DEVELOPMENT AND MIX OPTIMIZATION OF ONE PART ALKALI ACTIVATED BINDER AS A SUSTAINABLE CONSTRUCTION MATERIALS

Ariful Islam*[1], Apurba Sutradhar[2], Md. Jihan Hasan[3] and Ismail Saifullah[4]

[1] *Undergraduate Student, Department of Civil Engineering, Gopalganj Science and Technology University, Bangladesh, e-mail: arifulislam00035@gmail.com*
[2] *Undergraduate Student, Department of Civil Engineering, Gopalganj Science and Technology University, Bangladesh, e-mail: apurbasutradhar075@gmail.com*
[3] *Lecturer, Department of Civil Engineering, Gopalganj Science and Technology University, Bangladesh, e-mail: jihanhasan@gstu.edu.bd*
[4] *Professor, Department of Civil Engineering, Khulna University of Engineering & Technology, Bangladesh, e-mail: saifullah@ce.kuet.ac.bd*

***Corresponding Author**

ABSTRACT

The scarcity of sustainable resources and the significant CO_2 emanation associated with the Ordinary Portland Cement (OPC) based concrete have given rise to the demand of eco-friendly material usage in the construction. Alkali Activated materials have emerged recently as a sustainable and environmentally friendly alternative to OPC as they offer a substantial reduction in carbon footprint. This study focuses on the development of dry Alkali Activated Mortar (AAM) mixes using Fly Ash (FA) and Blast Furnace Slag (Slag) as precursors. Mono (100% FA as precursor) and Binary (combination of FA and Slag-80% FA and 20% Slag by weight) paste, and mortar mixes were trialed for this study following dry mixing techniques where each precursor combination were activated using alkaline powder. During mix proportioning the ratio of the precursor and activator were kept constant where 15% of total binder weight was activator whereas precursor content was limited to 85% of total binder weight. Water to binder ratio varied in the range of 0.30 to 0.40 while trialing different variations of paste and mortar mixes but superplasticizer content was limited to 1% of total binder content. In case of mortar mixes three variations of binder to sand ratio (1:0.5, 1:0.75, and 1:1 by weight of binder) were trialed for this particular research program. All the specimens were cured under water and in ambient condition (25 ± 2^0C and 95±2% relative humidity). Various combinations of sodium metasilicate, calcium hydroxide, and sodium sulphate in powder form were used as alkaline activators. Sodium metasilicate or its anhydrous form alone was observed to be insufficient to achieve desirable mechanical strength. However, the incorporation of calcium hydroxide powder (33% of total activator) with sodium metasilicate (67% of total activator) considerably improved mechanical properties and enhanced early strength development. The combination of sodium sulphate and calcium hydroxide based AAM mixes showed comparatively higher compressive strength. The maximum 28 day compressive strength was observed to be 25.68 MPa which was attained with 100% GGBFS activated by Na_2SiO_3-$9H_2O$ + $Ca(OH)_2$ under ambient curing condition. Almost all the trial paste and mortar mixes showed considerable flow characteristics. Based on the findings, an optimized AAM mix variations were recommended for future research implementations to establish a viable and environmentally friendly alternative to OPC based mortar.

Keywords: *Alkali Activated Mortar; sustainable binder; one-part mixing; powder based alkaline activator.*

1. INTRODUCTION

Cement is the most essential and widely used binding material in the construction process (Manzur et al., 2019; Pacewska & Wilińska, 2020). It is estimated that the annual production of cement worldwide will increase by 50% within 2050 as a result of urbanization (Monteiro et al., 2017) . The production of Portland Cement (PC) requires a huge amount of natural resources, higher temperature and uses huge amount of energy that directly contributes to carbon dioxide (CO_2) emissions in the atmosphere that contributes around 5-8% of global CO_2 emissions (Askarian et al., 2019; Hasan & Hossain, 2023; Hossain et al., 2020; Worrell et al., 2001). Therefore, it is necessary to consider using supplementary cementitious materials like fly ash and slag, or alternative cement free binders instead of Ordinary Portland Cement (OPC).

Geopolymers are becoming a sustainable alternative to cement that provides an eco-friendly construction materials and incombustible (fire-resistant) inorganic polymers (Amran et al., 2022). Geopolymers belong to a subclass of alkali activated materials (AAMs) (Askarian et al., 2019) that uses Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBFS), and silica fume, or natural materials like metakaolin clay, volcanic ash, and red mud as source materials along with alkaline activator such as sodium hydroxide, sodium silicate, potassium hydroxide, potassium silicate, sodium carbonate, sodium sulphate, and calcium hydroxide (Singh & Middendorf, 2020). Geopolymers require lower energy for production and is responsible for significantly less CO_2 emission as compare to OPC (Komnitsas, 2011). The carbon footprints of FA based AAMs are approximately 9 times less than that of OPC (Chindaprasirt & Rattanasak, 2017). The production of FA-based geopolymer concrete leads to at least 80% lower CO_2 emissions and about 60% less embodied energy than the making of ordinary Portland cement (OPC) (Castaldelli et al., 2016). The use of industrial waste materials as precursors improves sustainability and reduces environmental impact and supports a greener future. This makes geopolymers a promising alternative for fully replacement of OPC as a binder in concrete production (Singh & Middendorf, 2020).

The term geopolymer was initially introduced by Davidovits. In 1978, Joseph Davidovits developed and patented binders produced by the alkali activation of metakaolin (Pacheco-Torgal et al., 2008). Geopolymers are produced by polymerisation of silicon, aluminium and oxygen species to form an amorphous three-dimensional framework structure. Geopolymerization is a process where silicon, aluminum, and oxygen atoms combine to form chains of SiO_4 and AlO_4 tetrahedra (Majidi, 2009). Based on chemical composition of the precursor AAM system can be described as three different types with varying reactivity. In low calcium based AAM system, lower percentage of calcium oxide content (such as in metakaolin and fly ash) and presence of high aluminosilicate results in a N-A-S-H gel system and contribute towards lower reactivity of such system under ambient condition. On the contrary, C-A-S-H gel formation is predominant in high calcium system (such as AAM with slag) and improved strength development is observed due to high reactive nature of slag (high CaO content) (Provis and Van Deventer, 2013; Sun et al, 2022). Ismail and El-Hassan (2018) stated coexistence of both gel in an AAM system combining both fly ash and slag.

The traditional approach of two-part geopolymers are prepared by mixing concentrated alkaline solutions such as sodium hydroxide, sodium silicate with solid aluminosilicate precursors. However, handling large volume of viscous, corrosive, and hazardous alkaline activator solution is difficult and unsafe. In order to solve these problems, researchers have developed one-part or “just add water” geopolymers that is easier and safer to use (Allali et al., 2024; Sood et al., 2019). They are prepared by mixing a solid aluminosilicate precursor such as fly ash, slag, or metakaolin with a solid alkali activator like sodium metasilicate, sodium hydroxide, sodium sulphate and calcium hydroxide etc. Only a dry mixture and water is required to prepared one-part mixtures. The dry mixture is prepared by mixing a solid alkali activator with a solid aluminosilicate precursor.

Previous studies reported that, fly ash based one part alkali mortar recorded 28 days compressive strength in the range of 0.57 MPa to 9.45 MPa while maximum 7 days compressive strength was 3.2

MPa under ambient condition. Sodium silicate was used as solid activator in all these mixes (Yang et al., 2008). Another study showed that the 28 days compressive strength was 3.5 MPa where fly ash used as precursor and combination of solid silicate and sodium hydroxide used as activator (Yang & Song, 2009) . The compressive strength of fly ash based geopolymer mortar and concrete found less than 10 MPa after 3 days (Nath & Sarker, 2015). The 7 days compressive strength of fly ash based geopolymer concrete was found 7.1 MPa where NaOH and $NaSiO_3$ were used as solid activator (Xie & Ozbakkaloglu, 2015). The compressive strength of the fly ash based geopolymer reached 8.20 MPa when 10% solid activator (powder Na_2SiO_3-GD) of the total binder was used and increased to 12.1 MPa when 15% Na_2SiO_3-anhydrous was used as the activator (Nematollahi et al., 2015). Another research reported a compressive strength of 3.6 MPa when Class F fly ash was used with $Ca(OH)_2$ and Na_2SiO_3-$5H_2O$ in a 1:2.5 ratio. However, Class F fly ash recorded a lower compressive strength compared to Class C fly ash which achieved 17.3 MPa under the same activator conditions. Most of the previous studies have trialled Activator to Binder ratio varying in the range of 0.09-0.16 for different combination of Na- and Ca-based activator (Nematollahi et al, 2015; Sood & Hossain, 2021; Teo et al, 2022; Srinivasa et al, 2023; Hamsashree et al, 2025).

This paper focuses on the development of a one-part alkali activated material (AAM) using fly ash and slag as the precursor and combination of Na_2SiO_3-anhydrous, Na_2SiO_3-$9H_2O$, Na_2SO_4 and $Ca(OH)_2$ as solid alkaline activators. For this study the Activator to Binder ratio was kept constant at 0.15. The Activator to Binder ratio was selected based on previous research recommendations (Nematollahi et al, 2015; Sood & Hossain, 2021; Teo et al, 2022; Srinivasa et al, 2023; Hamsashree et al, 2025). The w/b ratio was varied between 0.3 and 0.4 while the superplasticizer content was fixed at 1% of the total binder. The performance of the developed mixes were evaluated in terms fresh (mini slump flow and setting time) and mechanical (compressive strength) properties. The findings showed that the maximum compressive strength of 25.68 MPa was achieved for the 100% slag-based alkali activated mixture. The average compressive strength values under ambient curing were observed between 0.3 to 9.45 MPa whereas compressive strength ranging from 1.39 to 5.89 MPa were observed under water curing condition. The Na_2SiO_3-$9H_20$ and $Ca(OH)_2$ activated mixes required about 160 minutes to 560 minutes till final setting while Na_2SO_4+$Ca(OH)_2$ based mix required 1200+ minutes for the final set. As for workability, the maximum relative slump of 3.62 was recorded when 80% fly ash and 20% slag were used as source material. Based on the observation, 100% slag activated using combination of Na_2SiO_3 and $Ca(OH)_2$ was found to be optimum one part alkali activated materials that could be used for future AAM development.

2. MATERIALS AND METHODOLOGY

This study focused on developing and evaluating performance of Alkali Activated Binders (AABs), prepared using conventional one-part (dry mix) technique. Various precursor combinations of Low Calcium Fly Ash (FA-F) and Ground Granular Blast Furnace Slag (GGBFS) were activated using different blends of powder based Na_2SiO_3-anhydrous, Na_2SiO_3-$9H_2O$, $Ca(OH)_2$ and Na_2SO_4. As for mortar mixtures the developed AAB pastes were mixed with locally available white river sand.

2.1 Materials

The AAB mixes were developed using various combination of FA-F and GGBFS as source materials whereas mortar mixes were prepared mixing white river sand with the developed AAB mixes. Two types of mixes (mono-only FA-F as precursor and binary-combination of FA-F and GGBFS as precursor) were prepared. The aluminosilicate source materials were activated using different blend of Na_2SiO_3-anhydrous, Na_2SiO_3-$9H_2O$, $Ca(OH)_2$ and Na_2SO_4 as specified in Table 1. FA-F and GGBFS used were supplied by a local cement company of Bangladesh. The white river sand, used as fine aggregates has a fineness modulus (FM) of 1.28. The physical properties of the precursors and fine aggregate are shown in Table 2 and their respective particle size distributions are presented in Figure 1.

Table 1: Summary of alkaline activator and their mix ratio with code

Code	Activator-1	Activator-2	Blending Ratio
JS-1	Na_2SiO_3-$9H_2O$	$Ca(OH)_2$	2
JS-2	$Ca(OH)_2$	Na_2SO_4	2
JS-3	Na_2SiO_3-$9H_2O$	$Ca(OH)_2$	2
JS-4	Na_2SiO_3-$9H_20$		-
JS-5	Na_2SiO_3-anhydrous		-

Table 2: Physical properties of the materials

Material	Unit Weight (Kg/m^3)	Specific Gravity
Fly Ash (FA)	815	1.96
GGBFS	1230	2.33
Sand	1519	2.56

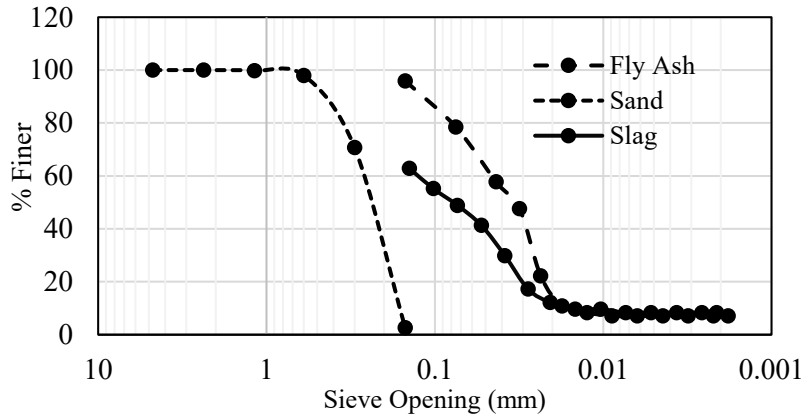


Figure 1: Particle size distribution curve of the materials

2.2 Mix Proportion

In this study, a total of fourteen (10 mono and 4 binary) alkali-activated paste and mortar mixes were prepared with varying proportions of precursors, activators, and fine aggregates. All the mono AAB mixes contain 100% FA-F as precursor whereas the binary blends contain FA-F and GGBFS as precursor in the ratio of 80 to 20. AA-14 mix contained only 100% slag as precursors. The total precursors were 85% of total binder and the activator content was kept fixed with 15% of total binder as per previous research recommendations, as discussed beforehand. The binder is the combination of precursors and activators. About 1% of High Range Water Reducing Admixtures (HRWRA) was added in all of the Alkali Activated paste and mortar mixes to ensure adequate workability. Table-3 summarizes the mix proportioning considered for this research project.

2.3 Preparation of AAM Binders

The preparation of the one-part alkali activated binder was carried out as per the procedure described here below to ensure homogeneity and proper activation of the precursors. At first, the solid precursors (FA-F or FA-F+Slag) were dry mixed using a stirrer for 1 minute to achieve uniform blending. The powder activators were added to the precursors and the dry mixed for another 1 min to ensure even distribution of the activator materials. The combined dry mixture was later placed to a mechanical mixer machine and mixed for an additional 3 minutes at a slow speed. After the 3 minutes of slow mixing, two thirds of the required water was added to the dry mix and blended thoroughly at lower speed during the water addition. The remaining one-third of the water was first mixed with the superplasticizer (SP) and then gradually added to the mixture while operating the mixer machine at a

higher speed. The entire mixing process was carried out for approximately 12-14 minutes to produce a uniform and workable one part alkali activated binder.

Table 3: Mix proportion of one part alkali activated materials

Mix ID	Binder	Precursors			Activator	Activator /Binder	FA	SP	w/b
		Total	Fly Ash	Slag			Sand		
AA-1	1	0.85	1	0	JS-1	0.15	0	0.01	0.3
AA-2	1	0.85	0.8	0.2	JS-1	0.15	0	0.01	0.3
AA-3	1	0.85	1	0	JS-1	0.15	0.5	0.01	0.33
AA-4	1	0.85	0.8	0.2	JS-1	0.15	0.5	0.01	0.33
AA-5	1	0.85	1	0	JS-1	0.15	0.75	0.01	0.36
AA-6	1	0.85	0.8	0.2	JS-1	0.15	0.75	0.01	0.36
AA-7	1	0.85	1	0	JS-1	0.15	1	0.01	0.4
AA-8	1	0.85	0.8	0.2	JS-1	0.15	1	0.01	0.4
AA-9	1	0.85	1	0	JS-2	0.15	0	0.01	0.3
AA-10	1	0.85	1	0	JS-2	0.15	0.33	0.01	0.33
AA-11	1	0.85	1	0	JS-2	0.15	0.5	0.01	0.35
AA-12	1	0.85	1	0	JS-4	0.15	0	0.01	0.3
AA-13	1	0.85	1	0	JS-5	0.15	0	0.01	0.3
AA-14	1	0.85	0	1	JS-3	0.15	0	0.01	0.3

*All the data expressed by weight of binder as percentages; SP used 1% by weight of binder
Binder= Precursors +Activator; SP=Superplasticizer; w/b= water to binder ratio

2.4 Casting and Curing Condition

The freshly prepared one-part alkali activated paste/mortar was placed into 50 mm cubic molds (50 mm x 50 mm x 50 mm) in two layers and compacted properly. At least 6 cube specimens were prepared for each binder composition. After casting, the specimens were covered with plastic sheets to prevent moisture loss and left undisturbed for 24 hours before demolding. The samples were demolded after 24 hr-48 hours based on mix design. For the Mix IDs AA-9 to AA-11, specimen is demolded after 48 hr based on the final setting time consideration. After demolding, the specimens were subjected to different curing condition to evaluate the mechanical properties of the binder. The samples were cured under two different conditions **(**underwater curing and ambient curing). For underwater curing, the cubes were submerged in water at room temperature until the testing date. In the case of ambient curing, the samples were kept in the environment chamber at a temperature of 25 ± 2 °C with Relative Humidity (RH) 95±2%. Mix IDs AA-1 to AA-8 were subjected to both curing conditions where AA-9 to AA-14 were subjected to ambient curing condition.

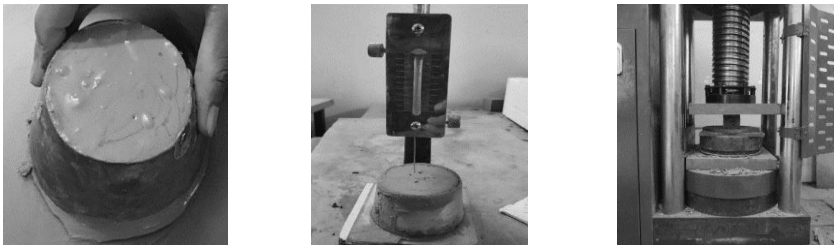
2.5 Test Method

The performance of the developed Alkali Activated mixes were evaluated in terms of fresh and mechanical properties. As for fresh property assessment, this experimental program includes determination of setting time and mini slump flow. Furthermore, the mechanical performance was evaluated in terms of 7-day and 28-day compressive strength values. The compressive strength of 50 mm^2 cube specimens was determined in accordance with ASTM C109 (ASTM *C109/C109M*). The initial and final setting times of the binders were measured using the Vicat apparatus as per ASTM C191 (ASTM C191).

The mini slump flow was performed to determine the slump flow spread diameter (in mm) of the mixes as per ASTM C1437 (ASTM C1437). The relative slump (a dimensionless value) was evaluated on the basis of equation (1) (Nematollahi and Sanjayan, 2014).

$$T=\left[\frac{D}{d}\right]^2-1 \qquad (1)$$

Where D (in mm) is the average of two measured diameters of the matrix mix and d is bottom diameter of the conical cone (100 mm). All the test setup and methodology used has been shown in Figure 2.



(a) (b) (c)

Figure 2: Test set up for (a) mini slump flow test, (b) setting time and (c) compressive strength

3. RESULT AND DISCUSSION

3.1 Workability of Paste and Mortars

Figures 3 represents relative slump and flow spread diameter (in mm) of different alkali activated mixes. The relative slump observed to vary in the range of 1.03 to 3.62 and the corresponding flow spread diameters varied between 142.5 mm and 215 mm. The pastes mixes showed higher flow spread compared to mortar mixes which can be attributed to the inclusion of the fine aggregates resulting in a leaner mix. The AA-1 mix (initial setting time = 180 minutes and final setting time = 560 minutes) showed better workability as indicated by about 55–135% higher relative slump and 15-30% higher flow spread diameters than AA-3, AA-5, and AA-7 mixes (mortars) that contain 50%, 75% and 100% of sand by weight of total binder, respectively. All these mixes contain 100% FA-F as precursors. When 20% of the FA-F precursors were replaced by slag (AA-2), the relative slump and flow spread was increased by 34% and 14%, respectively, in comparison with the mix containing 100% FA-F (AA-1). Compared to AA-2 (without sand), the relative slump reduced by 33%, 56%, and 58% whereas the flow spread decreased by 17%, 29%, and 30% for AA-4, AA-6, and AA-8, respectively that contain binder to sand ratio of 0.5:1, 0.75:1 and 1:1. The initial and final setting times were measured 160 and 490 minutes, respectively, for AA-2 that was reduced by 11.1% and 12.5% compared to AA-1. Mixes AA-1 to AA-8 were prepared using Na_2SiO_3-$9H_2O$ and $Ca(OH)_2$ as activators.

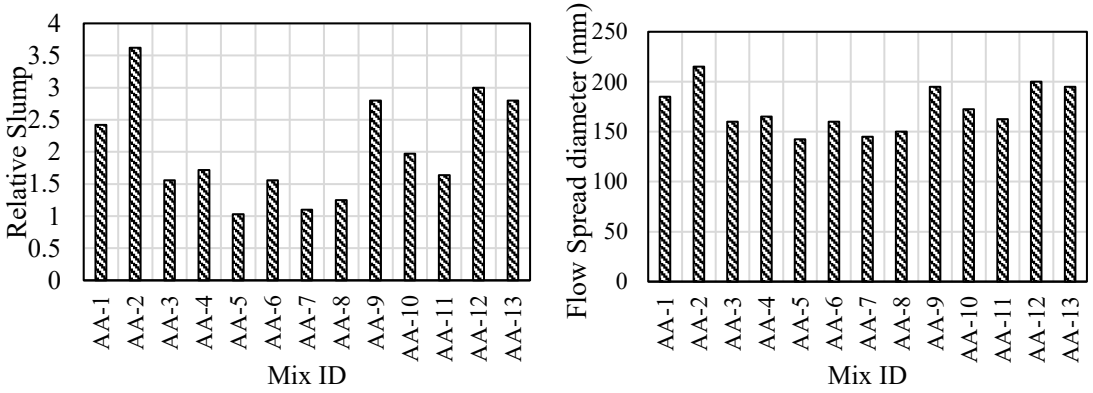


Figure 3: Workability of AAB mixes: relative slump (Left), flow spread diameter (mm) (Right)

The relative slump decreased by approximately 29.6% for AA-10 and 41.4% for AA-11 compared to AA-9. In contrast, AA-9 showed longer setting times compared to AA-1 and AA-2 with an initial setting time 700 minutes and final setting at 1200+ minutes where 100% fly ash was used as

precursors. Mix AA-12 was prepared using Na_2SiO_3-$9H_2O$ that showed slightly higher workability compared to AA-13 which was prepared with Na_2SiO_3-anhydrous. The relative slump of AA-12 was approximately 7.1% higher while flow spread was about 2.6% greater than AA-13. This indicates that the hydrated form of sodium metasilicate improves the workability of the mix. The addition of fine aggregate to the mix significantly reduces the flow spread and relative slump.

3.2 Variations in Compressive Strength

3.2.1 Compressive Strength Variations of AAM Mixes Cured Under Water

Figure 4 represents the 28 days compressive strength under water curing of AAMs. The 28-day compressive strength results under underwater curing conditions showed distinct trends influenced by both the precursor composition and sand content. Between the paste mixes, AA-1 achieved 85% higher compressive strength as compared to AA-2 that is prepared by 80% fly ash and 20% slag which indicates the reduction in compressive strength under water curing due to the addition of slag. This can be linked to the slower reaction of slag system instigated by the leaching of Na^+ and OH^- at early stages (Liu et al, 2023). For sand content of 50% by weight of binder mixes, AA-4 (80% fly ash + 20% slag) reached 5.89 MPa which is 36% higher than AA-3 (100% fly ash) with 4.34 MPa. The result showed that inclusion of slag improved strength when sand was added. The compressive strength of AA-5 and AA-6 were decreased about 34% and 71%, respectively, than their 50% sand containing counterparts AA-3 and AA-4 mixes. The lowest strengths were recorded at 100% sand by weight of binder which can be due to reduction in aluminosilicate rich material content. AA-7 showed about 37% lower compressive strength values than that of AA-1 and AA-8 exhibited about 42% lower value than AA-2. The addition of sand content to the mixes caused reduction in the compressive strength of the alkali activated materials. The results demonstrate that 100% fly ash mixes maintained relatively higher strengths across all sand proportions but 50% sand addition along with 20% slag showed the maximum compressive strength. All the trial Alkali Activated mortar mixes underperformed when compared with typical compressive strength (28- 50 MPa for varying curing regime-under water curing and air curing at varying temperature) (Ezziane et al, 2007; Sajedi and Razak, 2011) of OPC based mortar which can be attributed to the variations in reaction mechanism and source material.

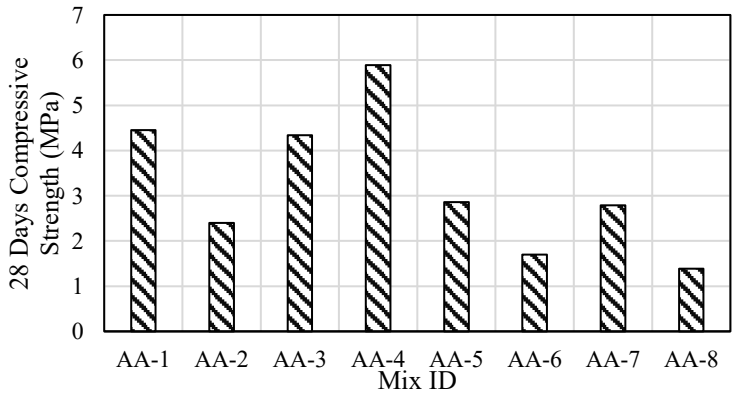


Figure 4: Variations in 28 days compressive strength of AAM mixes cured under water

3.2.2 Compressive Strength Variations of AAM Mixes Cured Under Ambient Condition

The ambient curing results shown in the Figure-5 varied noticeably between paste and mortar mixes at both 7 and 28 days. In the paste group, AA-1(fly-ash only) attained 1.63 and 2.13 MPa at 7 and 28 days, respectively. After the addition of 20% slag in mix AA-2, the strength slightly decreased by

0.6% at 7 days but increased by 31% at 28 days. This shows that adding slag delayed early reaction but helped to enhance long term geopolymerization. The lower reactivity of low calcium AAM system (comprising primarily of N-A-S-H gel due to initial silicate and aluminate monomer development) contributes towards lower early strength of fly ash based AAM mixes requiring higher curing temperature due to the typical chemical composition aluminosilicate rich fly ash (Provis and Van Deventer, 2013; Sun et al, 2022). As for addition of slag with fly ash as precursor in AAM systems, enhanced strength under ambient curing is observed due to development and simultaneous presence of both C-A-S-H (due to presence of high calcium in slag) and N-A-S-H gel (from aluminosilicate rich fly ash) forming a packed AAM system (Ismail and El-Hassan, 2018). Among the mortar group (mix AA-3 to AA-8), mix AA-4 gave the highest compressive strength at 7 days which is about 55% higher than AA-3 while AA-6 recorded the highest compressive strength at 28 days. The result indicated 18% and 41% improvements over the mix AA-3 and AA-4, respectively. A large reduction (%) in compressive strength was observed in mixes AA-7 and AA-8 when compared with other mortar mixes at both 7 and 28 days. Even under ambient curing Alkali Activated Mortars underperformed as compared to OPC based mortar mixes. When comparing paste and mortar, the best results of mortar mix AA-6 (2.19 MPa) nearly matched the values of paste mix AA-2 (2.79 MPa) at 28 days. However, in case of 7 days compressive strength, AA-2 showed about 35% contrast against AA-6 mixes. The compressive strength of the AA-9 increased from 7.16 MPa at 7 days to 9.5 MPa at 28 days with an increase of 32.7%. At 7 days, AA-10 (containing 33% sand by weight of binder) recorded 5.5 MPa which is 23.2% lower than AA-9 whereas AA-11 (with 50% sand by weight of binder) recorded 4.13 MPa that is 42.3% lower than AA-9. Similarly at 28 days, AA-10 reached 6.2 MPa that is 34.7% lower than AA-9 and AA-11 recorded 4.72 MPa with 50.3% reduction in compressive strength. The downward trend indicates that an increase in sand content reduces the compressive strength. The alkali activated paste recorded the highest compressive strength value while the mortar mixes (AA-10 and AA-11) showed lower values as the sand content increased. Compared to AA-9 (Na_2SO_4+ $Ca(OH)_2$ as activator and 100% FA-F as precursor), the AA-1 mix (Na_2SiO_3-$9H_2O$ + $Ca(OH)_2$ as activator and 100% FA-F as precursor) showed about 77.2% lower 7-day and 77.6% lower 28-day compressive strength which indicate weaker geopolymer formation. This attributed to the C-S-H gel formation in higher amount from high calcium content of activator blend-Na_2SO_4+ $Ca(OH)_2$ ($Ca(OH)_2$:Na_2SO_4=2:1) as compared to Na_2SiO_3-$9H_2O$+$Ca(OH)_2$ blend (Na_2SiO_3-$9H_2O$:$Ca(OH)_2$=2:1).

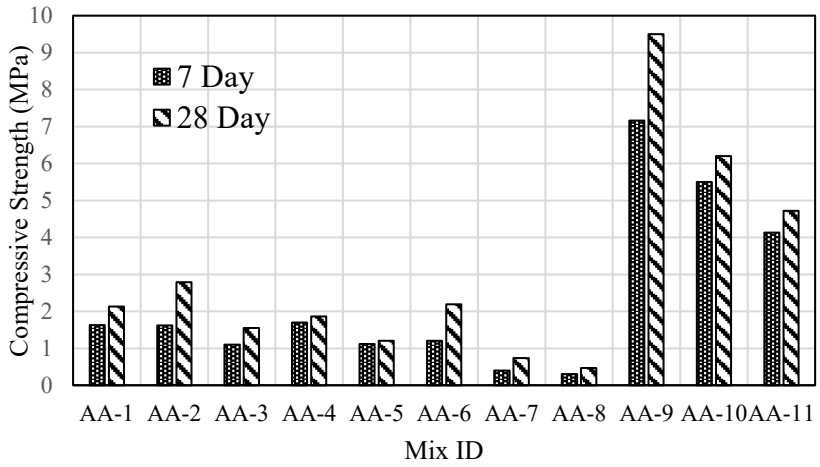


Figure 5: Variation in compressive strength of different AAM mixes under ambient curing condition

3.2.3 28 Days Compressive Strength of Underwater vs Ambient Curing Condition

The observed contrasting effect of underwater and ambient curing on 28 days compressive strength of AAM mixes prepared using activator blend JS-1 [Na_2SiO_3-$9H_2O$+ $Ca(OH)_2$] has been shown in Figure 6. The result indicated that curing environment significantly affects the geopolymerization

process. Underwater curing provided higher compressive strength for most mixes compared to ambient curing except for AA-2 and AA-6 which was recorded about 16.3% and 28.8% higher strength, respectively when cured under ambient condition. For the fly ash-based alkali activated materials without slag (AA-1, AA-3, AA-5, and AA-7) recorded higher strength when cured under water. The compressive strength of underwater curing increased by approximately 109% for AA-1, 180% for AA-3, 138% for AA-5, and 279% for AA-7 compared to ambient curing. The impact of sand content was also noticeable across all mixes. For mixes AA-2 and AA-6, the compressive strength under ambient condition increased 16.25% and 28.82% respectively compared to under water curing. Mixes AA-4 and AA-8, cured under ambient condition, recorded 68.42% and 66.19% decreased compressive strength, respectively as compared to under water curing. As the fine aggregate content increased from 0 to 100% by weight of binder, the compressive strength consistently reduced under both curing regimes.

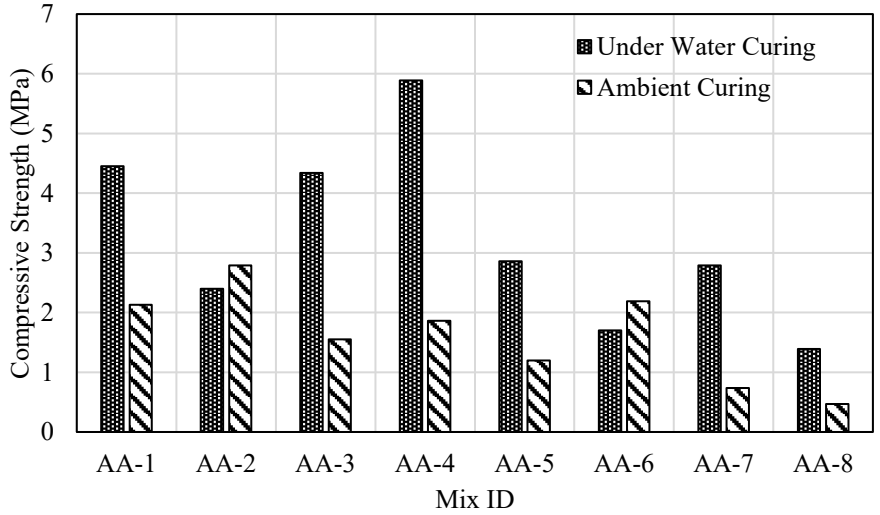


Figure 6: Comparison of compressive strength between under water and ambient curing condition

3.2.4 Variations in Compressive Strength of Alkali Activated Paste Mixes with Various Activator Blend

The compressive strength of alkali-activated paste mixes prepared using different activator blend cured under ambient conditions have been shown in Figure 7. Mix AA-1 prepared with 100% fly ash activated by a combination of Na_2SiO_3-$9H_2O$ and $Ca(OH)_2$ exhibited relatively lower compressive strength. The 28-day compressive strength of mix AA-1 increased by approximately 30.7% when compared to its 7-day strength. At 7 days, AA-2 (80% fly ash + 20% slag) showed almost similar strength to AA-1 with only a 0.6% decrease in value. The result indicated that the small amount of slag had a limited effect at early age. However, AA-2 showed a 31% higher strength than AA-1 at 28 days suggesting accelerated later age compressive strength gain from inclusion of slag. AA-9 (100% fly ash activated by Na_2SO_4 + $Ca(OH)_2$) resulted a remarkable improvement in compressive strength values at both 7 and 28 days which can be attributed to the promoted additional hydration and geopolymerization reactions from combination of sodium sulfate and calcium hydroxide as alkaline activator. On the other hand, AA-12 (activated by only Na_2SiO_3-$9H_2O$) showed the lowest performance with compressive strength decreased 57% at 7 days and 29% at 28 days when compared with AA-1. When anhydrous form sodium metasilicate was used (Mix AA-13) 7-day compressive strength was observed to increase from 0.7 MPa to 3.6 MPa while 28-day compressive strength value increased from 1.5 MPa to 5.32 MPa in comparison with mix activated using Na_2SiO_3-$9H_2O$ (AA-12). Both AA-12 and AA-13 mixes were prepared with 100% fly ash as precursor materials. The highest compressive strength was recorded for AA-14 where 100% slag was used and activated with a blend of Na_2SiO_3-$9H_2O$ and $Ca(OH)_2$. It reached 5.65 MPa at 7 days and 25.68 MPa at 28 days. The drastic increase showed the superior reactivity of slag in the presence of Na_2SiO_3-$9H_2O$ and $Ca(OH)_2$ which

can be due to the formation of C-(A)-S-H gels from calcium (source- $Ca(OH)_2$ and Slag) and silicate (source- Na_2SiO_3-$9H_2O$) ions (Sun et al, 2022).

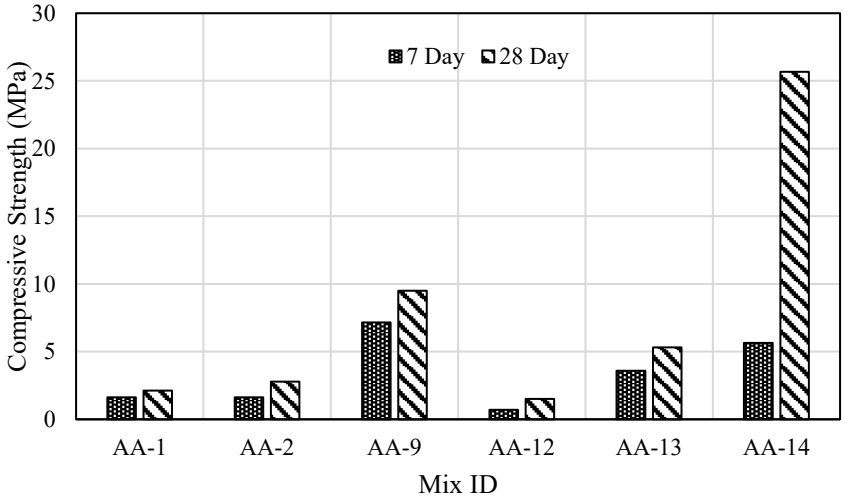


Figure 7: Compressive Strength of different one part alkali activated paste mixes.

4. CONCLUSIONS

This paper focused on the development of one part alkali activated material with the different combination of activator types and precursors. Based on the observed findings following concluding remarks can be made-

- Activator composition and precursor type significantly influenced the setting time and compressive strength. The mixes with Na_2SiO_3-$9H_2O$ + $Ca(OH)_2$ showed moderate setting time while Na_2SO_4 + $Ca(OH)_2$ delayed setting time but improved later age strength.
- Workability improved with hydrated sodium metasilicate and slag inclusion but decreased with inclusion of sand content. Increasing the sand content to 100% of binder resulted in approximately 69% reduction in relative slump. Typical relative slump values was observed in the range of 1.03 to 3.62 (flow spreads 142.5–215 mm).
- Underwater curing recorded higher compressive strength for most mixes, particularly in case of Fly ash-based mixes whereas ambient curing benefited binary mixes (80% Fly ash + 20% slag) through improved long term geopolymerization.
- Maximum 28 days compressive strength was observed to be 25.68 MPa which was attained with 100% GGBFS activated by Na_2SiO_3-$9H_2O$ + $Ca(OH)_2$ under ambient curing.
- As for FA based AAB mix containing FA-F as precursor and Na_2SO_4 + $Ca(OH)_2$ as alkaline activator showed compressive strength of 9.5 MPa under ambient curing condition.

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DECLARATION OF USE OF AI

The authors declare that AI-based tools were only used to resolve grammatical mistakes in the manuscript. These tools were not involved in the research problem formulation, research design, data analysis, and presentation of findings or drawing of conclusions. The authors have complete responsibility of the work and its integrity.

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