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Influence of a low-activity slag and silica fume on the fresh properties and durability of high performance self-consolidating concrete

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ABSTRACT

Advances in concrete technology have resulted in the development of a new type of concrete, known as High Performance Self-consolidating Concrete (HPSC). Three main characteristics should be satisfied by this concrete, namely, high workability, high strength (greater than 50 MPa) and satisfactory durability parameters.

The research objective is to investigate the effect of cement replacement by low-activity blast furnace slag and silica fume on the properties of HPSC. The tests conducted to investigate the fresh properties included slump flow, T50 and J-ring. The hardened specimens were tested for compressive strength, capillary absorption and surface resistivity at 28 days age.

Fresh tests results revealed that use of 10% silica fume besides 10% Iranian slag leads to the highest flowability of the fresh HPSC. In the hardened state, results indicated that use of low-activity slag decreases the strength value. Also, use of either slag or silica fume reduces the permeability of HPSC.

Keywords: Slag, Silica fume, High performance, Self-consolidating, Durability

1- INTRODUCTION

Most of the current design specifications for concrete structures, such as ACI, IS 456, AASHTO LRFD bridge specifications are still based on tests conducted using normal strength concrete (NSC). New types of concrete possessing unique characteristics emerged as the concrete technology improved, High performance concrete (HPC) and Self-consolidating concrete (SCC) are among these new types (Khaliq and Kodur, 2011).

Considering the difference between two concepts of high strength concrete and durable concrete, HPC has been defined as a concrete that is properly designed, mixed, placed, consolidated, and cured to provide high strength and durability (Safiuddin et al., 2012). High workability, compressive strength and durability parameters are all properties of high performance concrete that greatly influence the structural designs. On the other hand, Self-consolidating concrete (SCC) is an innovative concrete that does not require vibration for placing and compaction. It is able to flow under its own weight, completely filling formwork and achieving full compaction, even in the presence of congested reinforcement. HPC usually contains two extra ingredients including a chemical admixture (superplasticizer) and a mineral admixture (e.g., fly ash, blast furnace slag, silica fume).

Silica fume (SF) as a pozzolan enrich the concrete workability because of its minute grains size (Hassan et al., 2012) and durability properties by creating additional cementitious products due to reaction with the calcium hydroxide formed during portland cement hydration (Hassan et al. 2012, Hubertova, 2007). Therefore, it can reduce porosity and $Ca(OH)_2$ content in the interfacial transition zone (ITZ) between the cement paste and the aggregate, as well as the ITZ's width. Due to the better engineering and performance properties, mineral admixtures such as Silica Fume (SF), Fly Ash (FA) and Ground Granulated Blast-Furnace Slag (GGBFS) are normally included in the production of high-performance concrete (Brooks, 2000). Proper selection of constituents and mixture proportions are crucial to ensure that the advantageous properties of SCC and HPC can be achieved economically.

In this study, the effect of a GGBFS and SF as pozzolanic materials on the fresh and hardened properties of high performance self-consolidating concrete was investigated. To study the fresh behaviour of mixtures, slump flow, T50 time and J-ring tests were conducted. Furthermore, compressive strength, electrical resistivity and capillary water absorption tests were carried out in the hardened state.

2- EXPERIMENTAL PROGRAM

2-1-Material

ASTM C 150 type I Portland cement was used in all the concrete mixtures. The chemical compounds of the portland cement are presented in Table 1. The physical and chemical properties of cement, SF and GGBFS are also shown in Table 1.

For all mixtures, coarse aggregates were crushed calcareous stone with a maximum size of 9.5 mm and fine aggregate was natural sand. The coarse aggregates had a specific gravity and a water absorption of 2510 kg/m3 and 1.90%, respectively, and the fine aggregate had a water absorption of 2.75% and a specific gravity of 2570 kg/m3. In addition, siliceous sand and siliceous filler (finer than #200 sieve) were used to improve the packing of the aggregates. The selected grading for the aggregates is presented in Table 2.

Table 1. Characteristics of portland cement, SF and GGBFS

	Cement	SF	GGBFS
Chemical components			
Calcium oxide (CaO) (%)	65.30	1.50	34.8
Silicon dioxide (SiO_2) (%)	20.80	85.00	37.5
Aluminium oxide (Al_2O_3) (%)	4.34	1.02	6.4
Ferric oxide (Fe_2O_3) (%)	2.20	2.05	0.51
Magnesium oxide (MgO) (%)	2.17	2.10	8.6
Potassium oxide (K_2O) (%)	0.63	-	0.9
Sodium oxide (Na_2O) (%)	0.36	-	0.38
Titanium oxide (TiO_2) (%)	0.25	-	-
L.O.I (%)	0.91	3	-
Mineralogical composition			
C_3S (%)	66.37	-	-
C_2S (%)	9.65	-	-
C_3A (%)	7.78	-	-
C_4AF (%)	6.69	-	-
Physical characteristics			
Specific Gravity	3.15	2.19	2.85

A poly-carboxylic based superplasticizer (GLENIUM 110) was employed to increase the mixtures workability and adjust the spread diameter of all mixtures in slump flow test to 70± 3 cm.

Table 2. Selected Grading for Aggregates

Sieve size	Cumulative passing (%)		
	Coarse aggregates	Natural sand	Siliceous sand
1/2	100	100	100
3/8	75	100	100
4	25	77.00	100
8	0	54.33	69.67
16	0	33.33	0.67
30	0	25.33	0.67
50	0	10.93	0.67
100	0	1.47	0.67

2-2-Mixture proportion

The mixture proportions of high performance concrete mixtures containing different percentages of silica fume (SF) and GGBFS are presented in Table 3. A total of five mixtures were produced, including a control mixture containing no filler, SF and GGBFS. In the next step, siliceous filler was added to study its effect on workability and hardened properties of concrete mixtures (F-CTL). Then, three mixtures containing 10% SF as well as 0, 10% and 20% GGBFS as a partial cement replacement (designated as 10S0G, 10S10G, 10S20G) were prepared. For example, the '10S20G' designation was used for the concrete made with 10% Silica fume and 20% blast furnace slag. After selection of the total cementitious materials content, w/cm ratio and replacement levels, the mixture proportions were determined according to "abstract volume" method.

Cubic and cylinder specimens were cast without application of any vibration. Then the specimens were cured in temperature controlled water until the test age.

Table 3. Concrete mixture proportions

Mixture ID	Cementitious materials			Aggregates			
					Fine		
	SF (Kg/m^3)	GGBFS (Kg/m3)	Cement (Kg/m3)	Coarse aggregate (Kg/m3)	Natural sand (Kg/m^3)	Siliceous Sand (Kg/m^3)	Siliceous Filler (Kg/m^3)
CTL	0	0	700	581	563	308	0
F-CTL	0	0	700	561	544	298	52.5
10S0G	70	0	630	551	534	292	52.5
10S10G	70	70	560	549	532	291	52.5
10S20G	70	140	490	546	530	290	52.5

2-3-Tests on fresh and hardened concretes

The flowability of fresh SCC mixtures were evaluated using slump flow and V-funnel tests. The V-funnel test is primarily used to measure the filling ability of SCC and can also be used to evaluate segregation resistance. To perform the test, the concrete is poured into the funnel with a gate blocking the bottom opening without tamping or vibration and the concrete is left undisturbed for 1 minute. Then, the gate at the bottom of the funnel is opened and the time for all concrete to exit the funnel is recoded. Again, the V-Funnel is filled with concrete, kept for 5 minutes and trap door is opened. V-Funnel time is measured again and this indicates V-Funnel time at T_5min.

Hardened properties and durability characteristic of concrete determine service life of concrete structures. Compressive strength, capillary absorption, and electrical resistivity tests were conducted to evaluate the hardened properties of mixtures.

Three cubes of 100×100×100 mm dimension were cast for compressive strength. They were tested for compressive strength after 3, 7, 28 days of water curing by a 2000 kN hydraulic press at the loading rate of 0.5 N/mm2/s.

The electrical resistivity meter was used to measure the surface resistivity at the ages of 3, 7 and 28 days. Three saturated 100x200mm cylinders were tested according to "Florida Method of Test for Concrete Resistivity as an Electrical Indicator of its Permeability FM 5-578" at each age. The electrical resistivity test for concretes was carried out by the four-point Wenner array probe technique. The probe array spacing used was 40 mm. The resistivity measurements were taken at four quaternary longitudinal locations and the average value was considered as concrete electrical resistivity.

Capillary Absorption was carried out after 28 days of curing. The capillary absorption rate of specimens were calculated using their weight after 48 hours being in 110^{oC} as initial weight, and the measured weight after 72 hours of being partly in the water (on side exposed to water at 5 mm depth).

Table 4. List of tests in this study

	Fresh properties		**Hardened properties**		
Test	Slump flow	V-funnel	Compressive strength	Electrical resistivity	Capillary Absorption
Age	-	-	3, 7, 28	3,7, 28	28
Unit	Seconds	Minutes	Days	Days	Days

3. RESULT AND DISCUSSION

3.1. Fresh and hardened properties

3.1.1. Slump flow and V-funnel

Table 5 presents the results of various fresh tests which were carried out on mixtures. To set a common basis for comparison, the spread diameter of all mixtures in slump flow test was regulated to be 700± 30 mm. Usually the spread value range of 600–850 mm is introduced for self-consolidating concrete (EFNARC, 2005; Khayat, 2009). The superplasticizer dosages which were consumed to reach this flowability for different mixtures are presented in Table 5. The highest dosage was used for 10S0G mixture. On the other hand, the lowest dosage was used for 10S10G mixture, containing 10% slag and 10% silica fume.

EFNARC (2002) suggests 6-12 seconds as the acceptance range for V-funnel test of self-consolidating concrete. V-funnel and V-funnel at T_{5min} values were significantly decreased by 8-9 Secs in the presence of GGBFS. This fact implies the positive effect of slag incorporation on reducing the plastic viscosity of the mixture.

Table 5. Fresh state tests results

Mix ID	Slump flow		V-funnel		Super plasticizer dosage*
	Dia (mm)	T_{50} (sec)	T_0 (sec)	T_{5min} (sec)	%
CTL	680	5	10.5	12.6	1.14
F-CTL	735	5	13	17	1.17
10S0G	685	4	6.6	8	1.20
10S10G	715	4.5	5	7.8	0.85
10S20G	712	3	7	9	0.96

* percent of total cementitious materials

3.1.1. Compressive strength

The compressive strength of all five mixtures were measured at 3, 7 and 28 days. The measurements are presented in Figure 1. The highest strength value (102.2 MPa) at 28 days is gained by 10S0G, which contains 10 percent SF and doesn't include GGBFS. Considering the strength values for specimens containing slag (10S10G and 10S20G), it appears that incorporation of GGBFS has negative effect on compressive strength, especially at early ages, which is related to the low reactivity of the used slag. It should be noticed that cement replacement level of 20% by GGBFS has led to higher 28-day strength values comparing to 10% GGBFS incorporation. This is in accordance with another project's findings which is carrying out by the authors on the same GGBFS (Ramezanianpour et al., 2012). Regarding the consumed siliceous filler, comparing the CTL and F-CTL reveals that it has positive effect on the strength values, mainly in early ages of 3 and 7 days, which has caused 22 and 43 percent increase in compressive strength respectively.
Another fact which could be drawn from the strength values is that 28-day strength values of all mixtures are higher than 80 MPa, certainly being in the category of High-performance concrete.

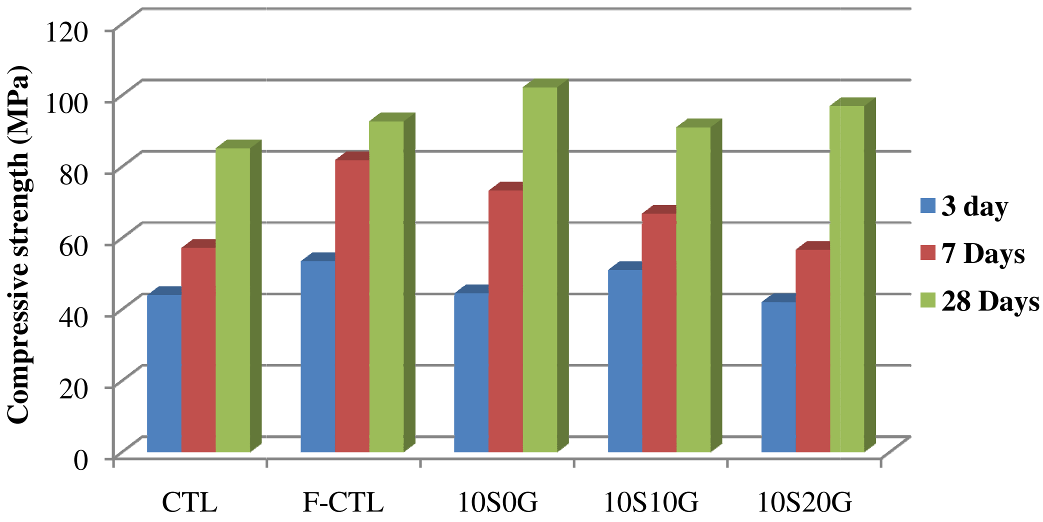

Figure 1. Compressive Strength of mixtures at different ages

3.2. Durability characteristics

3.2.4. Surface Electrical Resistivity

Electrical resistivity is a sign of the corrosion-resisting performance of concrete which refers to the resistance that an electrical charge experiences while passing through the concrete (Ramezanianpour et al., 2011). This test was conducted on all mixtures at the ages of 3, 7 and 28 days and the results are presented in Fig 2. The electrical resistance will grow with the concrete age due to pozzolanic reaction (Hwang, 2005). The lowest electrical resistivity at 28 days was obtained for CTL mixture, which didn't contain any supplementary cementitious material, while 0S0G developed higher resistivity values at early ages which hint positive effect of siliceous filler on concrete impermeability. After 28 days of curing, 10S10G mixture has developed the maximum resistivity value, which implies the combination of 10% slag and 10% silica fume as the optimum combination.

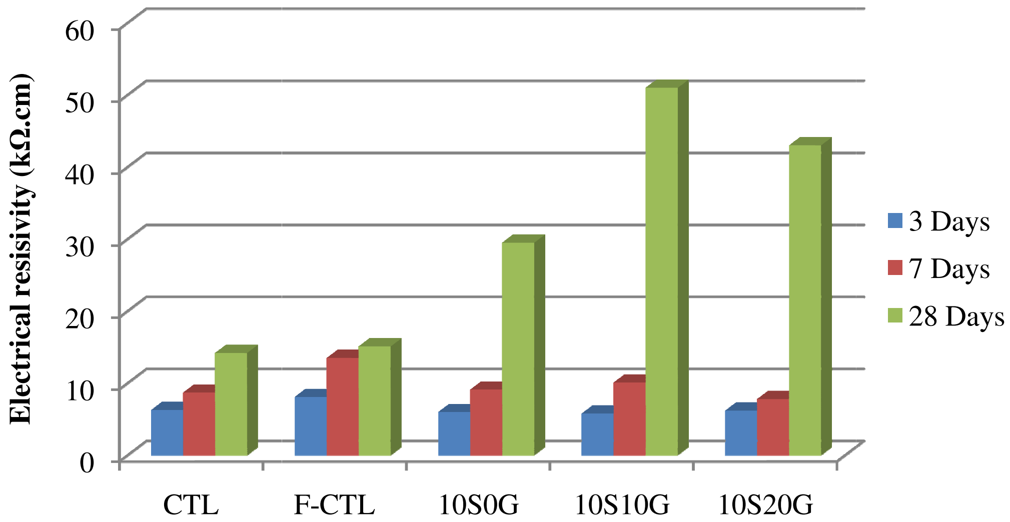

Figure 2. Electrical resistivity of High-Performance Self-Consolidating mixtures at different ages

Moreover, considering Florida guide, only 10S20G and 10S10G have reached the permeability class of "Very Low", which corresponds to surface resistivity values higher than 37 kΩ.cm. This fact implies high performance of ternary blends regarding durability issues.

3.2.2. Capillary absorption

Capillary absorption test was carried out at the age of 28 days. The test results are presented in Table 6.

Table 6. Capillary absorption of HPSC mixtures at 28 days age

Mix ID	Capillary absorption (%)
CTL	1.06
F-CTL	0.95
10S0G	0.70
10S10G	0.75
10S20G	0.92

The highest capillary absorption percentage belongs to CTL mixture, which didn't contain any siliceous filler, slag or silica fume. A 0.16 percent decrease in capillary absorption is observed in this mixture as a result of siliceous filler addition (F-CTL). On the other hand, the lowest capillary absorption value belongs to 10S0G mixture, containing siliceous filler and 10% of silica fume. This implies the negative effect of cement replacement by the slag on water absorption after 28 days of curing.

3.2.3. Water absorption

Table 7 represents the water absorption of high performance self-consolidating concrete specimens after 28 days of water curing. The water absorption of high quality concrete is usually less than 5% (Safiuddin et al., 2012). Similar to capillary absorption, the highest absorption rate is measured for CTL mixture. This approves the relatively poor quality of this mixture regarding permeability. On the other hand, the results imply that combination of 10% silica fume and 10% slag leads to the lowest permeability, a conclusion which was approved by RCPT and electrical resistivity tests, too. This could be a hint for minor similarities in mechanism of these three tests.

Table 7. Water absorption of HPSC mixtures

Mix ID	Bulk water absorption (%)
CTL	4.18
F-CTL	3.71
10S0G	2.98
10S10G	2.89
10S20G	3.29

4. CONCLUSIONS

According to the experimental results of the tests which were carried out in this research, following conclusions are drawn:

- Considering the fresh state test results, it seems that addition of GGBFS reduces the plastic viscosity of the mixtures. It is of high importance in HPC mixtures which contain high powder content and low w/b ratio. V-funnel time and high superplasticizer dosage in mixtures without GGBFS proves that usage of this industrial by-product improves the fresh state behaviour of the HPSC mixtures.

- Considering the compressive strength values, it seems that addition of local GGBFS has negative effect on compressive strength, while silica fume increases the strength value, especially at 28 days. This could be due to the low-reactivity of GGBFS. The highest compressive strength value was measured for 10S0G mixture which contains 10% silica fume

- The results indicated that usage of silica fume and GGBFS has a positive effect on impermeability of high performance concrete mixtures.

- Considering all aspects (i.e. fresh and hardened state), it seems that 10S10G mixture (containing 10% GGBFS and 10% silica fume) could be introduced as the optimum high performance self-consolidating mixture.

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