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Effect of Fly Ash on Durability of High Performance Concrete Composites

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Abstract: A parametric experimental study has been conducted to investigate the effect of fly ash on the durability of the concrete composites. Four different fly ash contents (10, 15, 20 and 25% respectively) were used. The durability of concrete composites includes water impermeability, dry shrinkage property, the carbonation resistance and the freeze-thaw resistance. The results indicate that the addition of fly ash has greatly improved the water impermeability and restricted the dry shrinkage of concrete composites. With the increase of fly ash content, the length of water permeability and the dry shrinkage strain of the specimens have a tendency of decrease with the increase of fly ash content. However, the addition of fly ash has a little adverse effect on the carbonation resistance and freeze-thaw resistance of concrete composites. With the increase of fly ash content, the carbonation depth is increasing and the relative dynamic elastic modulus of the freeze-thaw specimen is decreasing gradually.

Keywords: Durability, fly ash, high performance concrete

INTRODUCTION

High Performance Concrete (HPC) can be defined as the concrete, which meets special performance and uniformity requirements that can't always be achieved by conventional materials, normal mixing, placing and curing practices (Bharatkumar *et al*., 2001; Zain *et al*., 2002). The requirements may involve enhancements of characteristics such as placement and compaction without segregation, long-term mechanical properties, early-age strength, volume stability or service live in severe environments. Swamy *et al*. (1983) states that High Performance Concrete (HPC) is that which is designed to give optimized performance characteristics for the given set of materials, usage and exposure conditions, consistent with requirements of cost, service life and durability. Architects, engineers and constructors all over the world are finding that using HPC allows them to build more durable structures at comparable cost. HPC is being used for buildings in aggressive environments, marine structures, highway bridges and pavements, nuclear structures, tunnels, precast units, etc. (Bharatkumar *et al*., 2001; Mittal and Basu, 1997). The major difference between conventional concrete and HPC is essentially the use of chemical and mineral admixtures. Use of chemical admixtures reduces the water content, thereby reducing the porosity within the hydrated cement paste (Hover, 1998). Pozzolanic materials are crucial to HPC as far as flow ability is concerned (Chang, 2004). Mineral admixtures, also called as cement replacement materials, act as pozzolanic materials as well as fine fillers, thereby the microstructure of hardened cement matrix becomes denser and stronger.

As a by-product from thermal power stations, fly ash has been used in blended cements (Nochaiya *et al*., 2010) and it has been used successfully to replace Portland cement up to 30% by mass as pozzolanic materials in HPC (Berry and Malhotra, 1980; Al-Ani and Hughes, 1989; Naik *et al*., 1995; Lam *et al*., 1998; Han *et al*., 2003). Because fly ash causes environmental pollution and the cost of storage of fly ash is very high, the utilization of fly ash in concrete technology, both in regard to environmental pollution and the positive effect on a country's economy are beyond dispute. The fly ash HPC system offers a holistic approach that can help us to achieve the goals of meeting the rising demands for concrete, enhancement of concrete durability with little or no increase in cost (in some instances reduced cost) and ecological disposal of large quantities of the solid waste products from coal-fired power plants (Malhotra, 2002). Several laboratory and field investigations reported that HPC containing fly ash had exhibited excellent mechanical and durability properties (Malhotra, 1990; Bilodeau and Malhotra, 2000).

The durability of concrete is one of its most important properties, aside from its compressive strength, because distresses in concrete are mostly due to durability failures rather than insufficient strength.

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Permeability is considered to be one of the most important properties affecting concrete durability because many concrete degradation mechanisms are a function of the rate of water or solution flow through the concrete and it controls the rate of entry of moisture that may contain aggressive chemicals and the movement of water during heating or freezing (Marsh *et al*., 1985; Tam *et al*., 2012). Dry shrinkage, one of the main causes of cracks that directly affect the strength and durability of concrete, usually occurs in hot and dry environments due to the loss of internal water in the concrete to the environment. This results in the reduction of concrete volume and leads to crack formation in hardened concrete. Furthermore, most of this drying shrinkage cannot be regained by rewetting the concrete (Weerachart and Chai, 2010). Early age cracking of concrete results from the interplay between the volume instability, the mechanical properties of concrete and different types and degrees of restraint (Radocca, 1998). When the concrete behaves like a fluid, i.e., during the very early age, its volumetric changes are usually not of a great concern in terms of stress generation because the concrete deforms plastically without generating stresses. However, once it has transformed a visco-elastic solid, the stress is generated (Lee *et al*., 2006). Carbonation of concrete has great negative impact on durability of concrete. The main harm of concrete carbonation is that it can increase PH of concrete, which will weaken the alkaline protection of the reinforcing rebar in concrete (Das *et al*., 2012). As a result, the reinforcing rebar has larger possibility of corrosion and the reinforced concrete is likely to be damaged. Freezing-thawing durability of concrete composite has the significant effect on the service life and service quality of concrete structures and besides, the area coverage of the freezing injury of concrete is quite wide. Freezing-thawing durability is so important in the mix design and application of concrete composite, especially when the concrete composite is used in the severe cold region. Studying the durability is certainly necessary and helpful to promote the application of the concrete composites containing fly ash. This article reports the investigation of the effect of fly ash on durability (water impermeability, dry shrinkage, carbonation resistance and Freezing-thawing durability) of high performance concrete composites.

MATERIALS AND EXPERIMENTAL PROGRAM

Raw materials: Ordinary Portland cement (Class 42.5R) produced by Tongli Factory and Grade I fly ash were used in this study. The cement and fly ash properties are given in Table 1. Fly ash was mixed in concrete by replacing the same quantity of cement and the content of fly ash (by mass) varies from 10% to 25%. The water to be mixed into the concrete mixture was local tap water. Coarse aggregate with a maximum size of 20 mm and fine aggregate with a 2.82 fineness modulus were used in this experiment. The specific gravity and silt content of the coarse and fine aggregates were 2.75 and 0.5% and 2.62 and 0.9%, respectively. A high range water reducer agent with a commercial name of polycarboxylate HJSX-A was used to adjust the workability of the concrete mixture. Mix proportions of the HPC are given in Table 2.

Table 1: Properties of cement and fly ash

Composition (%)	Cement	Fly ash
Chemical compositions		
SiO_2	20.17	51.50
Al_2O_3	5.58	18.46
Fe_2O_3	2.86	6.71
CaO	63.51	8.58
MgO	3.15	3.93
Na_2O	0.12	2.52
K_2O	0.57	1.85
SO_3	2.56	0.21
Physical properties		
Specific gravity	3.05	2.16
Specific surface (cm^2/g)	3295	2470

Water impermeability test: A series of frustum specimens with the size of Φ175×150×Φ185 mm were used to determine the water impermeability of concrete composite. The water impermeability of concrete composite can be evaluated by the length of water permeability of the specimen under the action of pressure water. The shorter length of water permeability indicates that the concrete composite has better water impermeability. For water impermeability of concrete composite test, each set of per composition includes 6 specimens and the average value of the 6 data was computed as the final result (JTJ E30, 2005). Before testing, the specimens were cured for 28 days at 100% relative humidity and controlled temperature (21±2°C). The tests of water impermeability of concrete composite were carried out by water impermeability instrument in accordance with the Chinese Standard (JTJ E30, 2005). The side face of the specimens were adhered a layer of sealant, which was made of grease and cement by mixing. The sealant can ensure the tightness between the side face of the specimen and the in wall of the specimen sleeve. The water pressure was controlled at 3.5 MPa and the floating pressure did not exceed 0.05 MPa. The test should last 24 h before the specimens were taken off from the water impermeability instrument. After the test finished, the specimen was split in half along the longitudinal section on the pressure testing machine. Finally, the average length of water permeability of the specimen can be measured.

Dry shrinkage test: The tests of dry shrinkage properties of concrete composite were carried out in accordance with the Chinese Standard (JTJ E30, 2005). A series of beam specimens with the size of 100×100×400 mm^3 were used to determine the shrinkage properties of the concrete composite.

Table 2: Mix proportions of the HPC

Mix no	Cement (kg/m^3)	Fly ash (%)	Fly ash (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	Water reducer agent (kg/m^3)
1	494.0	-	-	647	1151	158	4.94
2	444.6	10	49.4	647	1151	158	4.94
3	419.9	15	74.1	647	1151	158	4.94
4	395.2	20	98.8	647	1151	158	4.94
5	370.5	25	123.5	647	1151	158	4.94

For the shrinkage properties of concrete composite test, each set of per mix includes 6 specimens and the average value of the 6 data was computed as the final result. After the specimens were cast, the moulds should be removed the next day and the specimens were put into the standard and curing room to be cured at 100% relative humidity and controlled temperature (20±2°C). After the specimens were cured for two days, the initial lengths of the specimens should be measured and then they were put into the shrinkage room to be further cured at 60±5% relative humidity and controlled temperature (20±2°C). At the end of 90 days, the length variation of the specimen was measured by the dial indicator to calculate the dry shrinkage strain.

Carbonation test: A series of cube specimens with the size of 100×100×100 mm were used to determine the carbonation resistance of concrete composite. The carbonation resistance of concrete composite can be evaluated by carbonation depth of the specimen under the action of CO_2 pressure. The shorter carbonation depth indicates that the concrete composite has better carbonation resistance. For carbonation resistance of concrete composite test, each set of per composition includes 15 specimens and the average value of the 15 data was computed as the final result. Before testing, the specimens were cured for 28 days at 100% relative humidity and controlled temperature (21±2°C). The test of concrete carbonation was carried out in concrete carbonation box in accordance with the Chinese Standard (GB 11974, 1997). Before carbonation test, the specimens were baked for 48 h in the oven under the temperature of 60°C. In the concrete carbonation box, the CO_2 concentration should be controlled at 20±3% and the humidity and temperature should be controlled at 70±5% and 20±5°C, respectively. The carbonation test should last 24 days. After the test finished, the specimen was split in half and the fracture surface was sprayed phenolphthalein alcohol solution with the level of 1%. Finally, the average carbonation depth of the specimen can be measured.

Freezing-thawing test: Freezing-thawing durability of concrete composite can be measured referring to the standard of ASTM C666 (1997b). The freezing-thawing durability of concrete composite was evaluated by the relative dynamic elastic modulus of the specimen after 300 freezing-thawing cycles. The higher relative dynamic elastic modulus indicates that the concrete composite has better freezing-thawing durability. On the contrary, the material has worse freezing-thawing durability with lower relative dynamic elastic modulus. Relative dynamic elastic modulus of concrete composite can be measured referring to the standard of ASTM C215 (1997a). A series of prism specimens with the size of 100×100×400 mm were used to determine the relative dynamic elastic modulus of concrete composite. For freezing-thawing test of concrete composite, each set of per composition includes 3 specimens and the average value of the 3 data was computed as the final result. Before testing, the specimens were cured for 28 days at 100% relative humidity and controlled temperature (21±2°C) and the specimens have been soaked in saturated lime water in the last 4 days of the curing period. One freezing-thawing cycle should be carried out in 2 h to 5 h and the thawing time should not be less than a quarter of the total time of one cycle. At the end of freezing and thawing, the temperature of the specimen centre should be controlled at -18 and 5°C, respectively.

RESULTS AND DISCUSSION

Effect of fly ash content on length of water permeability: The variations of the length of water permeability of concrete composites versus fly ash content of the water permeability specimen are illustrated in Fig. 1. From the figure, it can be seen that the addition of fly ash can decrease the length of water permeability of the specimen evidently. In other words, the water impermeability of concrete composite was improved with the addition of fly ash. The length of water permeability is decreasing gradually with the increase of fly ash content when the fly ash content is not beyond 25%. As the fly ash content is increased from 0 to 25%, the length of water permeability decreases 33.7% from 19.9 mm to 13.2 mm. When the fly ash content is less than 20%, the decreasing rate of the length of water permeability is lower with the increase of fly ash content, while the decreasing rate is much higher when the fly ash content is beyond 20%. The main reason why the water impermeability of concrete composite containing fly ash is much higher than that of the concrete composites without fly ash is that the glass microspheres of SiO_2, Al_2O_3 and Fe_2O_3 account for 70% of the fly ash component, which have lubrication action around cement particles in concrete composite. As a result, the glass microspheres can improve the flow ability of fresh concrete mixture and decrease bleeding and segregation of the fresh concrete mixture. Furthermore, the glass microspheres of SiO_2

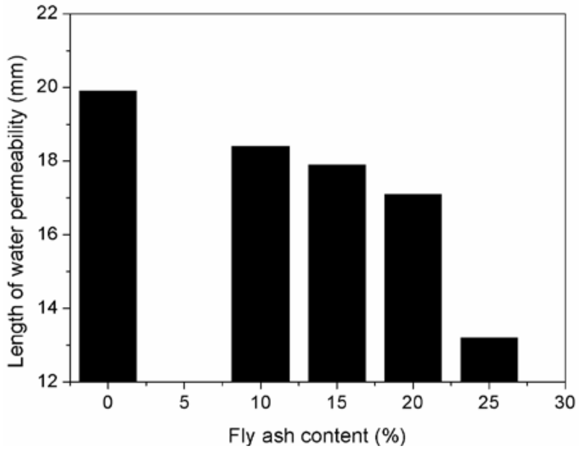

Fig. 1: Effect of fly ash content on length of water permeability

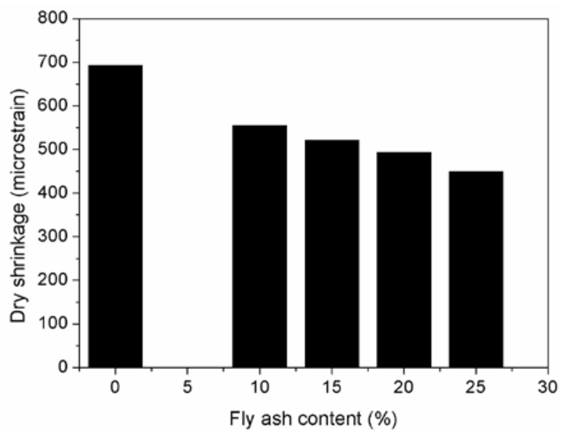

Fig. 2: Effect of fly ash content on dry shrinkage

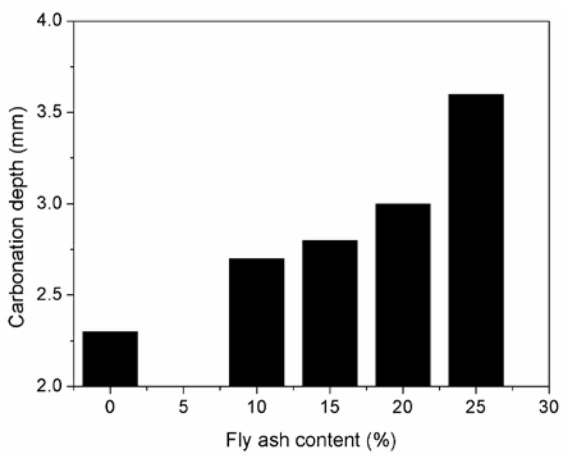

Fig. 3: Effect of fly ash content on carbonation depth

and Al_2O_3 in fly ash can react with Ca $(OH)_2$ generated from cement hydration to produce hydrated calcium aluminate and hydrated calcium silicate with high cementing property, which improve the compactness of concrete.

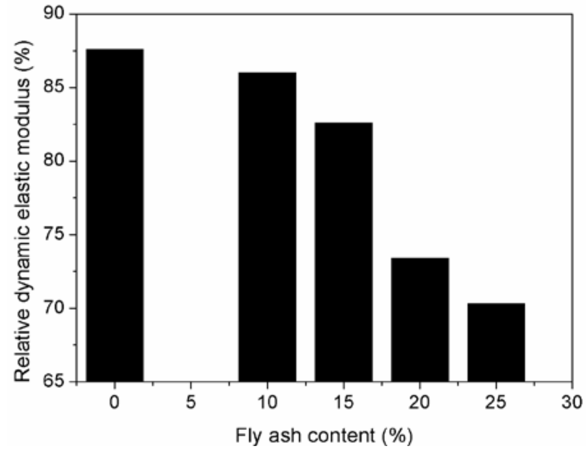

Fig. 4: Effect of fly ash content on relative dynamic elastic modulus

Effect of fly ash content on dry shrinkage strain: Figure 2 shows the varying rules of the dry shrinkage strain of 90 days of the beam specimen of fly ash concrete as the content of fly ash varies. It was clearly observed in Fig. 2 that the concretes with 10%, 15, 20 and 25%, respectively fly ash had lower shrinkage strain than that of the control concrete when the fly ash content is not beyond 25%. In other words, the anti-dry-shrinkage cracking property of concrete composite may be improved with the addition of fly ash. This beneficial effect appeared to be more pronounced with increasing replacement level of fly ash. As the fly ash content is increased from 0 to 25%, the maximum dry shrinkage strain of 90 days ages decreases 35% from 693 microstrain to 450 microstrain. The addition of fine particles of fly ash caused the segmentation of large pores and increased the nucleation sites for precipitation of hydration products in cement paste resulting in the pore refinement. Fly ash addition also contributed to the better cohesion of the fresh mixture and lower early plastic shrinkage deformations.

Effect of fly ash content on carbonation depth: The variations of the carbonation depth of concrete composite versus fly ash content of the carbonation specimen are shown in Fig. 3. A considerable increase for the carbonation depth of the concrete was observed by increasing the content of fly ash. Compared with the mix without fly ash, the increase was determined as 56.5% for 25% fly ash content. As seen from the variation curve, the increasing speed of the carbonation depth is relatively high with the increase of fly ash content when the fly ash content is more than 20%. When the fly ash content was increasing, the cement content was decreased with cement replaced by fly ash and the quantity of cement clinker was reduced. As a result, the quantity of Ca $(OH)_2$ released became less and less, especially when the fly ash content is much larger. Besides, the secondary response of concrete with high dosage fly ash will also consume a great deal of Ca $(OH)_2$. Therefore, the carbonation depth of concrete composite was increased evidently with the increase of fly ash content.

Effect of fly ash content on relative dynamic elastic modulus: Figure 4 illustrates the varying rules of the relative dynamic elastic modulus of fly ash concrete composites as the content of fly ash varies. From the figure, it can be seen that the addition of fly ash decreases the relative dynamic elastic modulus of concrete evidently. In other words, the freezing-thawing durability of concrete composite was lowered with the addition of fly ash. The relative dynamic elastic modulus is decreasing gradually with the increase of fly ash content when the fly ash content is not beyond 25%. As the fly ash content is increased from 0 to 25%, the relative dynamic elastic modulus decreases 19.7% from 87.6% to 70.3%. When the fly ash content is less than 10%, the decreasing rate of the relative dynamic elastic modulus is lower with the increase of fly ash content, while the decreasing rate is much higher when the fly ash content is beyond 10%. Fly ash is made up of a great quantity of glass microsphere, which has large surface area and the grain size of fly ash is smaller than that of cement. As a result, the addition of fly ash can improve the pore structure of concrete and increase the compactness of concrete; however, the air content of the concrete is decreased at the same time. Besides, the tiny particles of activated carbon of incomplete combustion can adsorb the tiny bubbles in concrete composite, which also decreases the air content of the concrete. The lower air content of concrete has adverse impact on the freezing-thawing durability of concrete. Therefore, the addition of fly ash decreases the freezing-thawing durability of concrete composite containing fly ash evidently.

CONCLUSION

This study reported experimental results of durability studies conducted on high performance concrete composite containing fly ash. The following conclusions can be draw from the results presented in this study:

- Effect of fly ash on the length of water permeability of concrete composites is significant and the addition of fly ash can reduce the length of water permeability and improve the water impermeability of the concrete composite evidently and the water impermeability is becoming better and better as the fly ash content is increasing gradually.
- Addition of fly ash has restricted the dry shrinkage of concrete composite. The dry shrinkage strain in the concretes containing fly ash was smaller than that in the concrete without fly ash and a considerable decrease for the dry shrinkage strain of the concrete was observed by increasing the dosage of fly ash.
- Addition of fly ash in concrete composites has increased the carbonation depth considerably. Carbonation depth of the concrete is increasing gradually as the fly ash content is increasing gradually. The addition of fly ash has adverse effect on the carbonation resistance of the concrete composite evidently.
- Freeze-thaw resistance of concrete containing fly ash was found to evidently decrease when compared to concrete without fly ash. Moreover, there is a tendency of decrease in the freeze-thaw resistance with the increase of fly ash content.

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