

Properties of ambient cured blended alkali activated cement concrete

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Abstract. This paper presents results of the development and strength properties of ambient-cured alkali activated geopolymer concrete (GPC). The study looks at the strength properties, such as compressive strength, splitting tensile strength, and elastic modulus of such concretes and its dependency on various parameters. The parameters studied in this work are the type and proportions of pre-cursor materials, type of activator and their respective ratios and the curing time. Two types of pre-cursor material; low calcium fly ash (FA) and ground granulated blast furnace slag (GGBFS) were activated using different proportions of sodium silicate and sodium hydroxide solutions. The results indicate that ambient cured geopolymer concrete can be manufactured to match strength properties of ordinary Portland cement concrete (OPC). The strength properties of GPC are dependent on the type and ratio of activator and the proportion of GGBFS used. Increasing the percentage of GGBFS increased the compressive and tensile strengths, while reducing the setting time of the mix. The effect of GGBFS on strength was more pronounced in mixes that contained sodium silicate as activator solution. Unlike OPC, ambient-cured GPC containing sodium silicate gain most of their strength in the first 7 days and there is no change in strength thereafter. However, GPC mixes not containing sodium silicate only achieve a fraction of their strength at 7 days and extended curing is required for such concretes to gain full strength. The results also indicate that the elastic modulus values of GPC mixes without sodium silicate are comparable to OPC while mixes with sodium silicate have elastic modulus values much lower than ordinary concrete.

1. Introduction

With a recent shift of focus in the construction industry to move towards a low carbon future, efforts are being made to find viable and effective alternatives to OPC concrete. Currently, concrete is the most used commodity second only to water with an average global consumption of 1m³ per person [1] and is responsible for the production of 5% of the global CO₂ emissions in developed countries while as high as 10% in developing countries [1, 2]. To put these numbers in perspective, the total greenhouse gas emission by a highly industrialized country like Germany is documented in the Paris Agreement Article 21 Annex I to be 2.56% of the global emissions [3].

In the last decade, or so, extensive research has been undertaken to find alternates to Ordinary Portland Cement (OPC) concrete for construction. Among other alternatives, Alkali Activated Materials (AAM) [sometimes referred to as geopolymer concrete] have come to the forefront and offer a viable alternate to OPC. AAMs can be formed by reacting a silica (SiO₂) and alumina (Al₂O₃) rich material, such as metakaolin, Fly Ash (FA), Silica Fume (SF), Rice Husk Ash (RHA) or Slag with alkali liquids such as a soluble metal hydro-oxide and/or alkali silicate [4-6]. Such binders combined with traditional coarse and fine aggregates to form concrete with fresh and hardened properties similar to or even superior to OPC. Consequently, and contrary to OPC, AAM concrete does not depend on calcining calcium



carbonate, which is the major source of CO₂ emission in OPC concrete [7], and hence can reduce emissions by 45 to 80% for each cubic metre of OPC concrete replaced [6, 8].

Despite the advantages, there are several challenges that need to be overcome for AAMs to be used as a mainstream construction material. One such challenge is the dependency of the properties of these binders on the pre-cursor source and the activation system. Broadly AAM are categorized as low and high calcium system with hybrid systems gaining popularity in recent years [9].

Several studies on the mechanical behaviour of heat cured AAM are available in the literature [9-19], however, work on ambient cured AAM is rather limited. For heat cured AAMs the mechanical properties and microstructure of the matrix is highly influenced by the mixing conditions, rest period, curing time and temperature, and the concentration of the activating solutions. Nath and Sarker [19] recently reported on the modulus of elasticity and the flexural strength of ambient cured blended geopolymers. They also proposed analytical relationships between experimental and predicted values of modulus for such materials. They concluded that the modulus of elasticity of ambient cured blended AAMs is 25-30% lower than that of OPC with comparable strength. The effect of moisture condition on the strength gain of heat and ambient cured geopolymer concrete was studied by Jiting and Kayali [20], while Nath and Sarker studied the effect of OPC on the early strength properties of geopolymer concrete cured at room temperatures [21]. Despite these relatively recent studies, there is an obvious need for further investigation on the various parameters that effect the properties of ambient cured AAMs. The work reported here is part of a wider investigation into the study of development and characterization of ambient cured blended AAMs. Initial findings of this investigation include the strength development and its dependency on the proportion of the precursor blend and the activator used.

2. Experimental work

2.1. Materials

Locally acquired low calcium Class F fly ash and GGBFS was used as pre-cursor material in this study. The composition of the pre-cursors materials (FA and GGBFS) used in this work, as found using X-Ray Fluorescence (XRF) are tabulated in Table 1. Sodium silicate and sodium hydroxide solutions were used as alkaline activators. Sodium silicate solution (Na₂SiO₃) with density between 1.296 and 1.396 gram/ml produced by Merck, KGaA, Germany and procured from ESTS, UAE was used. Sodium Hydroxide solutions (12M) were made from 98% purity flakes supplied by ESTS, UAE. Locally sourced, natural crushed aggregates, nominal sizes 20 and 10mm was used as coarse aggregates (with specific gravity of 2.68 and absorption of 0.7%), while a mixture 60%-40% of 5mm crushed aggregates and dune sand was used as fines (with specific gravity of 2.62 and absorption of 1%) in the mix.

Table 1. X-ray fluorescence (XRF) of fly ash and GGBFS used.

Material	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	SO ₃	K ₂ O	CaO	TiO ₂	MnO ₂	Fe ₂ O ₃	NiO	ZnO	SrO
FA	1.045	7.51	10.97	59.83	1.545	1.42	8.75	1.08	0.175	7.525	0.03	0.04	0.08
GGBFS	-	6.58	5.71	32.36	2.38	-	51.01	0.64	0.73	0.59	-	-	-

2.2. Specimen preparation and mix proportions

Fine and coarse aggregates in SSD condition were mixed with fly ash and GGBFS for 2 minutes. Silicates solution, if any, was then added to the dry mix and mixed for 3 minutes. Hydroxide was then added and mixed for 2 more minutes. Additional water along was then added and mixed for additional 2 minutes. The mix proportions used in this study are summarized in Table 2 and are based on the work of Junaid et al [22]. For all tested mixes, the water to binder ratio (w/b) was kept constant at 0.32. The ratio was calculated using the following equation:

$$w/b = \frac{W_{free} + W_{OH} + W_{Si}}{FA + G + S_{OH} + S_{Si}} \quad (1)$$

Where;

W_{free} = Weight of free water in the system

W_{OH} = Weight of water content of the OH solution

W_{Si} = Weight of water content of the silicate solution

G = Weight of GGBFS

S_{OH} = Weight of solid content of the OH solution

S_{Si} = Weight of solid content of the silicate solution

Cylinders with nominal measurements of 100mm dia and 200mm height were mixed and casted. The specimen were wrapped in watertight membrane to minimize water loss during setting. The moulds were removed after 24 hours and the samples were placed in an environmental room with RH of 40% and temperature of 25°C till the time of testing. Compressive strength, splitting strength, and modulus of elasticity tests were performed using the ASTM C39/C39M-14 [23], ASTM C 496/C 496M-04 [24], and ASTM C469/C469M-10 [25] standards, respectively.

Table 2. Mix proportions of the AAM used in the study.

Mix ID		SET 1					SET 2				
		S1M1	S1M2	S1M3	S1M4	S1M5	S2M1	S2M2	S2M3	S2M4	S2M5
		kg/m ³	kg/m ³	kg/m ³	kg/m ³	kg/m ³	kg/m ³	kg/m ³	kg/m ³	kg/m ³	kg/m ³
Coarse	20 mm	475	475	475	475	475	475	475	475	475	475
	10 mm	590	590	590	590	590	590	590	590	590	590
fine	Dune	260	260	260	260	260	260	260	260	260	260
	5mm	390	390	390	390	390	390	390	390	390	390
NaOH	(12M)	164	164	164	164	164	82	82	82	82	82
Na ₂ SiO ₃		0	0	0	0	0	82	82	82	82	82
FA		425	340	212.5	85	0	425	340	212.5	85	0
GGBFS		0	85	212.5	340	425	0	85	212.5	340	425
Water		58	58	58	58	58	66.5	66.5	66.5	66.5	66.5

3. Results and discussion

3.1. Setting time

The setting time of the mixes was determined using the Vicat needle apparatus and the final setting time is reported in Table 3. As is evident from the table that the setting times of mixes in Set 1 (without the silicate solutions) was generally higher than the corresponding mixes in Set 2 which had silicates and hydroxide in equal measure. Within a set, the mixes with higher amounts of GGBFS resulted in quicker setting times. The mix S1M1 was under observation for over 360 minutes, however a final setting time was not determined. This was due to the fact that this mix did not harden and the Vicat needle penetration readings did not change significantly during this time.

Table 3. Setting time of the tested mixes.

Sample ID	SET 1					SET 2				
	S1M1	S1M2	S1M3	S1M4	S1M5	S2M1	S2M2	S2M3	S2M4	S2M5
Final Setting Time (min)	360+	70	20	15	NT	120	65	15	10	NT

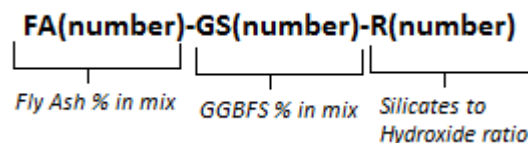
NT = not tested

Based on the above results, it can be concluded that an increase in the percentage of GGBFS, even in small amounts, decreases the setting time of the AAM mixes, significantly. This effect is more pronounced in mixes with equal amounts of silicates and hydroxides. The AAM mixes can therefore be designed to suit various application requirements as far as setting time is concerned. The setting

time of AAMs can be altered by varying the amounts and proportions of silicates, hydroxides, FA and GGBFS used in the mix for that specific purpose.

3.2. Strength

3.2.1. Compressive strength. The average 7-day compressive strength of the cylinders are given in Figure 1. For ease of readability in the results section the samples are identified using the following nomenclature:



For Set 1 (with only hydroxide activator; R=0) the compressive strength increased as the percentage of GGBFS increased reaching a maximum value of just 16 MPa for 100% GGBFS at 7 days. However, the rate of change of strength with increasing GGBFS percentage is rather slow, with the only noticeable difference between the samples S1M1 and S1M2 (with 20% replacement of FA with GGBFS). The strength of the sample with no GGBFS (S1M1) was markedly lower than all the other tested specimen indicating that for single-activator alkali activated systems the use of fly ash alone is not advisable. Moreover, for such mixes the strength development is not significantly affected by the percentage of GGBFS after 20%. For all samples in this set, the early strength is only a fraction required for practical structural applications.

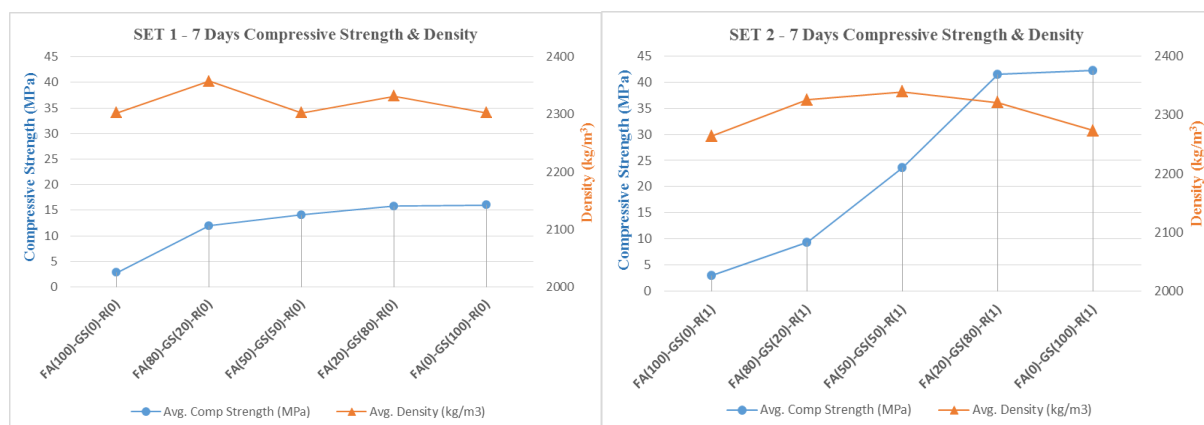


Figure 1. 7-day compressive strength of the samples for Set 1 and 2.

The average 7-day compressive strength of Set 2 (with silicate to hydroxide solution ratio R of 1) did not follow a similar trend as Set 1, with the most noticeable difference that the average strength values were significantly higher when compared to Set 1. The samples in this set returned a maximum strength value of just over 42 MPa at 7 days. The rate of strength development for this set was also much steeper than Set 1. When the GGBFS percentage was increased from 20% to 50% the strength also increased from 9.3 MPa to 23.6 MPa, an increase of just over 2.5 times. With a further increase of GGBFS from 50% to 80% the 7-day strength also increased from 23.6 to 41.5 MPa, an additional increase of over 1.7 times. Interestingly these increases in strength are in the same ratio as the increase in the GGBFS percentages of the mixes (from 20% to 50% and from 50% to 80%, an increase of 2.5 and 1.6 times, respectively). A further increase in the proportion of GGBFS had an insignificant effect on the 7-day strength of the specimen.

Nevertheless, the strength values of S2M1 and S2M2 were considerably lower than other samples in this set. It may, therefore, be concluded that for low proportions of GGBFS the early strength of all specimen tested is quite low and these mixes are not suitable for practical structural engineering applications at an age of 7 days.

The average 28 day compressive strength of samples in both sets are given in Figure 2 and they follow a similar trend to the strength acquired at 7 days. In general the samples in Set 1 returned a lower value of strengths with the maximum of under 25 MPa. Of interest is the strength gain of the samples in Set 1 at 28 days when compared to 7day strengths, with all samples gaining substantial strength, while those in Set 2 exhibit a slight gain only. Earlier work by researches [26, 27] suggest that AAMs gain all their strength in the first few days after casting and no further strength gain is expected after this initial period. However, the current finding may point to the dependency of the strength gain with time on the type of activator used and the precursor materials and its proportions, and further work needs to be done to reach a definite conclusion.

It is observed that the density of the alkali activated material is not significantly affected by the change in GGBFS percentage or the activator system. The average density of all samples was around 2300kg/m^3 , which is comparable to ordinary concrete. The variation in density does not have a measurable effect on the strength of the specimen from both sets.

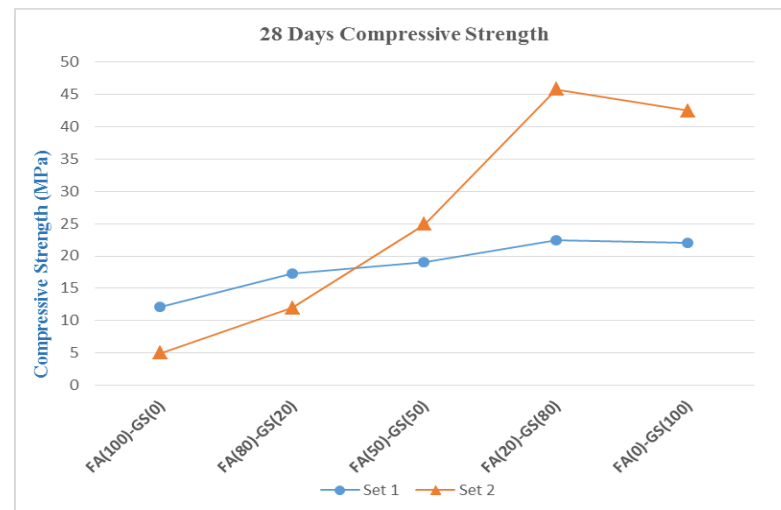


Figure 2. 28-day compressive strength of the samples for Set 1 and 2.

3.2.2. Splitting strength. The evolution of the splitting strength of AAM mixes of the two Sets of AAM samples are shown in Figure 3. As expected the splitting strength of the specimen follow the same trend as observed in the compressive strength development. The splitting strength of all samples at 7 days are approximately 10% of its compressive strength, which is widely used as a thumb-rule for determining the splitting strength of ordinary concrete. The maximum splitting strength at 7 days developed for Set 1 was just over 2.5 MPa, while that for Set 2 is 3.75 MPa. As is the case with compressive strengths, the tensile strength of Set 1 increased at 28 days when compared to 7 day values. However, the strength gain was not in the same proportion as for the compressive strength for this set. The tensile strength of Set 2 did not change with time, and follows the same trend as the compressive strength of this set.

3.3. Elastic modulus

Determination and prediction of elastic modulus of a building material is of immense importance as it is the primary factor in determining the flexural and axial stiffness of members. Comparative to OPC concrete, little work is reported on the elastic modulus of ambient cured AAM. There is a general agreement between all reported results that the elastic modulus of AAMs is lower than that of OPC with comparable strengths. The 28 day modulus of elasticity for the tested specimen (Set 1 and Set 2) are shown in Figure 4.

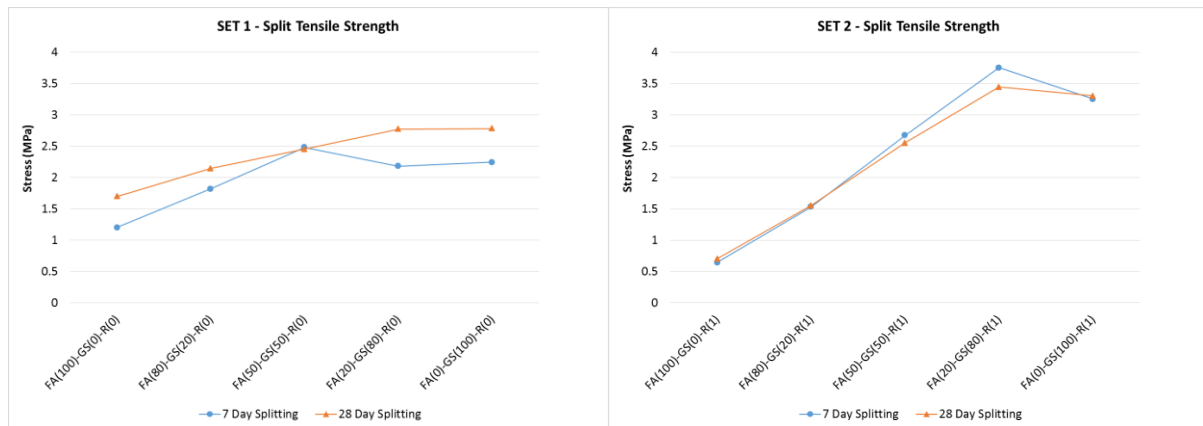


Figure 3. 7 and 28-day splitting strength of the samples for Set 1 and 2.

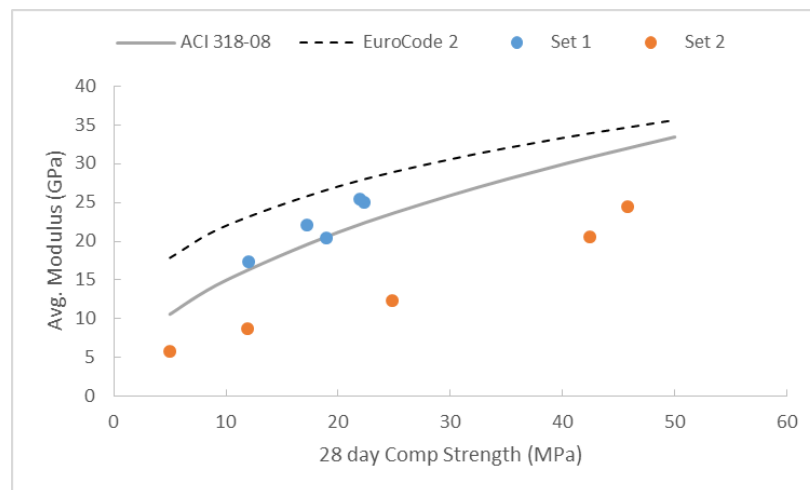


Figure 4. Young's modulus of AAMs as a function of compressive strength for Set 1 and 2.

Set 1 has a higher modulus value when compared to the samples of Set 2. These moduli values of Set 1 are a good fit with the prediction models for elastic modulus of OPC as put forward by ACI318-14 and EuroCode 2. However, the moduli values for the samples in Set 2 are much lower, although the samples reached a much higher strength. The only difference between the two sets is the presence of sodium silicate while all other parameters including the type and proportion of materials is the same. It may therefore be concluded that although sodium silicate has a positive effect on the strength of the AAMs, it may result in reduction of the elastic modulus. Also of note is the fact that both design code overestimate the modulus values of AAM containing silicates. It may therefore be concluded that standard equations can be used to predict the modulus values of AAM systems without silicate while other modified equations are required to accurately predict the modulus of AAM with silicates.

Junaid et al. [28] proposed a prediction equation for AAMs which is given in equation (2) below and demonstrated that this equation predicts with good accuracy the elastic modulus of AAMs.

$$E_c = 0.015 f_c'^{0.84} \rho^{1.43} \quad (2)$$

Where f_c' is the 28 day compressive strength (in MPa) and ρ is the density of the alkali activated concrete. The results of these tests are plotted using equation (2) and are presented in Figure 5. The results clearly show that the prediction model presented by Junaid et al can accurately predict the Modulus values of AAMs containing silicates and hydroxide as activator (Set 2), while it under predicts the modulus of AAMs activated using only hydroxides (Set 1). As Set 1 returned strength

values that are rather low and generally not suitable for structural applications, this proposed model presented above appears to be a suitable alternate for predicting AAM modulus values.

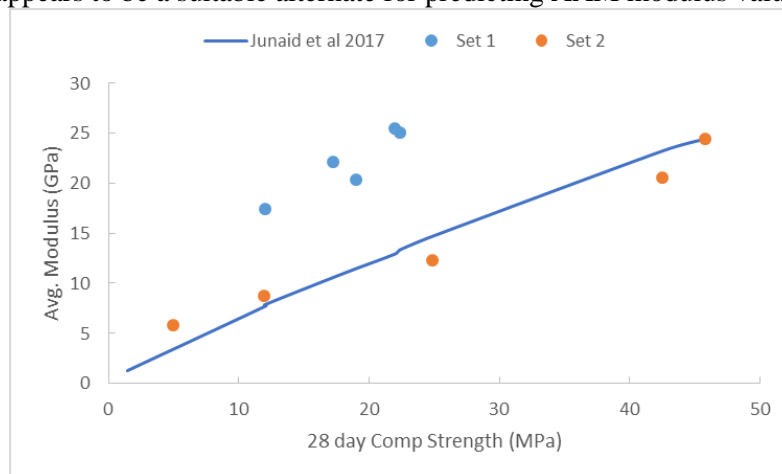


Figure 5. Young's modulus of AAMs as a function of compressive strength.

4. Summary and conclusions

A testing program was undertaken to determine the strength characteristics of ambient cured AAMs and their dependency on the various parameters such as precursor type and proportion, activator type and ratios, and curing time was studied. The compressive and splitting strengths along with modulus values were determined for different mixes. Based on the results of this study the following conclusion can be drawn:

- The strength properties of ambient cured alkaline activated binder concrete are greatly influenced by both the type and ratios of the precursor material and the activator solution. Addition of sodium silicate to the AAM system generally increases the strength of the binder but decreases the modulus of the resulting concrete.
- The splitting tensile strengths of AAM's is only a fraction of its compressive strength value and follows the same trends as the compressive strength. For systems with sodium silicate the splitting tensile strength is not effected by the curing time after the initial 7 days.
- The density of ambient cured AAMs is comparable to that of OPC concrete.
- Setting time of AAMs can be controlled by varying the proportion of GGBFS and sodium silicate in the system. Addition of both these compounds reduce the setting time of AAMs.
- The elastic modulus of AAMs is usually lower than OPC of comparable strength. It is therefore not recommended to use prediction models for OPC to predict the moduli of AAMs. The model proposed by Junaid et al [28] give accurate prediction value of the elastic modulus and is recommended to be used instead.

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