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EFFECT OF COMPOSITION OF FLY ASH ON COMPRESSIVE STRENGTH OF FLY ASH BASED GEOPOLYMER MORTAR

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ABSTRACT

This paper discusses the changes in compressive strength of fly ash (FA) based geopolymers due to variation of chemical composition, activator modulus (AM) and particle size distribution. Mortar specimens were prepared using Class F fly ash obtained from five different power stations in Australia. To optimize the best mix ratio for each type of FA based geopolymer, AM was varied between 0.625 and 1.75 by fixing Na_2O dosage to 15. A variation in compressive strength for the five FA based geopolymers was observed between 21.2MPa and 60.6MPa. In addition to the specific chemical composition of the individual FA this variation also attributed to the carbon content and fineness ratio of FA, both of which enhance the activator solution demand well beyond that needed to merely activate the source material.

KEYWORDS

Compressive strength; Class F fly ash, geopolymer mortar, activator modulus, Na_2O dosage.

INTRODUCTION

Though ordinary Portland cement (OPC) is a well established and proven binder for concrete, its production generates almost 1 ton of carbon dioxide (CO_2) per 1 ton of cement (Davidovits 1994, Rehan and Nehdi 2005). Production of Portland cement has a high embodied energy and contributes 4-8% to the total world-wide CO_2 production (Gartner 2004). Thus, a small reduction of Portland cement production could result in significant environmental benefits in terms of CO_2 emission. One possible alternative is the use of alkali activated binders using fly ash (Davidovits 1994). The most emphasized advantage of this is the reduction of CO_2 emission by 50-90% with the replacement of OPC with flyash or slag with no economic sacrifices (Davidovits 1994). An added benefit is to convert a waste product into a useful by-product, conserving landfills and storage lagoons (Khale and Chaudhary 2007). However, in the extensive research that has been published on the development of geopolymer using wide range of mix designs and activators, distinct variations in compressive strength have been noted (Van Jaarsveld et al. 2003, Diaz et al. 2010). Little research has been undertaken on understanding the chemistry behind these variations and in characterising the components of the fly ash (FA) and the activators and how their interaction and relative concentrations determine the strength of the geopolymer produced. Activation of the FA has been hypothesized as being due to a number of factors, both the activator modulus (AM) and the Na_2O:FA ratio have been identified as having a significant impact upon the strength (Adam 2009). AM is defined as the SiO_2:Na_2O ratio in alkali activator solution. The Na_2O dosage is calculated by the Na_2O in the alkali activator solution divide by the mass of fly ash. This paper reports the changes in strength of FA based geopolymer mortar due to the variation of the AM, chemical composition and Particle size distribution (PSD).

EXPERIMENTAL PROCEDURE

Materials Used

In this research, Class F FA obtained from five different power stations in Australia was used as a base material to make the geopolymer mortar. The chemical composition and PSD of each FA are shown in Table 1 and Table 2, respectively. The method employed to perform the chemical analysis and PSD was X-ray fluorescence and laser-based particle size analysis, respectively. The activator solution used comprised of a 15M NaOH solution and Na_2SiO_3 (45% by weight and SiO_2 to Na_2O ratio of 2:1) solution. Demineralized water was used throughout the experiment and normal river sand with a specific gravity of 2.5 and a fineness modulus of 3.0 served as fine aggregate.

Table 1.Chemical composition of fly ash

Fly ash (FA) Type	by weight (%)										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	TiO_2	P_2O_5	MgO	Na_2O	SO_3	*LOI
Gladstone (GFA)	50.82	29.89	10.26	3.24	0.58	2.05	1.61	0.80	0.00	0.28	0.43
Port Augusta (PAFA)	49.97	31.45	3.22	5.03	1.87	2.54	1.77	1.54	1.85	0.33	0.51
Collie (CFA)	52.67	29.60	11.27	0.94	0.65	1.83	1.13	0.72	0.00	0.48	0.63
Mount Piper (MPFA)	65.18	25.30	1.90	0.63	3.65	1.53	1.21	0.00	0.00	0.23	1.30
Tarong (TFA)	73.12	21.50	1.36	0.29	0.63	1.84	1.06	0.00	0.00	0.00	1.16

*LOI: Loss on Ignition (Unburnt carbon content)

Table 2.Particle size distribution of fly ash

FA Type	Passing (%)										Surface Area (m^2/kg)
	10μm	20μm	30μm	40μm	45μm	50μm	60μm	70μm	80μm	90μm	
GFA	43.1	61.9	73.2	79.8	82.7	85.3	89.6	91.2	92.6	93.8	2003
PAFA	46.7	62.1	71.4	77.4	80.9	82.9	87.9	90.1	92.1	93.8	2161
CFA	40.9	54.6	62.7	67.7	70.0	72.3	76.7	79.0	81.3	83.6	1934
MPFA	36.0	57.1	69.9	77.4	80.7	83.8	89.0	91.2	93.0	94.6	1555
TFA	43.0	63.0	73.6	79.3	81.8	84.2	88.3	90.2	91.9	93.4	1766

Mixing, Casting and Testing

The total mass of each material used in each geopolymer mix design is shown in Table 3. Table 4 shows tested mortar specimens in each FA based geopolymer over a range of mix designs. Previous studies had shown that the Na_2O dosage has a significant influence on strength, and a ratio of 15 produced the highest strength for geopolymer mortar (Adam 2009). Thus, the Na_2O dosage is kept in 15 for all mix designs. The AM is varied from 0.625 to 1.75 by blending liquid sodium silicate and sodium hydroxide in different proportions. The water to solid ratio is fixed to 0.37 while the sand to fly ash ratio is fixed to 2.75 according to ASTM C109/C109M-07. First, fly ash and sand were mixed for 4 minutes using a 5-litres Hobart mixer. Then activator solution and water is added to the mixer and mixed for 1 minute by hand. To improve uniform mixing, whole mix then is blended with Hobart mixer in two rotating speeds (150 and 300rev/min) with 4 and 2 minutes, respectively. Then mixer placed in 50x50x50 mm cubic Teflon moulds and vibrated for 20 seconds. The moulds were then kept at room temperature for 1 day and then cured in an oven for 24 hours at 80°C temperature with 95% relative humidity. Moulds were removed from the oven, then demoulded, and kept at room temperature until being tested at 3,7 and 28 and 28 day. The compressive strength test was performed in accordance with ASTM C109/C109M-13 and a loading rate of 0.34 $N/mm^2/S$ using a TCM machine. The reported compressive strength values are an average of 3 samples for each mix design.

Table 3.Mix design details for various geopolymer mortar (based on AM)

Geopolymer Mix design	Relevant AM	Mass ratio of materials for 1 liter (kg)					
		FA	Sand	Water	Activator Solution		Na_2SiO_3 / NaOH
					Na_2SiO_3	NaOH	
AM -0.625	0.625	1	2.75	0.083	0.257	0.374	0.7
AM -0.75	0.75	1	2.75	0.067	0.383	0.312	1.2
AM -1.0	1.0	1	2.75	0.067	0.510	0.234	2.2
AM -1.125	1.125	1	2.75	0.044	0.574	0.219	2.6
AM -1.25	1.25	1	2.75	0.042	0.638	0.175	3.6
AM -1.375	1.375	1	2.75	0.024	0.699	0.157	4.4
AM -1.5	1.5	1	2.75	0.015	0.765	0.117	6.5
AM -1.625	1.625	1	2.75	0.001	0.796	0.098	8.1
AM -1.75	1.75	1	2.75	0.000	0.867	0.072	12.0

Table 4. Tested mortar specimens in each FA based geopolymer

FA	Geopolymer Mix design								
	AM-0.625	AM-0.75	AM-1.0	AM-1.125	AM-1.25	AM-1.375	AM-1.5	AM-1.625	AM-1.75
GFA	-	-	G1.0	G1.125	G1.25	G1.375	G1.5	-	-
PAFA	-	-	PA1.0	PA1.125	PA1.25	PA1.375	PA1.5	-	-
CFA	-	-	C1.0	C1.125	C1.25	C1.375	C1.5	-	-
MPFA	MP0.625	MP0.75	MP1.0	-	MP1.25	-	MP1.5	-	-
TFA	-	-	T1.0	-	T1.25	-	T1.5	T1.625	T1.75

RESULTS AND DISCUSSION

Activator Modulus (AM) and SiO_2/Al_2O_3 Ratio

Figure 1 shows the compressive strength of different geopolymer mix designs based on AM. For the GFA, PAFA and CFA based geopolymers the AM was varied between 1.0 and 1.5 in order to achieve the optimum strength. The optimum strength (28-day) of both GFA and PAFA are obtained at AM of 1.25, and CFA is obtained at AM of 1.375. In TFA based geopolymer the AM was varied from 1.0 to 1.75, and optimum strength (28 day) is obtained at AM of 1.625. In MPFA geopolymer AM was varied between 0.625 and 1.5 until the best mix design is obtained based on strength.

The microstructure of geopolymer mortar consists with amorphous alumina-silicate gel and unreacted and partially reacted FA spheres (Fernández-Jiménez and Palomo 2005). These unreacted spheres make up a significant proportion of the total volume of the binder (Steveson and Sagoe-Crentsil 2005) and thus an increase of these has an adverse effect on the strength of the matrix, in particular at the interface between them and the geopolymer matrix. The SiO_2/Al_2O_3 (molar) ratio of mix corresponding to the optimum AM in GFA, PAFA, CFA, TFA and MPFA are 3.9, 3.7, 4.2, 7.6 and 5.1, respectively. Figure 2 shows the linear relationship between SiO_2/Al_2O_3 ratio and optimum AM. The optimum AM increases with an increase in the SiO_2/Al_2O_3 ratio. MPFA based geopolymer gives the optimum compressive strength (28 day) at AM of 0.75. However, using the relationship derived for the four other mixes the predicted range for the optimum AM is between 1.4 and 1.5 based on SiO_2/Al_2O_3 ratio of the mix. The optimum compressive strength (28 day) of each fly ash is compared in Figure 3 regardless of the AM. The highest and lowest compressive strengths of 60.6MPa and 21.2MPa are obtained by G1.25 and MP0.75 specimens, respectively. The T1.625 shows a moderate strength gain than PA1.25 (41.3 and 36.6MPa, respectively). The C1.375 mix has a slightly higher strength than the lowest (22MPa).

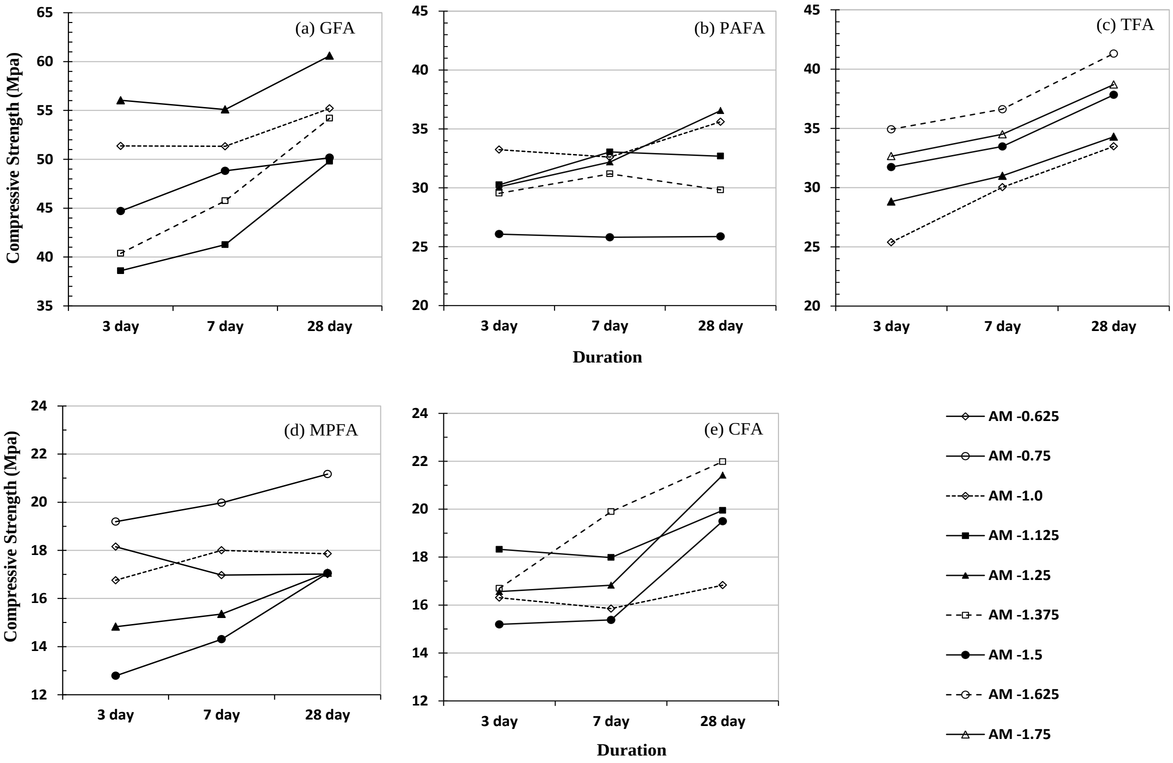

Figure1. Changing compressive strength with AM in five different FA based Geopolymers

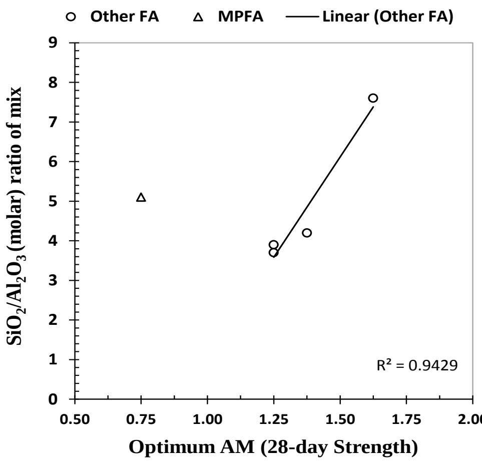

Figure 2. SiO_2/Al_2O_3 ratio vs. optimum AM

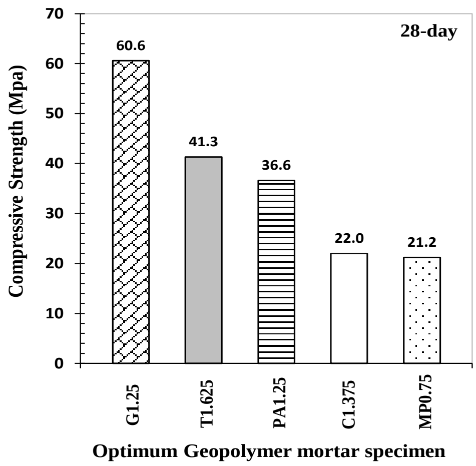

Figure 3. Optimum Compressive Strength

The data demonstrates that the starting material plays an important role in the compressive strength of geopolymer. While Steveson and Sagoe-Crentsil (2005) showed a trend of increasing strength with an increase of SiO_2/Al_2O_3 ratio; only the GFA and PAFA geopolymer confirmed this hypothesis in these trials. The SiO_2/Al_2O_3 of T1.625 mix is almost twice of G1.25 mix, but the compressive strength in T1.625 is significantly lower than that of G1.25. The CaO has been identified as an important factor affecting final strength in geopolymer concrete (Van Jaarsveld and Van Deventer 1999) but a high percentage of Fe_2O_3 reduce the strength in geopolymers (Fernández-Jiménez and Palomo 2005). Thus, SiO_2/Al_2O_3 ratio, CaO and Fe_2O_3 have all been hypothesized as affecting the strength. Based on the SiO_2/Al_2O_3 the TFA results appear anomalous while PAFA contradicts the CaO and Fe_2O_3 results previously reported. The PA1.25 has highest CaO and lowest Fe_2O_3 content compared to the G1.25. Overall the results suggest that several factors affect the optimum mix design to give the highest compressive strength and the inter relationship of these requires further analysis.

Carbon Content and Fineness Ratio of Fly Ash

The carbon acts as inert particles and absorbs the activator solution, consequently to obtain a workable mixture, a volume of activator solution well beyond that needed to merely activate the source material is required. This causes more unreacted and partially reacted fly ash spheres in the mix, leading to lower compressive strength (Fernández-Jiménez and Palomo 2003, Diaz et al. 2010).

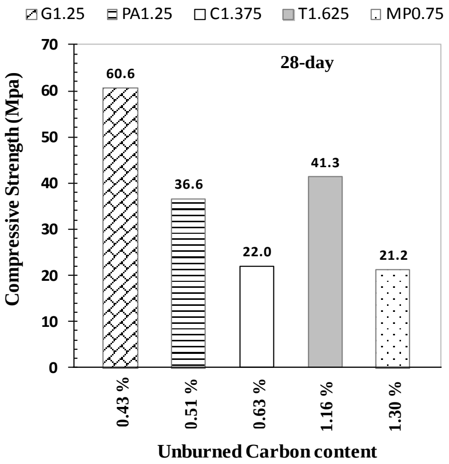

Figure 4. Effect of unburned carbon content

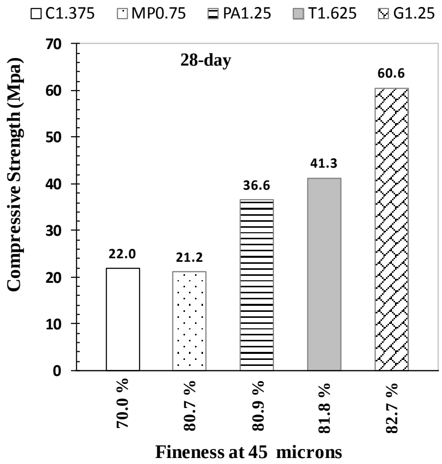

Figure 5. Effect of fineness ratio

The effect of fineness acts two ways; during the mixing of geopolymer, the activator solution demand rises as the fineness of the FA decreases due to the need to fill larger voids among coarser FA particles to achieve a workable material. On the other hand, the finer the FA particles the greater the surface area, increasing reactivity of fly ash, because a significant part of the reaction occurs at the particle-liquid interface (Diaz et al. 2010). Moreover, Fernandez-Jimenez and Palomo (2003) showed that when the particle fraction sizes larger than 45 microns are removed the compressive strength increased reaching 70MPa in one day. Optimum compressive strength (28-day) vs. unburnt carbon content and fineness at 45 μm of FA are shown in Figure 4 & 5, respectively. The G1.25 has highest fineness ratio with lowest unburnt carbon content, and gives the highest compressive strength. The MP0.75 shows the lowest strength, this may be due to the higher unburnt carbon content. The C1.375 had a similar strength to MP0.75 but only half of the MPFA's unburnt carbon content. The CFA has lowest fineness ratio (70%) which would be expected to result in larger voids between the coarser FA particles giving a smaller particle-liquid interface. This is hypothesized as the reason the C1.375 did not achieve the same strength gain despite having the lower carbon content. MPFA has larger unburnt carbon percentage that absorbs the activator solution. This may result in a lowering of the NaOH in activator solution, particularly at higher AM. Higher alkali contents in the mixture yield better reactivity with the FA (Thokchom et al. 2009). Thus, it appears that the optimum AM of MPFA has shifted to a lower value (0.75) despite the predicted range in Figure 2. TFA has second highest unburnt carbon percentage, more than twice of PAFA, though a slightly better fineness ratio than PAFA. However, T1.625 had a higher compressive strength. TFA had a significantly higher SiO_2 percentage than PAFA (73% and 49% respectively). Formation of alumina-silicate gel which develops the strength is dependant on the quantity of Si^{4+} leaching from the FA. Other authors have shown that higher amounts of reactive SiO_2 Other authors have shown that higher amounts of reactive SiO_2 result in a higher degree of geopolymerization and consequently higher mechanical strength (Van Jaarsveld et al. 2003). Therefore, leaching more Si^{4+} ions from T1.625 is hypothesized as the cause of the higher strength than PA1.25.

CONCLUSION

The 28-day compressive strength of GFA, TFA, PAFA, CFA and MPFA geopolymers, optimized for AM are 60.6, 41.3, 36.6, 22 and 21.2MPa, respectively. The differences in compressive strengths in different fly ash materials are attributed to a combination of factors with two major ones being fineness of fly ash and unburnt carbon content, along with the specific chemical composition of the FA.

- Gladstone Fly Ash with an activator modulus of 1.25 has demonstrated the highest compressive strength of geopolymer mortar. This is explained as due to the combination of highest fineness ratio and lowest unburnt carbon content.
- The Mount Piper fly ash with activator modulus of 0.75 shows the lowest compressive strength, which may be due to the higher proportion of unburnt carbon content.
- The C1.375 has lowest fineness ratio and also a lower carbon content. This combination of parameters is hypothesized as the reason for not achieving a high compressive strength.

Carbon content and fineness ratio of FA, both enhance the activator solution demand well beyond that needed to merely activate the source material. Results further show the linear relationship between SiO_2/Al_2O_3 ratio and optimum AM. The optimum AM increases with an increase in the SiO_2/Al_2O_3 ratio. TFA had a significantly higher SiO_2 percentage than PAFA, thus leaching more Si^{4+} ions from T1.625, which is hypothesized as the cause of the higher strength of TFA0.625 than PA1.25. The G1.25 shows a higher strength than PA1.25. This may be due to higher SiO_2/Al_2O_3 ratio. Overall results reported here indicate that several factors affect optimum mix design of geopolymer to obtain highest compressive strength and the inter relationship of these requires further systematic analysis.

REFERENCES

Adam, A. A. (2009)."Strength and durability properties of alkali activated slag and fly ash-based geopolymer concrete", RMIT University Melbourne, Australia.

Davidovits, J. (1994) "Global warming impact on the cement and aggregates industries", *World Resource Review,* Vol. 6, No. 2, pp. 263-278.

Davidovits, J. (1994) "High-alkali cements for 21st century concretes", *ACI Special Publication,* Vol. 144, No. pp. 383-398.

Diaz, E. I., E. N. Allouche and S. Eklund (2010) "Factors affecting the suitability of fly ash as source material for geopolymers", *Fuel,* Vol. 89, No. 5, pp. 992-996.

Fernández-Jiménez, A. and A. Palomo (2003) "Characterisation of fly ashes. Potential reactivity as alkaline cements", *Fuel,* Vol. 82, No. 18, pp. 2259-2265.

Fernández-Jiménez, A. and A. Palomo (2005) "Composition and microstructure of alkali activated fly ash binder: Effect of the activator", *Cement and Concrete Research,* Vol. 35, No. 10, pp. 1984-1992.

Gartner, E. (2004) "Industrially interesting approaches to low-CO2 cements", *Cement and Concrete Research,* Vol. 34, No. 9, pp. 1489-1498.

Khale, D. and R. Chaudhary (2007) "Mechanism of geopolymerization and factors influencing its development: A review", *Journal of Materials Science,* Vol. 42, No. 3, pp. 729-746.

Rehan, R. and M. Nehdi (2005) "Carbon dioxide emissions and climate change: policy implications for the cement industry", *Environmental Science & Policy,* Vol. 8, No. 2, pp. 105-114.

Steveson, M. and K. Sagoe-Crentsil (2005) "Relationships between composition, structure and strength of inorganic polymers", *Journal of Materials Science,* Vol. 40, No. 16, pp. 4247-4259.

Thokchom, S., P. Ghosh and S. Ghosh (2009) "Effect of water absorption, porosity and sorptivity on durability of geopolymer mortars", *Journal of Engineering & Applied Sciences,* Vol. 4, No. 7, pp. 28-32.

Van Jaarsveld, J. G. S. and J. S. J. Van Deventer (1999) "Effect of the Alkali Metal Activator on the Properties of Fly Ash-Based Geopolymers", *Industrial & Engineering Chemistry Research,* Vol. 38, No. 10, pp. 3932-3941.

Van Jaarsveld, J. G. S., J. S. J. Van Deventer and G. C. Lukey (2003) "The characterisation of source materials in fly ash-based geopolymers", *Materials Letters,* Vol. 57, No. 7, pp. 1272-1280.