PHYSICAL AND MECHANICAL PROPERTIES OF ALKALI ACTIVATED MATERIALS

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ABSTRACT

In this study, the effect of silica modulus (MS) on the properties of alkali activated material (AAM) was evaluated. The precursor material selected for the production of AAM was a blend of ground granulated blast furnace slag (GGBFS) and fly ash (FA). The activator was a mix of sodium hydroxide and sodium silicate having different silica modulus and constant Na_2O dosage of 4% by mass of GGBFS and FA. The experimental study investigated the basic mechanical and physical properties of the mortars such as compressive strength, flexural strength, void ratio, water absorption, and density. Test results showed that the physical properties of the AAM mixes such as water absorption and voids content were higher compared to the OPC mix, however, the oven-dry density values were at similar levels, indicating that within the scope of this study at similar density, the AAM produces a more porous microstructure. The compressive strength of the AAM mix having silica modulus of 1.0 (AAM-1.0) was comparable to the OPC mortar at 3 and 7 days however at 28 days the OPC mix possessed significantly higher strength. The AAM mixes produced a lower flexural strength compared to the OPC mix at 28 days and the flexural to compressive strength ratio was almost halved in the AAM mixtures.
Keywords: Alkali activated material, ground granulated blast furnace slag, fly ash, silica modulus, physical properties, mechanical properties.

1. INTRODUCTION

Ordinary Portland Cement (OPC) is one amongst the commonly used construction materials all over the world. The demand for cement-based concrete is increasing due to the rapid increase in construction activities. As strange as it may sound, concrete is the second most used commodity in the world after water [1].

Production of OPC requires a huge amount of natural resources that undergoes the energy-intensive process and releases plenty of carbon dioxide. Portland cement manufacturing is environmentally harmful as the processing of one tonne of cement consequences in about one tonne of carbon dioxide being released into the atmosphere [2]. It is predicted that the demand for Portland cement will exceed 3.6×10^9 tonnes by 2020 as the utilization of Portland cement has raised exponentially in the preceding 20 years. Manufacturers of Portland cement involve considerable exploitation of natural resources, predominantly limestone quarries. About 3.0

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billion tonnes of raw materials (about 70% of that are limestone) are required to produce the world's 2.0 billion tonne Portland cement output [3].

Undoubtedly, the cement manufacturing industrial sectors are placed under critical observation these days because of the huge volumes of greenhouse gases (particularly CO_2) emitted. In fact, cement industries are anticipated to exemplify about 5–7% of the total global anthropogenic carbon dioxide emissions, meaning that there is an urgent need for alternative binders [3-4]. Studies have been conducted in the development of substitute binders with lower energy and lower CO_2 emissions by the reuse of industrial by-products (blast furnace slag, fly ash, glass waste) which can perform as equivalent or higher compared to that of the ordinary Portland cement (OPC).

In the series of studies on alkaline activation, Glukhovsky discovered crucial components of alkaline binders in 1976. Further, he added industrial by-products like blast furnace slag, fly ash, glass waste and recycled aluminosilicates can be used as components of alkaline activated material [3]. However, German cement chemist and engineer Kühl in 1908 patented the reaction of alkali with alumina and silica-containing compound as a means of forming a solid material comparable to hardened Portland cement [1].

According to the American Society for Testing and Materials (ASTM) slag is defined as the non-metallic product consisting essentially of silicates and alumino-silicates of calcium and other bases that are developed in a molten condition simultaneously with iron in a blast furnace. The ground granulated blast furnace slag (GGBFS) consists primarily of the impurities from the iron ore (mainly silica and alumina) combined with calcium and magnesium oxides from the flux stone [5]. Whereas fly ash (FA) is a finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gases [6].

Several studies have been performed to determine the properties of alkali activated materials (AAMs) [7-9]. Bakharev et al. [10] studied the influence of temperature on the properties of alkali-activated slag (AAS) concrete and discovered that heat curing reduces the shrinkage of AAS concrete. Moreover, they concluded that the strength of AAS is significantly accelerated by heat treatment. However, heat treatment reduces the compressive strength of AAS concrete compared to that of concrete cured at room temperature on aging. Further studies were done and Puertas et al. [11] investigated the strength behavior and hydration products of fly ash/slag cement and reported an increase in slag content results in higher compressive strength. Furthermore, the concentration of activator (NaOH) has a direct effect on strength development, and NaOH of 10 M produces higher strength.

In this study, ground granulated blast furnace slag, fly ash, water glass, and sodium hydroxide were used as the main components to produce AAM. The compressive strength test (3, 7 and 28 days), flexural strength test (28 days) were performed to determine the mechanical properties and voids content, water absorption, and density tests were conducted to determine the physical properties of alkali activated fly ash-slag mortar. The aim of the conducted research was to identify the mechanical and physical properties of a blended fly ash-slag mortar using different silica modulus and to compare the results with the OPC mortar. The obtained data and findings will certainly be useful for the design of AAMs incorporating fly ash and slag both in environmentally and economical ways.

2. EXPERIMENTAL INVESTIGATION

2.1. Materials and Mix Design

The materials used to manufacture AAM were FA, GGBFS, water glass, sodium hydroxide, sand, and water. FA was obtained from Çatalağzı thermal power plant and GGBFS from Bolu Cement Company. SEM micrographs of the FA and GGBFS are shown in Fig. 1 demonstrate that the FA has a spherical shape and that the GGBFS has an irregular surface texture. Chemical composition and physical properties of binders used in the research are presented in Table 1. In the experimental study, 4 mixtures were produced and the mix design is shown in Table 2. The water to binder ratio was set constant as 0.50 and the GGBFS to FA ratio by mass was kept constant as 0.75 for the AAM mixes. The silica modulus (MS) of the AAMs differs as 1.0 and 2.0. The mass ratio of Na_2O to the total amount of the precursor materials (FA+GGBFS) was fixed as 4% in the AAM mixes. The mixes were coded according to the variation of MS (Table 2), where the symbol following the "AAM" letter represents the MS of the AAM mix. The OPC mix was designed with an equal portion of cement paste and sand by volume and the water to cement ratio was fixed as 0.5. The flow chart of the experimental study was summarized in Fig. 2.

Table 1. Chemical composition and physical properties of binders

Oxide % by mass	Cement	FA	GGBFS
SiO_2	19.9	52.6	40.6
Fe_2O_3	4.7	5.8	1.2
Al_2O_3	4.0	25.0	12.6
CaO	62.2	3.3	35.1
MgO	1.2	2.1	5.8
SO_3	3.74	1.0	0.1
Na_2O	0.83	0.3	0.8
K_2O	0.26	4.1	0.7
Density, g/cm^3	3.10	2.21	2.91

Table 2. Mix proportions by volume

Material	Mix ID		
	OPC	AAM-1.0	AAM-2.0
Cement	1.0	-	-
GGBFS	-	0.75	0.75
FA	-	0.25	0.25
Water/binder ratio	0.5	0.5	0.5
Sand	1.5	1.5	1.5
% Na_2O by mass of GGBFS+FA	-	4	4

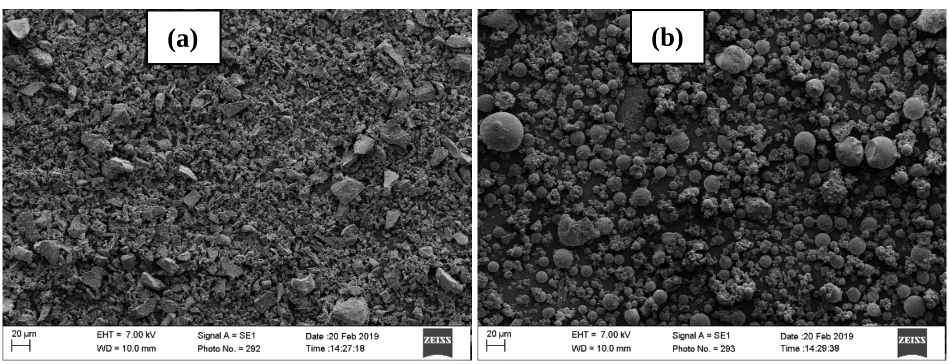

Figure 1. SEM micrographs of (a) GGBS and (b) FA

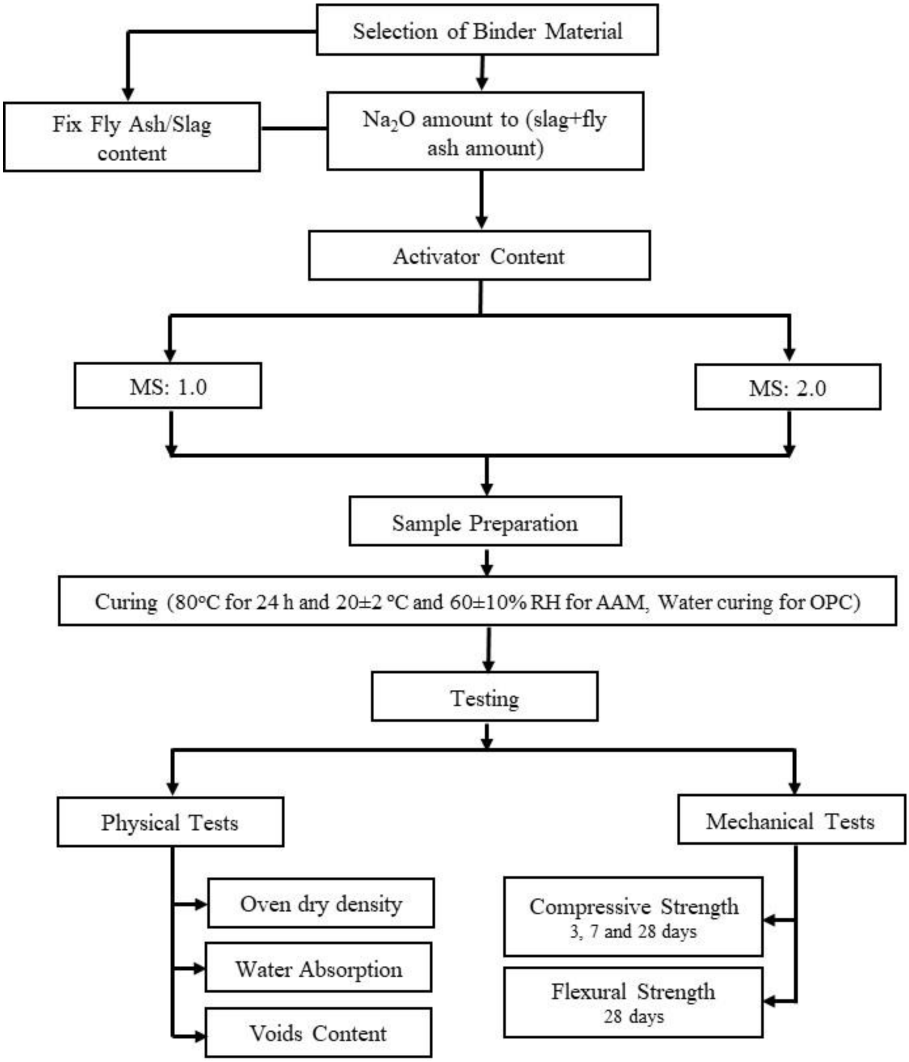

Figure 2. Flow chart of the experimental study

2.2. Casting and Curing

The manufacture of the OPC and AAM mixes was carried out in the Yildiz Technical University Construction Materials Laboratory. Fresh AAM mortar and OPC mortar were cast in the cubic moulds with dimensions of 50x50x50 mm (3 samples for each silica modulus), prism moulds with dimensions of 160x40x40 mm, and cylinders with diameter and height of 100 and 200 mm, respectively. AAM samples were demolded 24h after casting and were put in the oven for the next 24 h at 80 ºC and later stored in laboratory conditions at 20±2 ºC and 60±10% relative humidity till each experiment days. The OPC mortar samples were placed in the water with a temperature of 20±2 ºC until the testing date.

2.3. Testing Procedure

The compressive strength of the mortar samples was performed in accordance with ASTM C 109 [12] on 50 mm cube samples as shown in Fig. 3a. Three samples were used to determine the average compressive strength at 3, 7 and 28 days. The flexural strength of the mixes was determined at 28 days on three 160x40x40 mm prisms (Fig. 3b) for each mix and the average was noted as the flexural strength. The water absorption, oven-dry density and voids content of the samples were determined following the ASTM C642 [13] standard on two samples with diameter and height of 100 mm and 50 mm, respectively.

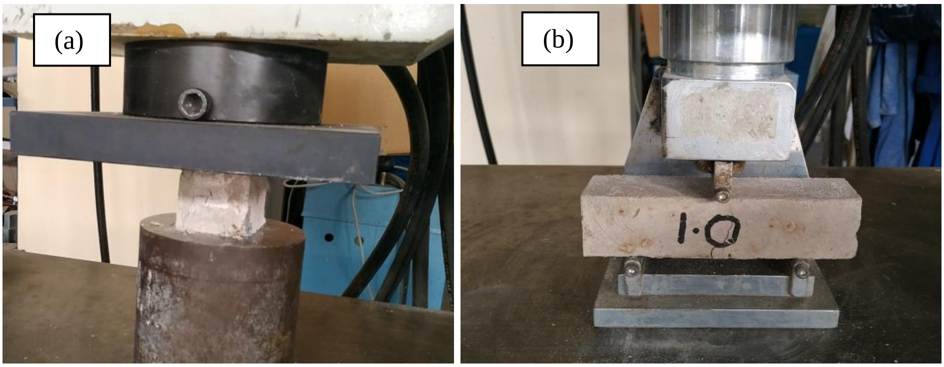

Figure 3. Mechanical testing of samples (a) compressive strength test (b) flexural strength test

3. RESULTS AND DISCUSSION

The average of the physical properties of the OPC mortar and the alkali activated mortar mixes are shown in Figures 4-6. Test results show that the oven-dry density, water absorption and voids content of the alkali activated mixes are slightly or significantly higher compared to the OPC mix. An increase in the silica modulus resulted in a further increase in the physical properties tested. The oven-dry density of the AAM-1.0 and AAM-2.0 mixes were found to be 0.34% and 0.63% higher than the OPC mix, yielding only a slight increase. The water absorption and the voids content, on the other hand, significantly increased in the alkali activated mixes, and an increase in the MS ratio resulted in further increments. Compared to the OPC mix, the water absorption of AAM-1.0 and AAM-2.0 was found as 3.7% and 11.1% higher, respectively. Similarly, the voids content increased but at higher ratios. The voids content of AAM-1.0 and AAM-2.0 mixes were 7.2% and 15.0% higher than the OPC mix, respectively. The physical test results suggest that the AAMs formulated in the present study have higher capillary pores than the OPC mix, although the density values were similar. This could be as a result of the final strength values of the three mixes tested (Fig. 7). The OPC mix has significantly higher strength at 28 days and an increase in MS of 1.0 to 2.0 resulted in a further drop in the compressive strength of the AAM mixes. Similar results were found by other researchers [14,15]. Therefore more research should be conducted to verify the effect of MS on the reaction mechanism of alkali activated materials incorporating fly ash and slag. The occurrence of microcracks in the microstructure of the AAM mixes might be another reason for the increase in water absorption and voids content since the AAM has been reported to undergo higher drying shrinkage [16,17] compared to the OPC, which might have caused relatively higher microcrack formation.

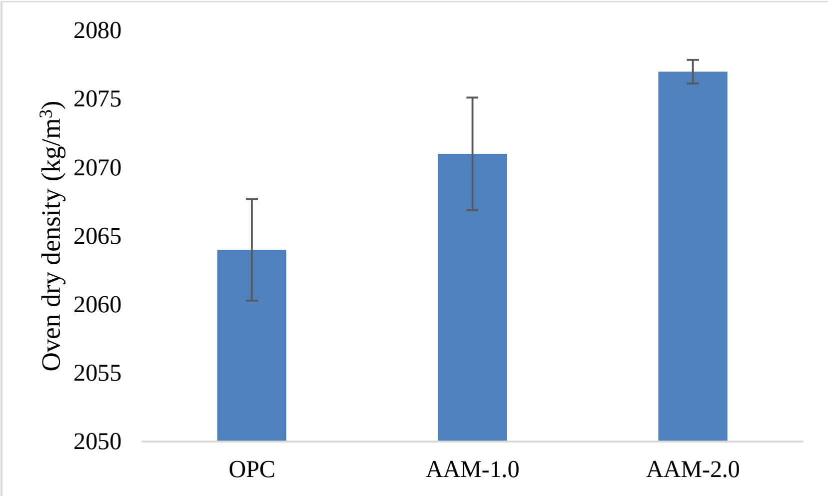

Figure 4. Dry density results of the mixes

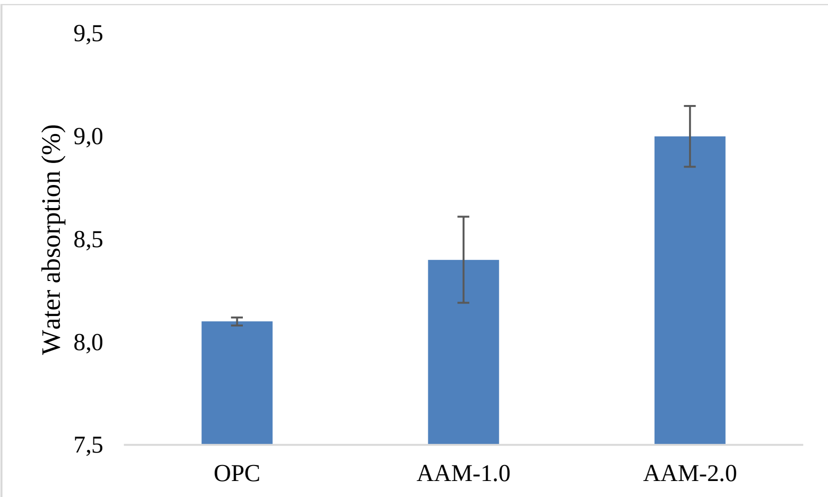

Figure 5. Water absorption results of the mixes

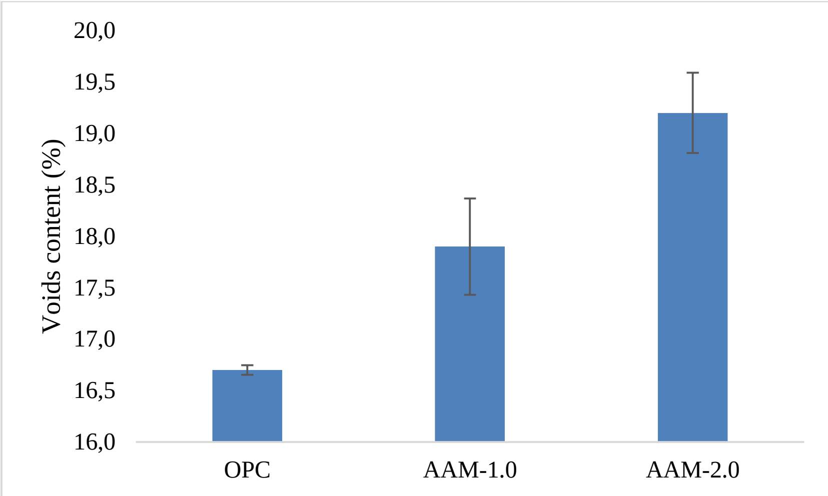

Figure 6. Voids content results of the mixes

The average of the mechanical test results of the OPC mix and the AAM mixes are shown in Figures 7 and 8. Test results showed that the final strength of the OPC mix at 28 days was significantly higher than the AAM mixes tested in this study. However, at the early ages (3 and 7 days) the compressive strength of the AAM-1.0 mix was comparable to the OPC mix, indicating that the strength development in the AAM mixes is significantly reduced at ambient curing (20°C and 55% RH). The curing procedure chosen for the AAM mixes in this study was heat curing at 80 ºC for 24 h where most of the reactions have possibly finished. Test results also prove this since the strength change beyond 7 days was found to be insignificantly changed. The flexural strength results indicated a lower strength could be achieved in the AAM mixes compared to the OPC. The flexural strength to compressive strength ratio results (Fig. 9) shows that the AAM mixes have significantly lower values than the OPC mix, which might be one of the most significant drawbacks of this material. This ratio was found as about 0.2 in the OPC mix and reduced to about 0.13 in the AAM mixes (about half of that of the OPC).

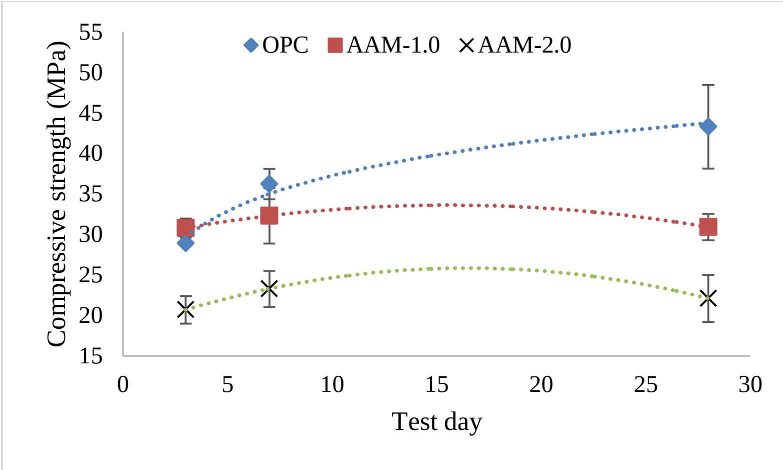

Figure 7. Compressive strength results

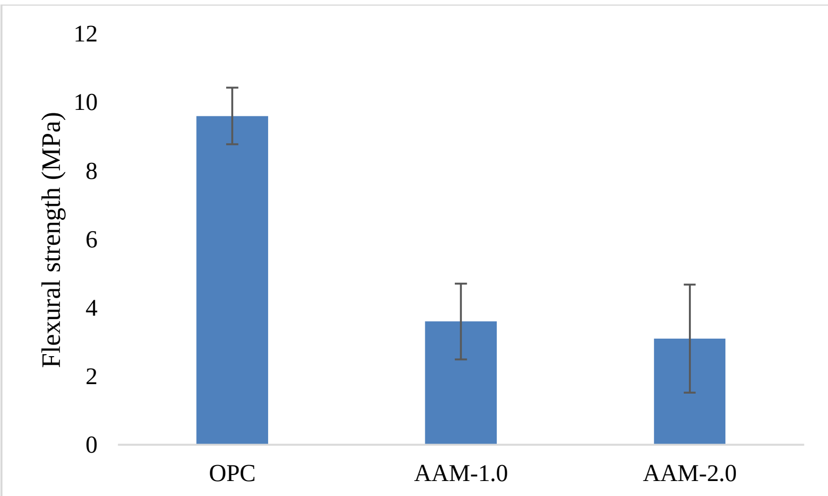

Figure 8. Flexural strength results

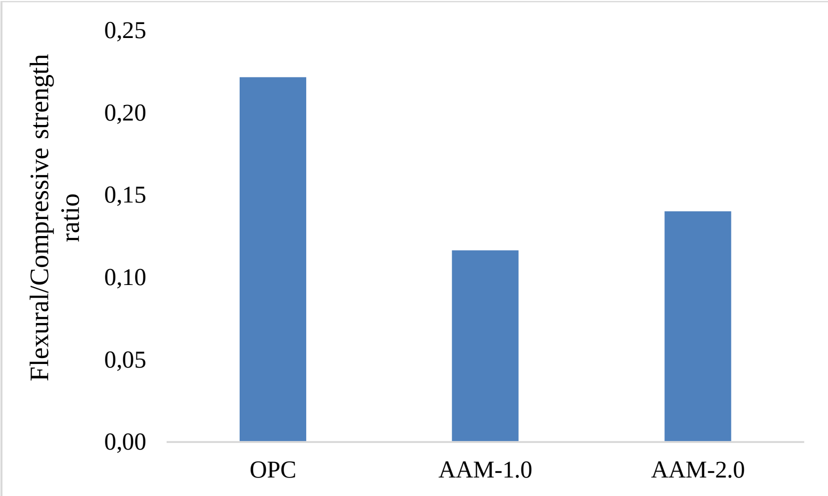

Figure 9. Comparison of flexural/compressive strength ratio of the mixes

4. CONCLUSIONS

The experimental study carried out aims to provide a better understanding of the physical and mechanical properties of specific AAM mixes incorporating FA and GGBFS in comparison with OPC where cement is the sole binder. Based on the test results following conclusions may be drawn:

- The physical properties of the OPC mortar and the AAM mixes showed distinct results, especially in terms of water absorption and voids content. The oven-dry density of the two different groups (OPC and the AAM mixes) were similar, however, the water absorption and the voids content of the AAM mixes were found to be significantly higher than the OPC mix. An increase in the MS consistently increased water absorption and voids content.
- The compressive strength of the AAM mixes increased up to 7 days and no further gain was observed later on. On the other hand, the compressive strength of the OPC mix consistently increased with curing time. Nonetheless, the AAM-1.0 mix had comparable compressive strength with the OPC mix at 3 and 7 days. However, an increase in the MS from 1.0 to 2.0 resulted in lower compressive strength.
- The flexural strength test results showed that the OPC mixes possessed a higher flexural strength compared to that of the AAM mixes. The reduction in the flexural strength might be due to the microcracks developed within the samples, the higher voids content and water absorption properties of the AAM mixes also support this suggestion. The ratio of flexural to compressive strength shows that the OPC has a higher ratio than the AAM mixes. This ratio was almost halved in the AAM mixes compared to the OPC.
- The results of the present study give an understanding of the basic AAM properties. Further studies can be operated to investigate the effect of Na_2O dosage on the physical, mechanical and durability properties of the AAM keeping the MS content as 1.0 which was found as the optimum in this study.

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