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Experimental investigation of the effect of alkaline activator and mix constituents on foam stability of foamed alkali-activated materials

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Abstract

Stable foamed concrete (FC) is formed by mixing pre-formed foam into a mortar base mix. For foam stability in normal FC, Kearsley and Mostert [1] indicated, using a modified hydraulic turntable test, that the base mix of normal FC requires a spreadability between 220 – 250 mm. Cho et al. [2], with the aim of 3D printing FC, showed that with the inclusion of nano-silica (nS) and calcium aluminate cement (CSA) a smaller base mix spreadability (<180mm) can be utilised. In this paper, foam stability in foamed alkali-activated material (F-AAM) with a target spreadability in the range of 220 – 235 mm is investigated. AAM is produced using cement-less binder, filler, and alkaline activator (AA). The effect of activator concentration is evaluated by producing mixes with varying AA concentrations. AAM spreadability is assessed using a modified hydraulic turntable test [1,2]. Foam stability is tested gravimetrically by filling a standard 100 mm cube mould and determining the density ratio.

Study results indicate that higher spreadability is associated with increased AA solution and less sand content. Based on isolated cases of material attaining stability, it can be concluded that stability does exist for the material for certain density ratios, despite a scattered data set.

Keywords: Foam concrete, Alkali-Activated Materials, Foam Stability, Spreadability

1. INTRODUCTION

One of the goals of sustainable development is climate action which has been threatened by the high levels of carbon dioxide (CO_2) emissions generated on the planet. The construction industry is one of the main contributors to CO_2 emissions, as CO_2 is a by-product of cement production [3]. This pitfall in construction has paved the way for environmentally friendly concrete such as geopolymer concrete. This type of cementitious material has provided the construction industry with a sustainable alternative to cement-containing concrete. Geopolymer concrete typically uses binders such as Fly Ash (FA), Ground Granulated Corex Slag (GGCS) and silica fume (SF) to eliminate the use of Ordinary Portland cement (OPC) [4,5]. Since AAMs are by-products of existing industrial processes, geopolymer concrete production forms part of the circular economy of construction.

The binders utilised in geopolymers are termed alkali-activated materials (AAMs) as they start chemically reacting once the binder encounters an alkali activator (AA), therefore geopolymerisation occurs. Common AA includes sodium hydroxide (SH), sodium silicate (SS) and calcium hydroxide (CH) [5]. Geopolymers are often distinguished between one-part and two-part geopolymers. The latter is the more conventional geopolymer type with superior mechanical properties [6, 7]. Two-part geopolymers are produced in a mix where the AA is in

solution form and mixed with a solid AAM. While in one-part geopolymers, a solid form of AA and AAM are mixed with just water to activate the mix. One-part geopolymers have been recognized by researchers for their applicability to much larger-scale production and potential in-situ casting [8].

Foamed concrete (FC) is a lightweight concrete (LWC) that can be designed to use high volumes of FA. The material is made by adding preformed foam to a mortar base mix, designed in a specific range of water content and consistency, that does not cause the foam to degrade. Kearsley and Mostert [1] determined that for FC with high FA replacement, a spreadability between 220 – 250 mm was the optimal range for mixed water content and subsequently, foam stability. In their study into 3D printable foam concrete, Cho [2] investigated a spread range of 180 – 220 mm and found stability at a spreadability of 180 mm. Researchers agree on FC's viability as a construction material, especially in non-structural applications and can be designed for densities between 400 and 1600 kg/m^3 [9].

This study aims to develop stable F-AAM by investigating foam stability in AAM with spreadability ranging from 220 - 235 mm. Literature indicates that F-AAM's vulnerability to collapse lies in its foam stability, which is affected by different factors [10, 11]. Factors include base mix composition and consistency which are assessed as spreadability using a hydraulic turntable test. This study investigates the effect of an SH and SS as an AA on the stability of a two-part F-AAM.

2. MIX DESIGN AND EXPERIMENTAL TESTING

2.1 Materials and Mix Design Methodology

In its basic form, F-AAM is composed of three components: binder material, alkali-activated solution, and foam. The binder material used in this investigation consists of locally sourced low calcium Class-F FA and GGCS with relative density 2.37 and 2.65, respectively. Their chemical compositions are shown in Table 1.

Graded fine silica sand with a maximum particle size of 0.6 mm and relative density of 2.65 was utilised to investigate the effect of sand on plain F-AAM. Additionally, 6 mm polypropylene (PP) fibres with a relative density of 0.91 were used as fibre reinforcement for F-AAM.

Table 1: Percentage of the chemical composition of FA and GGCS [12]

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	Ti_2O
Fly Ash	54.1	31.8	3.2	4.9	1.2	0.8	0.4	1.7
GGCS	31.8	14.5	1.3	36.5	11.7	0.6	0.1	0.5

AA solution comprising of a SS solution and SH pellets is utilised. The SS has a molar ratio of 2 and a relative density of 2.34. The SH is of 99% purity and has a relative density of 1.15. A hydrolysed protein-based foaming agent, FoamTech, was used to produce the pre-formed foam, with a relative density of 0.075 ± 0.005, by diluting it with water and ferrous sulphate at 1:40 and 1:80 ratios, respectively.

The mix design of F-AAM is formulated using mass and volume balance. The approach is adapted from McCormick [13] and Kearsley and Mostert [1] where the total mass (m_{tot}) of the mix constituents is equated to the design target density (ρ_m) and expressing the mix constituents as a ratio to the main binder. The volume of the total (V_{tot}) mix is then set to 1000 litres. In this investigation, FA is used as the unknown parameter, x, and all other constituents are determined as a ratio of FA, see equations (1) and (2).

$$m_{tot} = \rho_m = x\left[1 + \sum_{i=0}^{n}(a+b)_i\right] + sh + ss + RD_f V_f \quad (1)$$

$$V_{tot} = 1000 = x\left[\frac{1}{RD_x} + \sum_{i=0}^{n}(b+k)_i\right] + \frac{sh}{RD_{sh}} + \frac{ss}{RD_{ss}} + Vf \quad (2)$$

Where:

$$\sum_{i=0}^{n} b_i = (\mathrm{w}/s)\left(1 + \sum_{i=0}^{n} a_i\right)$$

$$sh = \left(x * \sum_{i=0}^{n} b_i * M * Mr\right)/(1000 * 99\%)$$

$$\sum_{i=0}^{n} k_i = \frac{a_0}{q_0} + \cdots + \frac{a_n}{q_n}$$

a_i represents the mass ratio of a mix constituent to fly ash and in the case of n=2, a_0, a_1 and a_2 refers to the GGCS, sand and fibre mass ratio, respectively. q_i is the relative density of each mix constituent, thus making k_i the volume of each constituent. 'sh' and RD_{sh} refer to the mass and relative density of SH, respectively. 'ss' and RD_{ss} refer to the mass and relative density of SS, respectively. M and Mr refer to the molarity and molar mass of SH, respectively. RD_f and V_f refer to the relative density and volume of foam in the mix.

2.2 Mix Design Methodology

In this investigation, 18 F-AAM mixes were designed using Equations (1) and (2) and are presented in Tables 2 and 3. For each mix design, AA was prepared by dissolving the required mass of SH in potable tap water and mixed with the aqueous SS solution. Thereafter the solution was left to cool down in a climate-controlled room for 24 hours. For each AA solution, an alkaline ratio (AR) of 1.5, 2.0 or 2.5 was chosen in combination with an SH molarity of 8M, 10M or 12M. For mixing, the dry materials were weighed off and added to a 25 L pan mixer, typically in the order of fly ash, slag, sand, and fibres, and mixed until uniform. For the mixes with sand, the sand was added at a ratio to the total binder, either 1, 1.25 parts or 1.5 parts to 1 part binder. Fibres were added as a percentage of the total volume of the mix (VF = 0.3%, 0.5% and 1%). The activator solution was then added to form the base mix (geopolymer) and mixed until homogeneous. The spreadability of the base mix was then determined using the modified hydraulic turntable test, described in Section 2.2, and accepted if a spread in the range of 220 – 235 mm was obtained. The water content of the base mix with a spread value

outside the optimum range was adjusted accordingly – by adding water if the spread was under 220 mm. The pre-formed foam was generated using a foaming agent, ferrous sulphate, and water in the foam generator shown in Figure 1 was added to accepted mixes and mixed for a further 5 minutes.

Figure 1: Foam generator

Table 2: F-AAM Mix design [kg/m^3] - Binder-only mixes investigating the effects and SH molarity, grouped by alkaline ratios.

	AR=1.5			**AR=2.0**			**AR=2.5**		
	8M	**10M**	**12M**	**8M**	**10M**	**12M**	**8M**	**10M**	**12M**
FA	639	487	607	609	497	512	539	557	622
GGCS	426	325	406	406	332	341	360	372	414
Water	172	285	164	184	251	216	225	187	126
SH	55	115	79	59	100	104	73	75	60
SS	83	172	118	118	201	207	182	188	151
Foam	24	17	24	24	19	20	21	23	26

Table 3: F-AAM Mix design [kg/m^3] - Mixes investigating the effects of sand and fibre.

	AR=2.0			**AR=2.5**			**AR=2.5**		
	s/b			**s/b**			**VF**		
	1	**1.25**	**1.5**	**1**	**1.25**	**1.5**	**0.3%**	**0.5%**	**1%**
FA	223	197	178	310	277	249	197	197	167
GGCS	148	132	119	208	185	166	131	131	112
Sand	371	412	444	518	575	621	492	491	420
Fibres	0	0	0	0	0	0	3	5	9
Water	260	259	260	126	126	125	207	207	251
SH	126	126	126	60	60	60	100	100	121
SS	252	251	252	151	151	151	250	250	301
Foam	18	18	18	27	27	27	21	21	18

2.3 Experimental Testing

As suggested by Kearsley and Mostert [1], the hydraulic turntable test evaluates the spread diameter using a Flow table test for hydraulic cement. An experiment was conducted using a mini-slump cone filled with fresh mortar. The spread diameter was taken as the average measured diameter in two directions perpendicular to each other. As prescribed by ASTM C-1437 Standard test method for flow of hydraulic cement mortar, the diameter measurements were taken after the cone was filled with the fresh geopolymer base mix and dropped 15 times from a height of 12.7 mm.

In addition to completing the hydraulic turntable tests on the AAM, the measured fresh density of the mix was calculated as in equation (3), with the density ratio then computed using equation (4). The density ratio is considered stable in the range of 0.98 - 1.02.

$$\text{Fresh density} = \text{M/V} = (\text{mass of fresh concrete})/0.001 \quad (3)$$

$$\text{Density Ratio} = (\text{Fresh Density})/(\text{Target Density}) \quad (4)$$

3. RESULTS AND DISCUSSION

To quantify stability, various mix design types were investigated as listed in Tables 2 and 3. Since density is not under investigation, a target density of 1400 kg/m^3 was kept constant throughout.

3.1 Effect of Mix Constituents on the Water Demand

Figure 3 shows the influence of mix constituents on water demand on the mixes. The water demand (adjusted w/s) is determined as a sum of the design w/s and additional water added to mixes with a spread less than 220 mm.

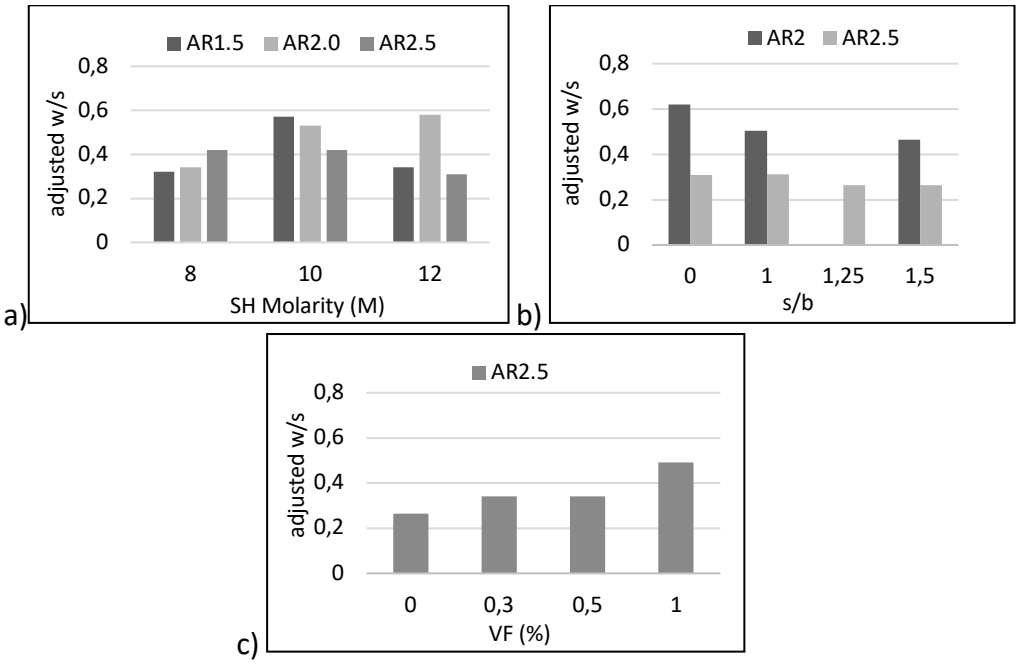

Figure 3: Effect on the water to solids ratio by a) SH molarity, b) Sand c) Fibre

According to Figure 3(a), an increase in AR results in an increase in the water demand of a mix. Increasing AR results in a decrease in water demand in 10M mixes, while there is no trend in 12M samples. A comparison of AR1.5 and AR2.5 across molarities does not show a linear relationship; however, for AR2, there is an increase in water demand for an increase in molarity. By the mix design equations, the activator content is proportional to the water demand of the mix. Therefore, an increase in activator content (AR) or activator concentration (molarity) will increase water demand.

The influence of sand content on the water demand of the mixes shows that water demand decreases with an increase in the sand. AR2.5 uses much less water in its mixes than AR2. Furthermore, fibre content affects water demand proportionally: an increase in fibre content causes an increase in water demand. The increase in solids, either fibres or sand, will decrease water demand, based on mix design derivation. This trend does not apply to the fibres. This could be due to the fibre nature but requires more research.

3.2 Effect of Activator Properties on Stability

The spreadability and fresh density ratio results are shown in Figure 4 (a) and (b). Table 2 shows that these mixes consist of binder material, activator, and foam only.

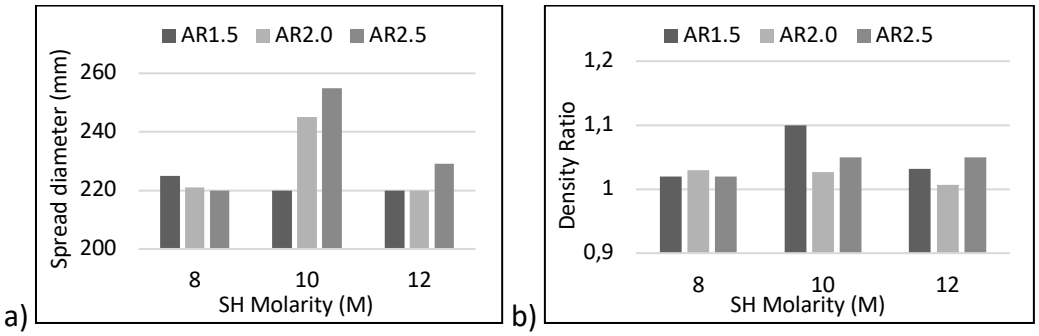

Figure 4: Graphs showing a) Spreadability - and b) Density Ratio with molarity.

Figure 4(a) shows that for an SH molarity of 8M, an increase in the AR results in a slight decrease in spread diameter. Conversely, for 10M and 12M, an increase in the AR results in an increase in spread diameter. Therefore, a mix with higher SH, and an increase in AR results in more consistency and spread. The spread diameter was expected to increase with AA concentration, to result in a much more flowable fresh mix, agreeing with the 10M and 12M mix trends.

For the density ratio, Figure 4(b), there is no trend between molarity and density ratio. For 8M mixes, AR1.5 and AR2 were within the suitable range. The 10 M mixes highly exceeded the upper limit of the suitable density ratio range but that was expected as the spreadability was out of the desired range. There is no trend for the 12M mixes. Thus, more research is required to determine the exact relationship between molarity and stability.

3.3 Effect of Sand on Stability

Figure 5 highlights the effect of sand to binder ratio (s/b) on foam stability. Only mixes with AR of 2.0 and 2.5 were selected to include sand as shown in Table 3.

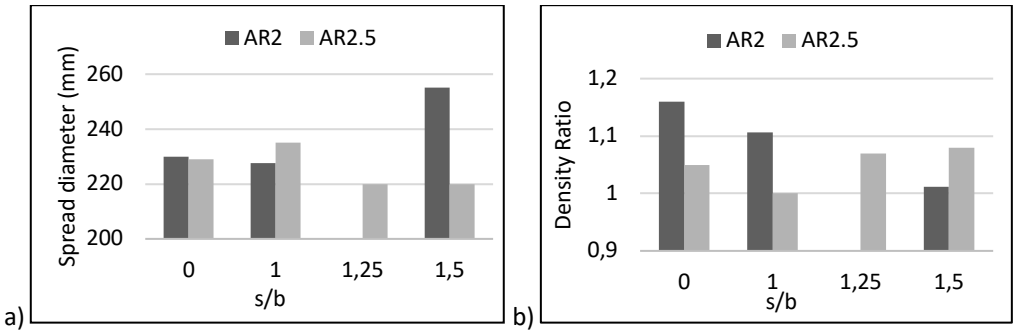

Figure 5: Effect of sand on stability parameters

In Figure 5(a), the AR2.5 mixes were in the required spreadability range, whereas the AR2 mix with an s/b of 1.5 had a spread above 250 mm. Based on Figure 3(b), an increase in sand content decreases the water demand, thus decreasing spreadability. From Figure 5(b) it is observed that AR2.5 mixes have density ratios close to 1, showing stability. However, for AR2 more frequent instability is noted. A contrasting relationship regarding density ratio and sand addition between mixes with an AR of 2 and 2.5 exists. In mixes with AR2, an increase in sand content results in improved stability whereas, in mixes with AR2.5 results in more instability.

3.4 Effect of Fibre Inclusion on Stability

Figure 6 shows the effect of fibre volume (VF) on spread diameter and density ratio.

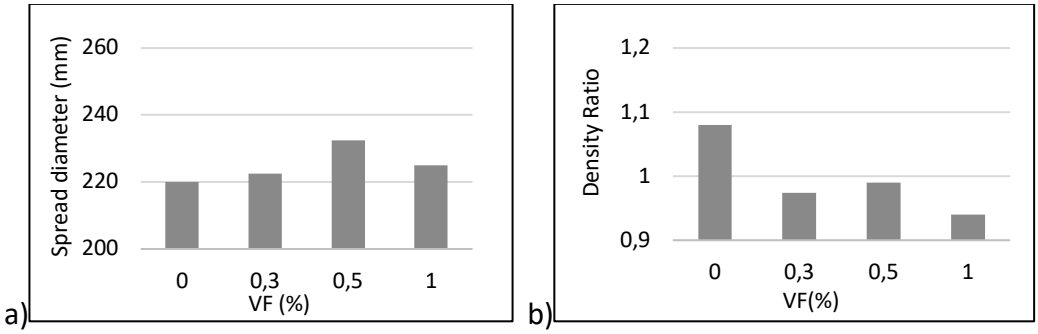

Figure 6: Effect of fibres on stability parameters

In Figure 6 (a), there is an increase in spreadability with an increase in VF between plain F-AAM and up to 0.5% fibre-reinforced F-AAM. Between 0.5% and 1% fibre-reinforced F-AAM, spreadability decreases. Typically, increasing fibre content would stiffen the fresh mix, thus decreasing the spread diameter. Thus, spreadability decreasing with an increase in dry materials is plausible.

The increase in spreadability with fibre could be attributed to the fibre property, but more research is encouraged to ascertain the true effect of fibre addition in the F-AAM fresh state. Figure 6 (b) shows that fibre inclusion increases the instability in the F-AAM mixes by decreasing the density ratio. Density ratios below 1 are recorded for VF. No trend between fibre volume inclusion and stability is observed.

4. CONCLUSION

The effect of varying AA solutions on foam stability in F-AAM mixes designed with low calcium FA, GGCS, sand, and fibres with spreadability values ranging from 220-250 mm was evaluated using modified hydraulic turntable and gravimetric stability tests. The purpose of this study was to correlate spreadability with stability by comparing mixes with spreadability of 220-235 mm with density ratios of 0.98 - 1.02. Based on the results the following conclusions can be drawn:

i. An increase in AAs and sand content decreases the water demand and spreadability. Further research is needed to determine the effects of fibre content.

ii. An increase in molarity results in improved stability in AR2.5 mixes, in contrast to AR2, where it leads to instability.

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