HIGH VOLUME FLY ASH CONCRETE AS A STRUCTURAL MATERIAL: DEVELOPMENT, APPLICATIONS AND RESEARCH NEEDS

Abstract

A major challenge currently faced by the concrete industry in the world is the high levels of carbon emissions associated with production of Portland cement. Some recent solutions developed to address the issue are the concrete materials with high volumes of cement substitutes. Geopolymer concrete is one such solution where alkali activated polymerization of fly ash or slag is used to develop a cement free concrete. One disadvantage of the material is the heat curing required to develop early strengths needed for structural applications. High volume fly ash (HVFA) concrete is an alternative where 50-70% replacement of Portland cement is being explored in making concrete suitable for structural applications.

The paper presents a comprehensive review of attempts made at developing sustainable concrete with normal production processes. Gaps in current research have been identified and early results of an experimental study conducted at RMIT University in Melbourne to develop a high volume fly ash concrete material are presented. Potential applications of the new material and further research needs are identified.

Keywords: High volume fly ash concrete, sustainable materials, alkali activated cement

1. Introduction

Concrete is a composite material in which coarse and fine aggregate are bound with cement paste (Neville, 1996). Good durability and low cost has made it a very popular construction material making it the most widely used construction material in the world. There is about 3.3 billion tonnes of cement produced in 2010 up from 1.37 billion tonnes in the year 1994 (U.S.G.S., 2011). However, use of cement in concrete has raised some issues on the sustainability of the material, considering that production of each tonne of cement releases one tonne of carbon dioxide to the environment. This concern has led to exploration of many supplementary cementitious materials which could substitute large proportions of cement used to produce concrete. Geopolymer concrete presents one extreme of such innovations, where 100% fly ash or slag is used instead of cement in making concrete. One disadvantage of the material is complex curing regimes needed for achieving a comparable strength to cement based concrete. Another material which is receiving a lot of attention is high volume fly ash concrete which overcomes the issues associated with curing. However strength development has been observed to be low in HVFA concrete.

A research project commenced at RMIT University in Melbourne has aimed to develop a high volume fly ash concrete without compromising the cost of the manufacturing process nor the rate of strength development. This paper presents the early results of the work.

2. The Differences between geopolymer concrete and high volume fly ash concrete

2.1 Geopolymer Concrete

Geopolymer concrete can use 100% fly ash or slag as the binder in concrete. Fly ash that are rich in Silicon (Si) and Aluminium (Al), are activated by alkaline liquids by the geopolymerization process to form the binder in geopolymer concrete. The alkaline liquids comprise a combination of sodium silicate solution and sodium hydroxide solution (Hardjito, 2005). A high range water reducer (superplasticiser) is normally used to improve the workability of fresh geopolymer concrete (Wallah and Rangan, 2006). Typical dosage of superplasticiser is around 4% by weight of fly ash. However, increasing the superplasticiser dosage above 2% often is found to have some negative effect on the compressive strength. (Hardjito, 2005), (Hardjito and Rangan, 2005).

The main parameters affecting the compressive strength of hardened fly ash-based geopolymer concrete are the curing temperature and curing time, the molar H_2O-to-

Na_2O ratio, and mixing time. Palomo et al (1999) concluded that the curing temperature accelerates the reaction in fly ash-based geopolymers, and significantly affect the mechanical strength, together with the curing time and the type of alkaline liquid. As the curing temperature increases within the range of 30^0C to 90^0C, the compressive strength of fly ash-based geopolymer concrete increases (Hardjito and Rangan, 2005). Longer curing time, in the range of 4 to 96 hours (4 days), produces higher compressive strengths in fly ash-based geopolymer concrete. However, the increase in strength beyond 24 hours is not significant (Hardjito and Rangan, 2005). Higher curing temperature and longer curing time were proven to result in higher compressive strength. Prolonged mixing time of up to sixteen minutes increases the compressive strength of fly ash-based geopolymer concrete (Hardjito and Rangan, 2005). Alkaline activator that contained soluble silicates was proven to increase the rate of reaction compared to alkaline solutions that contained only hydroxide (Hardjito, 2005). As the ratio of water-to-geopolymer solids by mass increases, the compressive strength of fly ash-based geopolymer concrete decreases (Hardjito, 2005). The "rest period", defined as the time taken between casting of specimens and the commencement of curing, of up to 5 days increases the compressive strength of hardened fly ash-based geopolymer concrete. The increase in strength is substantial in the first 3 days of rest period (Hardjito, 2005).

The calcium content in fly ash plays a significant role in strength development and final compressive strength, with a higher calcium content resulting in faster strength development and higher compressive strength. For optimal strength, low calcium fly ash less than 5% unburnt material, less than 10% Fe2Co3, 40-50% reactive silica and 80-90% particles smaller than 45 µm have been identified as needed. (Fernández-Jiménez and Palomo, 2003).(Wallah and Rangan, 2006).

Mechanical properties and durability of fly ash-based geopolymer is observed to be better than those of comparable Ordinary Portland Cement (OPC) concrete (Bakri et al., 2011). The average density of fly ash-based geopolymer concrete is similar to OPC concrete. The elastic properties of hardened fly ash-based geopolymer concrete with compressive strength in the range of 40 to 90 MPa, i.e. the modulus of elasticity, the Poisson's ratio, and the indirect tensile strength, are similar to those of ordinary Portland cement concrete (Hardjito, 2005). TRype of course aggregate has bene observed to have a more dominant effect of elastic properties than geopolymerisation. Therefore elastic properties of geopolymer concrete is observed to be within the expected range for OPC. (Hardjito, 2005). The stress-strain relations of fly ash-based geopolymer concrete in compression can be predicted using the expressions developed for OPC concrete, with the strain at peak stress in the range of 0.0024 to 0.0026 (Hardjito, 2005). The indirect tensile strength of fly ash-based geopolymer concrete is only a fraction of the compressive strength, as in the case of Portland cement concrete and are higher than those recommended by the relevant Australian Standard (Hardjito, 2005).

The heat-cured fly ash-based geopolymer concrete undergoes very little drying shrinkage in the order of about 100 micro strains after one year (Wallah and Rangan, 2006). The specific creep, defined as the creep strain per unit stress, after one year ranged from 15 to 29 x 10^{-6}/MPa for the corresponding compressive strength of 67 MPa to 40 MPa (Wallah and Rangan, 2006). It can be used in many infrastructure applications (Hardjito and Rangan, 2005).

One ton of low-calcium fly ash can be utilised to produce about 2.5 cubic metres of high quality geopolymer concrete, and the bulk cost of chemicals needed to manufacture this concrete is cheaper than the bulk cost of one ton of Portland cement (Hardjito and Rangan, 2005).

Despite many benefits offered by geopolymer concrete, their high dependence on the mixing, curing and chemical composition of fly ash has inhibited ready acceptance by the industry. Longer processing time including, mixing, rest period and curing often can increase the duration of construction period.

2.2 High Volume Fly Ash Concrete

High volume fly ash (HVFA) concrete uses high volumes of fly ash to replace the Portland cement content. Replacement levels as high as 60% has been reported to be succesful (Hardjito and Rangan, 2005). HVFA concrete has been proven to be more durable and resource-efficient than the OPC concrete (Malhotra, 2002). The HVFA technology has been trialled in the field, for example the construction of roads in India, implemented 50% OPC replacement by the fly ash (Desai, 2004). The use of fly ash can improve workability, easier flowability, pumpability, compactability, reduce heat of hydration and increase resistance to sulfate attack, alkali-silica reactivity (ASR) and other types of deterioration as compared to normal mixes (Solis et al., 2010). HVFA concrete have very high durability to the reinforcement corrosion, alkali-silica expansion, sulfate attack, and have superior dimensional stability and resistance to cracking from thermal shrinkage, autogenous shrinkage, and drying shrinkage (Mehta, 2004).

HVFA concrete has better surface finish and quicker finishing time when power finish is not required (Mehta, 2004). It has slower setting time and will have a corresponding effect on the joint cutting and lower power-finishing times for slabs. One major issue with HVFA is the slower strength gain where usually 90 days will be needed to gain the full strength potential (Mehta, 2004). With HVFA concrete mixtures, the strength enhancement between 7 and 90-day often exceeds 100%, therefore some researchers believe that it is unnecessary to overdesign them with respect to a given specified strength (Mehta, 2004).

HVFA concrete have much higher electrical resistivity and resistance to chloride ion penetration after three to six months of curing according to ASTM Method C1202 (Mehta, 2004).

HVFA concrete has better cost economy due to lower material cost and highly favorable lifecycle cost (Solis et al., 2010, Mehta, 2004). These concrete have superior environmental friendliness due to ecological disposal of large quantities of fly ash, reduced carbon-dioxide emissions, and enhancement of resource productivity of the concrete construction industry (Mehta, 2004).

Comparison of the geopolymer concrete and HVFA concrete indicates that there are distinct advantages in HVFA concrete where time and heat of curing is not a major factor affecting compressive strength. The work presented here attempted to develop a HVFA concrete which has similar compressive strength as OPC. In developing the research program, a review of previous attempts at HVFA concrete was conducted.

3. A summary of previous attempts at making HVFA concrete

A comprehensive review was conducted to understand the current state of the knowledge on HVFA concrete. A summary is given in Table 1. It was noted that percentage of fly ash used as replacement of OPC ranges from 15% to 85%. However, it is noted that when the proportion of fly ash increased to 85%, 28 day compressive strength was reduced by more than 60%. The larger the total cementitious content and the lower the water cementitious ratio, better compressive strength properties have been observed. Use of a polycarboxylate polymer has been shown to improve the properties, increasing the 7 day strength to be as high as 60 MPa with 40% fly ash in the concrete mix replacing cement.

Table 1: Details of HVFA from literature

References	*% Fly Ash*		*Cement Content (kg/m^3)*	*w/c*	*Compressive Strength (MPa)*			*Others*
					7 days(d)	*14 days(d)*	*28 days(d)*	
(Elsageer et al., 2009)	*40*		*202*	*0.30*	*~60(8d)*		*~74(32d)*	*Superplasticiser used: polycarboxylate polymer*
	30		*243*	*0.36*	*~61(8d)*		*~76(32d)*	
	15		*284*	*0.41*	*~65(8d)*		*~80(32d)*	
	0		*316*	*0.46*	*~62(8d)*		*~75(32d)*	
(Crouch et al., 2007)	*Class C*	*50.1*	*164*	*0.34*			*~50*	*Air Entrainer, Type E & A Admixture added*
		25	*251*	*0.40*			*~40*	
	Class F	*50.1*	*177*	*0.35*			*~33*	
		20	*268*	*0.45*			*~32*	
(Oner et al., 2005)	*37*		*320*	*0.50*			*39.5*	
	30		*320*	*0.54*			*42.7*	
	0		*400*	*0.60*			*41.5*	
(Mehta, 2004)	*50*		*154*	*0.39*			*25*	
	0		*307*	*0.58*			*25*	

(Yang et al., 2007)	*85*	*190*	*0.24*	*8.2(3d)*		*21.4*	*High-range water-reducing admixture & polyvinyl alcohol (PVA) fiber added*
	71	*362*	*0.26*	*17.1(3d)*		*38.4*	
	55	*571*	*0.26*	*30.6(3d)*		*52.6*	
(McCarthy and Dhir, 2005)	*45*	*350*	*0.26*	*45.0*	*55.5*		*Compressive Cube(100mm) strength test*
	0	*510*	*0.37*	*52.5*	*62.5*		
(Bouzoubaâ et al., 2001)	*55*	*170*	*0.32*	*20.9*	*27.1*	*30.5*	*Genesee fly ash, Air-entraining admixture & superplasticiser added*
	0	*385*	*0.40*	*32.5*	*34.4*	*38.6*	

4. Measures for improving performance of HVFA concrete

In identifying methods of improving the performance of HVFA concrete two potential avenues to enhance reactivity of fly ash have been identified.

According to Obla et al (2003), one method to enhance reactivity of fly ash is reducing particle size. In 1986, Xu (1997) found that fly ash particles in the range of 10 to 50 µm mainly act as void fillers in concrete, whereas the particles smaller than 10 microns are more reasonably classified as pozzolanic reactive. The use of ultra fine fly ash significantly increases the compressive strength of HVFA concrete if compared with the use of raw fly ash as reported by some researchers (Chindaprasirt et al., 2007, Kiattikomol et al., 2001). One attempt made to enhance the strength performance of fly ash is thus reduction of the particle size by grinding of fly ash.

It has been observed by other researchers that addition of lime to fly ash concrete improves durability. Since fly ash react with $Ca(OH)_2$ in concrete to form the binder, this phenomenon can be explained. A combination of reduced particle size and addition of lime was explored at RMIT to develop a better performing HVFA concrete.

The obvious method of increasing the curing temperature was not considered since it reduces the advantage in ease of manufacture.

5. Early results from HVFA concrete research

Reducing the fly ash particle size and use of lime water as an activator is being considered as potential methods of improving properties of HVFA concrete.

The surface area of raw fly ash and ultra fine fly ash were found by using Blaine test apparatus. After grinding by using micronizer, the surface area of raw fly ash, 364 m^2/kg was changed to ultra fine fly ash, 525 m^2/kg based on cement fineness (Solikin et al., 2010). The fineness of the fly ash was increased by 40% after the grinding process (Solikin et al., 2010). Scanning Electron Microscopic (SEM) analysis shows that the particle size of ultra fine fly ash is smaller than the raw fly ash (Solikin et al., 2010). Saturated lime water was used as mixing water in manufacturing HVFA concrete. The density of saturated lime water was slightly higher than the tap water since some hydrated lime particles are dissolved in it (0.08%) (Solikin et al., 2010). The alkalinity of saturated lime water is higher than that of the tap water. The increase of alkalinity in lime water resulting from $Ca(OH)_2$ (hydrated lime) was expected to be useful in activating fly ash further.

Table 2 (Solikin et al., 2010) shows the early results of these preliminary experiments.

Table 2: Early results at RMIT (Solikin et al., 2010).

Mix Proportion	*Cement (kg/m^3)*	*Fly Ash (kg/m^3)*	*Water (kg/m^3)*	*Aggregate*		*HRWR ($litre/m^3$)*	*f'c (MPa)*
				Fine (kg/m^3)	*Coarse (kg/m^3)*		
UFFA with tap water	*225.0*	*225.0*	*141.0*	*835.0*	*994.0*	*7.0*	*70.9*
Raw Fly Ash with, lime water	*225.0*	*225.0*	*139.0*	*811.0*	*994.0*	*10.2*	*66.7*
UFFA with lime water	*225.0*	*225.0*	*141.0*	*835.0*	*994.0*	*7.0*	*78.7*
OPC	*450.0*	*-*	*137.0*	*912.0*	*994.0*	*13.9*	*79.4*

6. Conclusions and plans for continuation

The review of published work has revealed that there is a gap in research to develop concrete mixes with high volumes of fly ash (over 70%), with comparable 28 day compressive strengths. Two methods of improving the strength properties have been identified. Initial experimental results have demonstrated that by reducing the particle size and addition of lime water can assist in developing HVFA concrete mixes with potential to offer similar compressive strengths as

OPC. However, further work is needed to ascertain the longer term properties such as creep and shrinkage of HVFA concrete as well as durability.

A current research program continuing at RMIT University in Melbourne plans to further the explore the mechanism of strength development of high volume fly ash concrete when the particle size is less than 10 microns and lime water of different concentrations is used to enhance strength development.

7. References

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