Alkali activated cement mixture at ambient curing: Strength, workability, and setting time

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Abstract
The success of ordinary Portland cement (OPC) comes at a risk to the environment because of the large carbon dioxide emissions associated with cement manufacturing. This has led the scientific community to look for alternative cementitious materials with lower environmental impact. Alkali activated cement (AAC) is an excellent alternative to this end. In this study, the effect of binder content, alkaline solid to binder ratio (AS/B), sodium silicate to sodium hydroxide solids ratio (SS/SH), and total water content to total solid binder ratio (TW/TB) on the strength, setting time and flowability of ambient cured AAC mixtures are studied using Taguchi method of experimental design. Binder content was varied from 550 to 750 kg/m³, AS/B ratio from 0.14 to 0.22, SS/SH ratio from 1.5 to 2.5, and TW/TB ratio from 0.29 to 0.39. The study results showed that within the investigated range, an increase in binder content has a minor effect on strength but resulted in a considerable increase in setting time and flowability. An increase in the AS/B ratio resulted in increased flowability and setting time and a decrease in strength. Moreover, the study also investigated the relationship between compressive strength and flexural strength.

KEYWORDS
alkali activated, ambient curing, blast furnace slag, flexural strength, fly ash, setting time, Taguchi experimental design, workability

1 | INTRODUCTION

Environmental issues are significant concerns in the global perspective of sustainable development. The infrastructure sector is a major greenhouse gas emitter and consumer of natural resources. One reason for this is ordinary Portland cement (OPC) concrete: the most commonly used construction material. The success of OPC comes at a risk to the environment because of the large carbon dioxide emissions associated with its production and its large consumption. One ton of OPC clinker production releases about 1 ton of CO₂ to the environment, making the cement industry contributor of about 8% of the global CO₂ emission. This high environmental footprint issue of concrete is a global problem in need of attention. This context has led the scientific community to look for building materials with lower embodied energy and lower environmental impact.
Alkali activated cement (AAC) is an excellent alternative for replacing OPC as it provides the required qualities. AAC is produced by activating source materials such as fly ash and slag with alkaline solutions. The source materials are usually byproduct or secondary product materials. The use of such materials saves raw materials and decreases the emission of CO₂ associated with the manufacture of cement. The footprints of the alkaline solutions can impact the overall sustainability of AAC.\(^\text{3,4}\) However, using greener production processes and waste-derived alkali activators can substantially reduce the impact.\(^\text{3,5}\) Concrete made from AAC has highly desirable characteristics such as rapid rate of strength development, good bond strength, resistance to acid attacks, and improved fire resistance.\(^\text{6–9}\)

By replacing OPC based concrete with AAC, it is possible to produce a material capable of reducing the environmental problems associated with OPC production.

Due to the lack of standard mix design methods and a detailed understanding of the different ingredients and their effects and behaviors, various mix design methods and concrete mixtures have been reported.\(^\text{10–14}\) Most of these studies are mainly devoted to heat-cured AAC systems, and they mainly focus on mechanical performance. Heat curing limits the applicability of AAC. The construction industry is not only looking for environmentally friendly concrete but also convenience and flexibility. Ambient cured AACs have wider application areas. Using ground granulated blast furnace slag (GGBS) as the source material enhances AAC’s ambient curing behavior.\(^\text{15}\) The high calcium oxide content and fineness of GGBS improve the binder’s reactivity and enhance reaction product formation at ambient curing conditions; however, it reduces setting time and flowability\(^\text{16–19}\) due to the early formation of calcium aluminosilicate hydrate (C-A-S-H) gel.\(^\text{17}\) Such low setting time and workability limit the application of AAC. Hence, it is essential to produce ambient cured AAC concrete with a better setting time and workability. To achieve this, it is critical first to understand how the various constituents of AAC affect the workability, setting time, and strength of the concrete.

Previous researchers have identified different factors affecting the properties of ambient cured AAC.\(^\text{17,18,20}\) The main factors identified are the alkaline liquid to binder ratio, the activating solution concentrations and ratios, and the binder content. The increase of alkaline liquid to binder ratio, for instance, results in the decrease of the strength and increase of setting time and flowability.\(^\text{17}\) However, it is unclear whether this effect comes from the increase in the alkaline solids or the increase in the alkaline solution’s water content. Similarly, the variation of the alkaline solutions’ ratio, such as sodium silicate to sodium hydroxide solution, may not clearly show the effect of the solid silicate to hydroxide ratio. As one varies this ratio, the mixture’s total water content will also change when the two solutions are of different concentrations. This study divides the AAC binder into solids and water parts analogous to OPC binder systems to avoid these issues. From the solids, the binder (source material) content (B), the alkaline solid to binder ratio (AS/B), and sodium silicate to sodium hydroxide solids ratio (SS/SH) were varied. The total water to total binder ratio (TW/TB) was varied to capture the effect of water. TW is the amount of the free water and the water from the alkaline solution, while TB is the total amount of binders used, that is, the source materials (B) and the alkaline solids (AS) together. The experiments are designed, and the factors are analyzed according to the Taguchi method. Furthermore, based on this method, optimum mixes are designed for strength, setting time, and workability. The research is part of an ongoing project on developing fine-grained AAC concrete systems for textile reinforcement. Hence, high binder content and only fine-grained aggregates, typical fine-grained concrete requirements, are used.

## 2 | EXPERIMENTAL DETAILS

### 2.1 | Materials

Fly ash (FA), GGBS, silica fume (SF), and metakaolin (MK) were used as the source materials. All the source materials are commercially available. The FA, GGBS, SF and MK comply with the EN 450-1,\(^\text{21}\) EN 15167-1,\(^\text{22}\) EN 13263-1,\(^\text{23}\) and ASTM C618-17\(^\text{24}\) requirements, respectively. The chemical compositions of these source materials are summarized in Table 1. Figure 1 shows the grain size distributions for each ingredient. The activator solution used is a mixture of sodium silicate and sodium hydroxide. The sodium silicate solution includes 26.82% silicate, 8.2% sodium oxide, and 64.98% water, while the sodium hydroxide is a 50% by weight solution. Furthermore, a fine aggregate with a maximum aggregate size of 2 mm and absorption capacity of 1.0% was used.

### 2.2 | Specimen preparation and test methods

The sodium silicate and sodium hydroxide solutions were mixed in the required proportion at least 24 h before mixing. AAC specimens were prepared by first mixing the dry materials (sand and binder) in a mixer for 2 min. Afterward, the prepared alkaline solution was mixed with the additional water, added slowly to the dry mixture, and mixed for 4 min.

The consistency of the fresh mixture is determined by flow tests according to EN 1015-3.\(^\text{26}\) After the flow test,
the fresh mixture was removed from the flow table and added back to the mixing bowl, and remixed. The mixture was then placed into 40 mm \( \times \) 40 mm \( \times \) 160 mm prisms for compressive and flexural testing according to EN 1015-11. Three prisms were produced for each mixture. These specimens were cast in two layers, and each layer was tamped 25 times. After casting, the specimens were placed in the environmental control room (20°C temperature and 65% relative humidity). The specimens were demolded after 24 h and kept in the environmental control room until the test day. The setting times were evaluated using the Vicat needle apparatus. The initial setting time is determined as the elapsed time between mixing the solution and binder system to the time at which the distance between the needle and baseplate is about 3 mm. The final setting time is the time between the mixing to the time at which the needle penetrates less than 0.5 mm into the specimen. The setting time test was conducted in the environmental control room to avoid uncontrolled temperature and humidity effects. The reported results are the average of two measurements.

### 2.3 Preliminary experiments

To optimize the proportions and types of source materials used in the AAC mixture, a preliminary experiment was conducted. Different mixes were designed at a constant SS/SH ratio of 2.5 and binder content of 750 kg/m³ and tested for workability and strength. Table 2 shows the mixture proportions.

Reduction of the GGBS content from 40% to 20% of the total binder reduced the strength by about half (T1 and T2 in Table 2) and increased its workability. Both strength and workability are desirable properties. GGBS had a more pronounced effect on strength than on workability. Therefore, for the main experiment, the GGBS content was fixed at 40%. Replacement of FA with MK and SF increased the strength (T2 and T5 in Table 2). However, the replacement of FA by SF reduced the strength of AAC (T1 and T4 in Table 2). This could be due to the higher alumina content of the FA. Hence, the increase in strength in the case of T5 compared with T2 came from the MK. However, workability is negatively influenced by MK (T4 and T6 in Table 2). Therefore, for the main experiment FA, GGBS, and SF were selected. For the main experiment, the proportions were 55%, 40%, and 5%, respectively, for FA, GGBS, and SF, a mix between T1 and T4. This proportion of source materials as per the chemical composition in Table 1 results in a CaO content of about 20%. Such mixes result in aluminum modified calcium silicate hydrate (C-A-S-H) along with aluminosilicate polymers phases; sodium aluminosilicate hydrate (N-A-S-H), leading to a suitable coexistence of N-A-S-H and C-A-S-H. According to Herrmann et al., this results in a good compromise between strength and durability.

All the mixes in Table 2 were air-cured in the environmental control room without covering the specimens.

### Table 1 Chemical composition of ingredients

| Composition | FA (%) | GGBS (%) | SFa (%) | MKa (%) |
|-------------|--------|----------|---------|---------|
| SiO₂        | 49.79  | 34.48    | 93.81   | 53.6    |
| Al₂O₃       | 26.71  | 11.48    | 0.48    | 29.2    |
| Fe₂O₃       | 8.57   | –        | 1.49    | 0.4     |
| MgO         | 2.47   | 7.08     | 0.46    | 0.4     |
| CaO         | 4.34   | 42.43    | 0.30    | 2.9     |
| K₂O         | 3.36   | 0.66     | 0.77    | 1.8     |
| Na₂O        | 1.28   | 0.56     | 0.42    | 9.7     |
| SO₃         | 1.49   | 2.17     | 0.20    | 0.1     |
| TiO₂        | 1.23   | 1.14     | –       | 0.3     |
| Specific surface area (m²/g) | 0.45 | 0.46 | 19.40 | 2.70 |
| Specific gravity (g/cm³)    | 2.28 | 2.91 | 2.20  | 2.60   |

*aManufacturer specification.*
Additional preliminary tests were carried out to identify the best curing method for the AAC mixture. T1 was prepared and cured in three ways. One batch was cured without any covering, another batch was covered with a plastic sheet, and the third batch was placed in water after demolding. All batches were placed in the environmental control room. The results show that the curing method has a significant effect on the strength of ambient cured AAC. Covered specimens showed the highest strength. On the other hand, the specimens without cover showed the lowest strength. For instance, the 28 days strength for the specimens without cover is 62 MPa, while those with cover is about 42% higher (88 MPa). The significantly lower strength in the case of the specimens without cover is due to their higher porosity. In AAC, water acts as a reaction medium where the source materials dissolve with the alkaline activator. The specimens without cover lose their water faster. This may influence the availability of dissolved ions, which negatively impact strength development. Furthermore, the covered specimens preserve the heat generated during the reaction, which is also advantageous for strength development. The specimens cured in water showed a medium strength. The water temperature was slightly lower (by about 1.5°C) than the temperature inside the plastic sheet covers. This lower temperature is probably the reason for the lower strength of the water-cured specimens. Hence, based on these observations, the specimens for the main experiment were covered with a plastic sheet. Figure 2 shows the strength development for each of the curing method.

### Table 2: Mix proportions and fresh and hardened properties for the trial set

| Ingredient (kg/m³) | T1  | T2  | T3  | T4  | T5  | T6  |
|-------------------|-----|-----|-----|-----|-----|-----|
| Sand (kg/m³)      | 1120| 1120| 1120| 1120| 1120| 1120|
| FA (kg/m³)        | 450 | 600 | 450 | 375 | 450 | 300 |
| GGBS (kg/m³)      | 300 | 150 | 225 | 300 | 150 | 300 |
| SF (kg/m³)        | –   | –   | 75  | 75  | 75  | 75  |
| MK (kg/m³)        | –   | –   | –   | 75  | 75  | 75  |
| SHL (kg/m³)       | 60  | 60  | 60  | 60  | 60  | 60  |
| SSL (kg/m³)       | 214 | 214 | 214 | 214 | 214 | 214 |
| Water (kg/m³)     | 63  | 63  | 63  | 63  | 63  | 63  |
| Flow (mm)         | 170 | 180 | 290 | 260 | 220 | 220 |
| 7 days strength (MPa) | 54.6 | 28.4 | 37.1 | 47.8 | 30.9 | 55.5 |

Note: SHL and SSL solutions of sodium hydroxide and sodium silicate, respectively. All specimens were cured in the environmental control room without covering the specimens.

2.4 | Design of experiment and data analysis

Taguchi method of experimental design was used for the design, analysis, and optimization using Minitab software. Taguchi method is a fractional factorial design method that uses a special set of orthogonal arrays (OA) to design experiments. It is originally used to improve the quality of products using statistical and engineering concepts. Due to the OA the method provides significantly reduced variance for the experiment, making it possible to investigate a large number of variables with a small number of experiments. The design of experiments using OA is quite efficient compared with traditional experiment design methods. The method has been successfully used in concrete technology to investigate physical and mechanical properties.

In the analysis and optimization of results, signal to noise (S/N) ratio is used. This is the ratio of the mean (signal) to the standard deviation (noise). The S/N ratio is generally identified as lower-the-better, nominal-the-better, and higher-the-better. In this study, higher-the-better is utilized to maximize the strength, setting time, and
flow values. The corresponding function for this is as shown in Equation (1).$$S/N = N - 10\log \frac{1}{\frac{\mu^2}{n}}$$

where, $\mu$ is the signal mean (compressive strength, setting time, or flow values) and $n$ is the number of test repetitions.

Four main parameters, binder content (B), alkaline solid to binder ratio (AS/B), sodium silicate to sodium hydroxide solids ratio (SS/SH), and total water to total binder ratio (TW/TB), were considered for the factorial analysis and optimization. The parameters selected, their designated symbols, and ranges are as shown in Table 3.

The Taguchi three level four factor design was selected to design the experiment. Each factor has 2 degrees of freedom (number of levels minus one), which means a total of 8 degrees of freedom is required. The total number of experiments should be greater than or equal to the total degrees of freedom plus one. The most appropriate orthogonal array for this is L9 (3^4), which has nine runs. Hence, a total of nine Taguchi Mixes (TM), as shown in Table 4, are selected. Two batches of these mixes were prepared at a similar condition except for the ambient laboratory temperature during mixing. In batch 1 the average ambient temperature was about 27°C and about 24°C in batch 2. This temperature variation is taken as a noise factor within the ambient curing regime for the Taguchi design.

### 3 RESULTS AND DISCUSSIONS

#### 3.1 Results

The compressive and flexural strengths, the setting time, and the flow values were used as evaluation criteria. Table 5 and Figure 3 give a summary of these results. The response index (a value showing the strength of the effect of that particular parameter on the response) for each of the mixes was calculated using the signal to noise ratio (S/N) based on Equation (1).

The effect of each of the factors on the particular behavior is investigated using the main effect plots of the S/N ratio in the following section. The response index for each parameter is obtained by taking the average of the S/N ratio for all the mixes containing that parameter. For instance, for binder content of 550 kg/m^3 using Equation (1), a 7-day compressive strength S/N ratio of 35.49, 34.06, and 32.37 were determined for TM 1, TM 2, and TM 3, respectively. Hence the response index for this parameter is 33.97.

#### 3.2 Factorial analysis and optimum mix design

##### 3.2.1 Compressive strength

Figures 4 and 5 show the contour plots of the 7-day strength and the main effect plots for 7-day and 28-day strengths. The contour plots show how two parameters affect the specific behavior under investigation when the other two parameters are kept constant. The colors show the strength of the response. For instance, in Figure 4, the contour plot for AS/B and B shows that at SS/SH ratio of 2 and TW/TB ratio of 0.34, increasing both AS/B and B decreases strength. However, AS/B has more influence as the strength along this axis changes from 42–45 MPa range to 54–57 MPa range while on the B axis, it stayed mostly in the 54–57 MPa range as B changes from 550 to 750 kg/m^3.

A ss h o w ni nF i g u r e 5, the most significant factor affecting both the 7-day and 28-day compressive strengths is TW/TB followed by AS/B. For the 7-day compressive strength, for instance, TW/TB has a 55% contribution while AS/B has 42% (calculated by dividing the squared deviation of a factor by the total sum of squared deviations for all factors). Except for the SS/SH ratio, the 7-day compressive strength decreases with each parameter (with no significant influence in the case of binder). However, the strength increase with the SS/SH ratio is much less significant (with only 3% contribution) than TW/TB and AS/B. Hadi et al. also observed similar behavior for the 7-day compressive strength. Bignozzi et al. reported that increasing the proportion of sodium silicate solution generally encourages gel formation, resulting in higher strength. However, Deb et al. and Nath and Sarker reported that strength increases with the decrease of SS/SH ratio. This difference could be due to the type of source materials used or the range of SS/SH ratio studied.

### Table 3 Parameters and proportions used in the Taguchi experiment design

| Parameters | Level 1 | Level 2 | Level 3 |
|------------|---------|---------|---------|
| B (kg/m³)  | 550     | 650     | 750     |
| AS/B       | 0.14    | 0.18    | 0.22    |
| SS/SH      | 1.5     | 2.0     | 2.5     |
| TW/TB      | 0.29    | 0.34    | 0.39    |

Abbreviations: AS, alkaline solid; B, binder (source material); TB, B plus AS; TW, total water.
Hence TW/TB has a more pronounced effect than the other parameters. As can be seen in Figure 5, the slope of strength versus TW/TB decreased as TW/TB increased. The relationship is similar to the strength to water to cement ratio relationship of OPC concrete. AS/B is the second most significant parameter. This parameter only considers the effect of the solid parts in the alkaline liquid. Previous studies reported that the increase in alkaline liquid to binder ratio decreases the strength. However, from these studies, it is impossible to verify if this effect comes solely from the water in the alkaline solution or from the increase in the alkaline solids. Ruiz-Santaquiteria et al. reported that an excess amount of alkali solution increases the amount of water in the system and hinders polymerization. It is well known that an increase in water reduces strength; however, the current study also confirms that the increase in alkaline solid also reduces strength. However, it should be noted that the effect of the AS/B is reduced at lower AS/B (slope decreases as AS/B decreases), meaning that there may be an optimum AS/B ratio. It has been reported that the compressive strength increases with alkali content up to an optimal alkali content as a higher alkali content increases polymerization. However, a further increase after the optimum alkali content will result in calcium hydroxide formation, which reduces the amount of calcium available for the formation of calcium silicate hydrate hence a lower compressive strength.

Hadi et al. observed that the 7-day strength increases as the binder content changes from 400 to 450 kg/m³ and decreases marginally from 450 to 500 kg/m³. This means that after an optimum level, binder content will have a negative effect on strength. A higher binder content is used in the current study, and the result shows that the binder content has no significant

### Table 4: Mix proportions according to Taguchi design

| Mix | TM1 | TM2 | TM3 | TM4 | TM5 | TM6 | TM7 | TM8 | TM9 |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| B (kg/m³) | 550 | 550 | 550 | 650 | 650 | 650 | 750 | 750 | 750 |
| AS/B | 0.14 | 0.18 | 0.22 | 0.14 | 0.18 | 0.22 | 0.14 | 0.18 | 0.22 |
| SS/SH | 1.50 | 2.00 | 2.50 | 2.00 | 2.50 | 1.50 | 2.50 | 1.50 | 2.00 |
| TW/TB | 0.29 | 0.34 | 0.39 | 0.39 | 0.29 | 0.34 | 0.34 | 0.39 | 0.29 |
| SSL (kg/m³) | 132 | 189 | 247 | 173 | 239 | 245 | 214 | 231 | 314 |
| SHL (kg/m³) | 62 | 66 | 69 | 61 | 67 | 114 | 60 | 108 | 110 |
| Water (kg/m³) | 63 | 65 | 67 | 147 | 31 | 53 | 121 | 142 | 2 |
| Sand (kg/m³) | 1453 | 1331 | 1208 | 1053 | 1218 | 1067 | 938 | 769 | 970 |
| SiO₂/Na₂Oₐ | 1.05 | 1.27 | 1.45 | 1.27 | 1.45 | 1.05 | 1.45 | 1.05 | 1.27 |

Note: B—55% FA, 40% GGBS, and 5% SF binder, SHL, and SSL solutions of sodium hydroxide and sodium silicate. Abbreviations: AS, alkaline solid; B, binder (source material); TB, B plus AS; TW, total water. *Solution molar ratio.

### Table 5: Setting time, flow, and strength result summary

| Mix | Setting time (minute) | Flow (mm) | 7-day strength (MPa) | 28-day strength (MPa) |
|-----|----------------------|-----------|---------------------|-----------------------|
|     | Initial | Final | Batch 1 | Batch 2 | Batch 1 | Batch 2 | Batch 1 | Batch 2 | Batch 1 | Batch 2 |
| TM 1 | 55     | 85   | 175 | 175 | 61.1 | 7.8 | 58.0 | 7.4 | 86.0 | 11.1 |
| TM 2 | 80     | 120  | 250 | 255 | 50.2 | 6.5 | 50.7 | 6.2 | 79.7 | 8.4 |
| TM 3 | 95     | 160  | 290 | 300 | 42.3 | 5.2 | 40.8 | 5.0 | 67.7 | 7.5 |
| TM 4 | 50     | 90   | 280 | 290 | 49.1 | 5.9 | 48.5 | 5.7 | 75.3 | 7.9 |
| TM 5 | 75     | 110  | 240 | 240 | 61.1 | 7.2 | 59.6 | 7.2 | 87.8 | 10.5 |
| TM 6 | 140    | 300  | 280 | 285 | 41.5 | 5.0 | 39.2 | 4.4 | 70.5 | 8.1 |
| TM 7 | 55     | 80   | 275 | 280 | 51.9 | 6.2 | 51.7 | 4.9 | 81.5 | 9.6 |
| TM 8 | 95     | 215  | 310 | 320 | 45.8 | 5.1 | 45.8 | 5.1 | 77.4 | 8.3 |
| TM 9 | 165    | 260  | 255 | 260 | 51.4 | 5.6 | 49.9 | 5.2 | 83.5 | 8.8 |
influence on the 7-day strength and only a minor effect on the 28-day strength (with 7% contribution). About 3 MPa increase in strength from 550 to 750 kg/m³ was observed in the latter case. This difference between 7-day and 28-day could be due to the progress of reaction between the alkali and the binder, which were unreacted.
during the 7-day test. The AS demand also increased with age as the unreacted binder requires more activators. As shown in Figure 5, the maximum strength shifted from 0.14 AS/B in the case of 7 days to 0.18 AS/B in the case of 28 days. Another way to look at this is by checking the percentage contribution of AS/B. The percentage contribution of AS/B decreased from 42% to 31% as the age increased from 7 to 28 days. The decreasing effect of AS/B with age means that its negative influence on strength is decreasing. This is due to more alkali demand with the progress of the reaction.

The flexural strength also showed a similar pattern as that of the compressive strength, that is, decreasing mainly with TW/TB and AS/B ratios, as shown in Figure 6. However, the binder content showed a more substantial effect on the 7-day flexural strength (19% contribution) than the corresponding compressive strength. A similar result was observed by Bu et al. As can be observed from Table 4, to keep unit volume, the sand content decreased as binder content increased, resulting in lower sand to binder ratio. When other parameters are kept constant, both compressive and flexural strengths increase with the sand to binder ratio up to an optimum ratio.

3.2.2 Setting time

Figures 7 and 8, respectively, show the initial setting time’s contour plots and the main effect plots of the initial and final setting times. As can be observed in these figures, the main parameter that affects the setting time is the AS/B ratio. This ratio has about 86% contribution for the initial setting and about 76% for the final setting time. Increasing this ratio increased the setting time. The binder content and SS/SH ratio also affected the setting time, however, at a lower significance. An increase of binder content increased the setting time while the reverse was observed for SS/SH. Nagajothi and Elavenil also observed a similar trend for sodium silicate to sodium hydroxide solution ratio.

The TW/TB is not a main significant factor for setting time; however, an interesting result was observed for this ratio. The initial setting time showed a decreasing tendency as this ratio increased. This is in contradiction with normal OPC behavior. An increase of water to cement ratio (W/C) normally increases both the initial and final setting time of OPC. To better understand the effect of TW/TB ratio on AAC, the setting times of two of the mixes (TM 6 and TM 8) were tested with a different TW/TB ratio, 0.29. Initially, TM 6 and TM 8 have a TW/TB ratio of 0.34 and 0.39, respectively. Figure 9 shows the evolution of the setting just after mixing for each of these mixes.

As can be seen in Figure 9, compared with their corresponding mixes, the high TW/TB ratio specimens showed a lower initial setting time and a gradual decrease in penetration depth. On the other hand, the low TW/TB specimen showed a higher initial setting time and a faster drop in penetration depth, meaning that the slope of the penetration depth changed as the TW/TB ratio changed. Because of the different slopes, the relationship between the final setting time and the TW/TB changed, that is, final setting time increased with TW/TB ratio, as shown from Figure 8. Such a change in slope with the TW/TB is different from what is generally observed for OPC. OPC has an almost parallel slope for different water to cement ratios.

The observed difference between AAC and OPC shows the basic difference in their chemical reactions, the setting process and the contribution of water. In the case of OPC, water takes part in the chemical reaction by reacting with the cement; however, in the case of AAC, water is not the main reaction participant. It is not clear why the setting time is behaving in such a way with the change of water content, and the results of this study are not enough to draw conclusions and give a detailed explanation of this phenomenon. Song and Jennings reported that the solubilities of the Si, Ca, Al, and Mg are strongly affected by the pH of the solution. High pH increases the concentration of Si and Al, but reduces that of Ca and Mg. Hence, an increase in TW/TB ratio decreases pH and results in better dissolution of CaO. This could be one reason for the lower initial setting time with a high TW/TB ratio. It is also possible that the higher water content initially expedites the reaction between the activator and the source material, which is the first process in the polymerization, hence resulting in a faster reaction. However, as the reaction proceeds, this effect lessens as the mixes with less water will have enough time for dissolution with the water available. Furthermore, evaporation of the water from the specimen may also contribute to the decrease in final setting time with the decrease of water.
As the ratio of SS/SH increased, the initial setting time decreased. For instance, the average initial setting time of all mixes with SS/SH ratio of 1.5 is 95 min, while those with 2.5 have an average of 75 min. This shows the effect of the chemical composition of the alkaline solid on the setting time of AAC. Nath and Sarker have observed a similar trend for sodium silicate to sodium hydroxide solutions ratio. A mainly decreasing trend of setting time with the increase of this ratio was also observed by Lee and Lee for AAC, with the ratio varying between 0.5 and 1.5 and at a much lower hydroxide solution concentration. Nath and Sarker explained that this behavior is due to the increase in the amount of silica in the solution with the increase of the ratio, which accelerates the polymerization process.

Palacios et al. and Puertas et al. reported that AAC activated with sodium silicate has a lower setting time than those with sodium hydroxide. This is due to the formation of primary calcium silicate hydrate (C-S-H) gel in the early stages of the reaction due to the bonding of the Ca\(^{2+}\) ions from the slag to the silicate ions in the sodium silicate.

### 3.2.3 Workability

Figures 10 and 11, respectively, show the contour plots of the flow values and the main effect plots for each of the parameters studied. All the investigated parameters...
increased workability. Tekle et al.\textsuperscript{25} reported a similar result. Like compressive strength, the TW/TB ratio, with 59% contribution, is the most significant factor for workability. This is followed by the binder content with a 22% contribution. The least significant factor for workability is the SS/SH ratio. SS/SH ratio has an opposite effect on setting time and flowability. An increase in this ratio decreased the setting time and increased the flow, that is, the 2.5 SS/SH ratio resulted in the lowest setting time while giving the highest flow value.

According to Nath and Sarker\textsuperscript{17} the increase of sodium silicate to sodium hydroxide solution ratio decreased the slump of the concrete. This opposite effect of the ratio, compared to the current study, could be due to the difference in source materials used; no SF was used in Ref. [17] and the proportion of GGBS and FA are different or it could be due to the type of activators used. The concentration of the sodium silicate and sodium hydroxide used in Ref. [17] is almost similar, that is, 40.4% solid in 1 kg solution for sodium hydroxide and 42.1% solid in case of sodium silicate. Hence, the difference observed is less likely to be from the different solution and solid ratio definitions.

3.2.4 | Optimum mix design

The above discussion based on the Taguchi method gives information on which factor is more significant to each behavior investigated. In order to validate the factorial analysis, three optimum mix proportions were prepared and tested. The first optimum mix was optimized for maximum 7-day compressive strength (TM-S). From Figure 5, it can be observed that lower binder content, AS/B ratio, and TW/TB ratio result in higher compressive strength. Hence, a binder content of 550 kg/m\textsuperscript{3}, AS/B ratio of 0.14, and TW/TB ratio of 0.29 were selected. As the 7-day compressive strength increases with SS/SH ratio, this ratio is set at 2.5. Based on Figures 8 and 11, the initial setting time (TM-Set) and Flowability (TM-F) were maximized similarly. The resulting mix proportion for maximum strength, initial setting time, and workability mixes are summarized in Table 6. Additionally, different random mix compositions were mixed and tested, and their predicted values were compared with the experimental values (TM 10 to TM 14). The prediction was performed using Minitab software.
As can be observed from Table 6, the optimized mixes resulted in the highest strength, setting time, and flow values compared with TM 1 to TM 9 mixes. Furthermore, the Taguchi method’s predicted results were also compared with the experimental values and were found to be sufficiently close. For instance, for optimum strength, the Taguchi method predicted a 7-day compressive strength of 62.2 MPa, and the experimental result was 61.8 MPa. The Taguchi method predicted the strength, setting time, and flow values of the optimum mixes and the random mixes satisfactorily. The average of predicted to experimental ratios is 0.98 for strength, 1.00 for setting, and 0.99 for flow values, while the standard deviation is 0.02, 0.09, and 0.02, respectively. This shows the accuracy of the studied relationships between the different factors. Furthermore, these relationships can satisfactorily be used for mix design in the range of behavior studied, as demonstrated by the additional random mixes.

### 3.3 | Flexural strength

Flexural strength is an essential mechanical property that represents the ability of a material to resist bending. It is highly related to compressive strength. Various standards give recommendations on the relationship between the flexural strength and compressive strength for OPC concrete. This relationship is dependent on the size of aggregate used. In the case of concrete (coarse aggregate), the flexural strength is related to the square root or the power (2/3) of the compressive strength. In the case of cement mortars, however, a linear relationship has been
Using least square regression, the various trial and main experimental results in this study are calibrated, and the flexural strength was found to be related linearly to the compressive strength. The result indicates that the flexural strength is around 11.4% of the cube strength. The resulting relationship for cube compressive strength versus flexural strength is shown in Figure 12.

4 | CONCLUSION

Based on the experimental results presented in this study, the following conclusions can be drawn:

- The compressive strength of AAC decreases as the TW/TB ratio increases, which is the main significant parameter. The AS/B ratio has more effect on the strength than SS/SH and binder from the solid parameters.
- The main significant parameter affecting the setting time of AAC is the AS/B ratio. Compared with the other factors, TW/TB ratio has only a minor effect on both initial and final setting times. Its effect on initial setting time is the opposite of that of conventional OPC mixtures.
- The flowability of AAC increases with the increase of binder content, TW/TB, SS/SH, and AS/B ratios, with the most significant parameter being TW/TB ratio followed by binder content.
- The Taguchi method can successfully be applied to optimize and predict the physical and mechanical properties of AAC mixtures.
- The flexural strength of AAC mixture with 2 mm sand is about 11.4% of the cube compressive strength.

Finally, the results from this study can help understand the influence of different parameters involved in AAC mix design at ambient curing conditions. These results are important in fine-grained AAC concrete design, a relatively new development in textile-reinforced concrete requiring high workability and bonding behaviors, which the authors are currently working on. However, it should be noted that the findings of this study are limited to the investigated AAC system due to the different varieties of AACs available. It is necessary to accumulate more experimental data considering the various AAC systems to further expand the knowledge in the field.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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