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Influence of Iranian low-reactivity GGBFS on the properties of mortars and concretes by Taguchi method

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Abstract. Ground Granulated Blast Furnace Slag (GGBFS) is widely used as an effective partial cement replacement material. GGBFS inclusion has already been proven to improve several performance characteristics of concrete. GGBFS provides enhanced durability, including high resistance to chloride penetration and protection against alkali silica reaction.
In this paper results of an experimental research work on influence of low-reactivity GGBFS (which is largely available in Iran) on the properties of mortars and concretes are reported. In the first stage, influence of GGBFS replacement level and fineness on the compressive strength of mortars was investigated using Taguchi method. The analysis of mean (ANOM) statistical approach was also adopted to develop the optimal conditions. Next, based on the obtained results, concrete mixtures were designed and water penetration, capillary absorption, surface resistivity, and compressive strength tests were carried out on high-strength concrete specimens at different ages up to 90 days. The results indicated that 7-day compressive strength is adversely affected by GGBFS inclusion, while the negative effect is less evident at later ages. Also, it was inferred that use of low-reactivity GGBFS (at moderate levels such as 20% and 30%) can enhance the impermeability of high-strength concrete since 28 days age.

Keywords: GGBFS; high-strength concrete; Taguchi method; mortar; permeability

1. Introduction

Blast furnace slag is a by-product of pig iron production, which is a stage process in the production of steel. it is estimated that approximately 300 kg of slag are generated per ton of pig iron (Neville 1997). Ground Granulated Blast Furnace Slag (GGBFS) is commonly used as a supplementary cementitious material in Portland cement mortars and concretes. Various factors

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influence the reactivity of GGBFS; including the surface area, chemical composition, and amorphous fraction. The surface area required for GGBFS as a cementitious material is normally greater than for Ordinary Portland Cement (OPC). This is usually needed to improve the GGBFS reactivity and thus the strength attained when it replaces OPC (Frigione 1986). In fact, a major practical inconvenience in the use of some mineral admixtures such as GGBFS is their slow hydration characteristics, particularly when their fineness is of the same order of magnitude as Portland cement (M. Pk. 1983, Bouikni and Bali 2009).

GGBFS inclusion has already been proven to improve several performance characteristics of concrete (Edamatsu 2003, Chopin and Bogdan Cazacliu 2004, Domone 1999, Boukendakdji *et al*. 2009). GGBFS provides enhanced durability, including high resistance to chloride penetration, resistance to sulfate attack and protection against alkali silica reaction (Boukendakdji *et al*. 2009). Utilizing GGBFS as a partial OPC replacement develops the strength and durability of concrete by creating a denser matrix and thereby enhancing the service life of concrete structures (Edamatsu 2003). Diffusion coefficients and chloride ion permeability were decreased as the amount of GGBFS was increased. However, at higher GGBFS contents, lower resistance to carbonation was reported (Chopin and Bogdan Cazacliu 2004). GGBFS can effectively reduce the pore sizes and cumulative pore volume (Domone 1999). Also, being an industrial by product, use of GGBFS has many environmental advantages such as low energy cost, use of secondary raw material and low pollutant gas emission (Garcia *et al*. 2013).

The optimum amount of GGBFS is usually in the range of 40–60% of the total mass of binder; its higher content can already impair the 28-day compressive strength of hardened concrete (Guo *et al*. 2007, Oner 2007, Atis 2007). Therefore, a relatively high amount of cement can be safely replaced by common slags. Although the mentioned properties are observed and reported by many researchers, there is limited knowledge available on the influence of low-reactivity slag on the properties of Portland cement concretes and mortars. Considering the large amounts of low quality GGBFS which are available in Iran, further research is needed to investigate the effects of inclusion of low-reactivity GGBFS in Portland cement materials.

The aim of this paper is to report the properties of low-reactivity GGBFS incorporated concretes and mortars. In the first stage Taguchi method was employed to study the effects of GGBFS replacement level and fineness on the compressive strength of mortar mixes at three different *w*/*c* ratios. During the second phase, concrete mixtures (proportioned based on the first stage results) were prepared and strength and permeability tests were performed at different ages up to 90 days. In particular, data are presented on the compressive strength, capillary absorption, water absorption, and electrical resistivity of these mixtures, as affected by the GGBFS incorporation.

2. Experimental program

2.1 Materials and aggregates grading

ASTM C150 Type I Portland cement was utilized in all the mixtures, and grade 80 GGBFS (as defined by ASTM C989) was used as a supplementary cementitious material. Different fineness levels were prepared in laboratory, while the GGBFS sample which was used in concrete mixtures was produced in Sepahan cement factory. By X-Ray Diffraction (XRD) analysis, the glass content of local GGBFS was measured 87% according to BS 6699-1992. The physical properties and chemical composition of the cementitious materials are summarized in Table 1.

In order to maintain the required workability of fresh concrete, a polycarboxylate-ether type High-Range Water Reducer Admixture (HRWRA) with specific gravity of 1.08, solids content of 28% and pH of 6.6 was consumed.

Natural sand and crushed gravel were used as aggregates in concrete mixtures. The coarse aggregates had nominal maximum size of 12.5 mm, specific gravity of 2.57, and water absorption of 1.6%. The specific gravity and water absorption of fine aggregates were 2.56 and 2.6%, respectively. The sieve analyses of fine, coarse and final mixture of aggregates used in the high-strength concrete mixtures are listed in Table 2. Also, natural silica sand conforming to the requirements mentioned in ASTM C 778 (2006) was used to prepare mortar mixes.

Table 1 Cementitious materials properties

	Portland cement	GGBFS
Chemical composition (%)		
SiO_2	20.8	37.5
Al_2O_3	4.3	6.4
Fe_2O_3	2.2	0.51
CaO	65.3	34.8
Na_2O	0.36	0.38
K_2O	0.63	0.9
MgO	2.17	8.6
TiO_2	0.26	-
SO_3	2.57	-
C_3S	68.3	-
C_3A	8.18	-
C_4AF	7.68	-
Physical properties		
Specific gravity	3.15	2.85
Blaine (m^2/kg)	320	Varies

Table 2 Sieve analysis of aggregates (Cumulative percentage passing**)**

Sieve size (mm)	River sand	Crushed gravel	Aggregate mixture
12.5	100	100	100
9.5	100	70	88
4.75	79.5	30	59.7
2.38	56.6	0	33.9
1.19	37.4	0	22.4
0.6	26.9	0	16.1
0.3	12.2	0	7.3
0.15	1.5	0	0.9

2.2 Mortars mix proportions (using Taguchi method)

The Taguchi method has been generally adopted to optimize the design parameters (Chou *et al*. 2009) because this systematic approach can significantly minimize the overall experimental costs. This method uses a special design of orthogonal arrays to determine the optimum experimental conditions. In this study, to investigate the effects of low-reactivity GGBFS on the compressive strength of mortars, three controllable factors were considered, each one with three levels (Table 3). Therefore, an L9 orthogonal array was selected, and the experimental conditions (Table 4) were obtained by combining Table 3 and the L9 orthogonal array.

Accordingly, an analysis of the signal-to-noise (S/N) ratio is needed to evaluate the experimental results. Three types of S/N ratio analysis are applicable: (1) Lower is Better (LB), (2) Nominal is Better (NB) and (3) Higher is Better (HB) (Chou et al. 2010). Since the higher compressive strength was desired, the S/N ratio with HB characteristic was applied, which is defined by Eq. (1)

$$\frac{\mathrm{S}}{\mathrm{N}} = -10\log\left(\frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{n}}\frac{1}{\mathrm{Y}_{\mathrm{i}}^{\,2}}\right) \tag{1}$$

where n is the number of repetitions under the same experimental conditions and Y represents the result of measurement, which is the slag cement mortar compressive strength in this study. The analysis of mean (ANOM) statistical approach was also adopted herein to develop the optimal conditions.

Initially, the mean of the S/N ratio of each controllable factor at a certain level must be calculated. For example, $(\mathrm{M})_{\mathrm{Factor=I}}^{\mathrm{Level=i}}$, the mean value of the S/N ratio of factor I in level i, is given by

$$(\mathrm{M})_{\mathrm{Factor=I}}^{\mathrm{Level=i}} = \frac{1}{\mathrm{n_{Ii}}}\sum_{\mathrm{j}=1}^{\mathrm{n_{Ii}}}\left[\left(\frac{\mathrm{S}}{\mathrm{N}}\right)_{\mathrm{Factor=I}}^{\mathrm{Level=i}}\right]_{\mathrm{j}} \tag{2}$$

In Eq. (2), n_{Ii} represents the number of appearances of factor I in the level i, and $[(\frac{S}{N})_{Factor=I}^{Level=i}]_j$ is the S/N ratio of factor l in level i, and it's appearance sequence in

Table 8 is the jth. By the same measure, the mean of the S/N ratios of the other factors in a certain level can be determined. Thereby, the S/N response table and figure are obtained, and the optimal conditions are established. Finally, the confirmation experiments on solidification under these optimal conditions are carried out.

In addition to ANOM, the analysis of variance (ANOVA) statistical method is also used to analyze the influence of each controllable factor on the slag cement mortar compressive strength.

The contribution percentage of each factor, ρ_f, is given by

$$\rho_F = \frac{SS_F - (DOF_F V_{ER})}{SS_T} \times 100 \tag{3}$$

Table 3 Factors and their levels

Factor	Description	Level 1	Level 2	Level 3
A	w/cm	0.4	0.485	0.55
B	Slag fineness (m^2/kg)	350	400	450
C	GGBFS Replacement level (%)	10	20	35

Table 4 Test conditions

	w/cm ratio	Slag fineness (m^2/kg)	Replacement level (%)
Test 1	0.4	350	10
Test 2		400	20
Test 3		450	35
Test 4	0.485	350	20
Test 5		400	35
Test 6		450	10
Test 7	0.55	350	35
Test 8		400	10
Test 9		450	20

Table 4 Mix proportions of high-strength concrete mixtures

Mix ID	Portland cement (kg/m^3)	GGBFS (kg/m^3)	w/cm	Sand (kg/m^3)	Gravel (kg/m^3)	28-day compressive strength
G0-0.35	375	0	0.35	1038	850	51.5
G0-0.40	375	0	0.4	1012	828	60.5
G20-0.35	300	75	0.35	1035	847	60.0
G20-0.40	300	75	0.4	1008	825	49.5
G30-0.35	262.5	112.5	0.35	1033	845	52.5
G30-0.40	262.5	112.5	0.4	1007	824	48.0

In Eq. (3), DOFF represents the degree of freedom for each factor, which is obtained by subtracting one from the number of the level of each factor (L = 3, DOF = 3-1). The total sum of squares, SST , is given by

$$SS_T = \sum_{j=1}^{m}\left(\sum_{j=1}^{n} Y_i^2\right)_j - mn(\overline{Y}_T)^2 \tag{4}$$

where $\overline{Y}_T$ is defined by Eq. (5), m represents the number of experiments carried out (m = 9) and n represents the number of repetitions under the same experimental conditions (n = 3).

$$\bar{Y}_T = \sum_{j=1}^{m} (\sum_{i=1}^{n} Y_i)_j \ /(mn) \tag{5}$$

The factorial sum of squares, SS_F, is given by

$$SS_F = \frac{mn}{L} \sum_{k=1}^{L} (\bar{Y}_k^F - \bar{Y}_T)^2 \tag{6}$$

where $\bar{Y}_k^F$ is the average value of the measurement results of a certain factor in the *k*th level. Additionally, the variance of error, V_{Er} is given by

$$V_{ER} = \frac{SS_T - \sum_{F=A}^{D} SS_F}{m(n-1)} \tag{7}$$

2.3 High-strength concrete mix proportions

According to the mortar compressive strength values, a total number of 6 concrete mixtures were designed to investigate the effect of Iranian GGBFS on the compressive strength and permeability of high-strength concrete. A minimum 28-day strength of 50 MPa was targeted for control mixtures, which was obtained after several trial batches.

The total cementitious materials content was kept constant at 375 kg/m^3 for all mixtures, while w/cm ratio was set at 0.35 and 0.4. Portland cement was replaced by GGBFS at 20 and 30 percent of total cementitious materials, by weight.

The mixture proportions are listed in Table 5. It should be mentioned that slump value for all mixtures was kept in the range of 70-100 mm by addition of sufficient HRWRA dosages.

The concrete mixtures were produced in a 60-liter horizontal pan mixer. Mixing sequence was initiated by dry mixing of aggregates for 1 minute. Then the GGBFS, cement, and two thirds of the mixing water were added to the dry mixture and mixed for 2 minutes. Finally, the remaining mixing water containing HRWRA was introduced to the mixture and mixed for 6 minutes.

2.4 Testing procedures

2.4.1 Compressive strength

During the first stage, 7-day and 28-day compressive strength of water-cured mortar specimens were determined (as the average of three 50 × 50 × 50 mm cubes) to facilitate the selection of GGBFS replacement level in concrete mixtures.

In the second stage, in order to investigate the effect of local GGBFS on the compressive strength of high-strength concrete mixtures, three 100-mm cube specimens of each concrete mixture were tested at the ages of 7, 28, and 90 days. The test was carried out using a 2000-kN hydraulic press at a loading rate of 0.5 N/mm^2/s.

Table 6 Permeability classes based on surface resistivity by FM 5-578

Chlorideion permeability	Surface resistivity (kΩ.cm)
High	<12
Moderate	12-21
Low	21-37
Very low	37-254
Negligible	>254

2.4.2 Surface resistivity

Surface resistivity (also called electrical resistivity) is a non-destructive test method which measures the resistivity of water saturated concrete in order to provide an indication of its permeability. Electrical resistivity refers to the resistance that any electrical charge experiences while passing through the concrete. The increased electrical resistivity of concrete impedes the movement of electrons from the anodic to the cathode regions, and consequently delays the propagation of the corrosion process (Ramezanianpour *et al*. 2013). As presented in Table 6, FM 5-578 test method (FM 5-578 2004) defines chloride ion permeability ratings according to surface resistivity test results.

The electrical resistivity meter was used to measure the surface resistivity of high-strength specimens at the ages of 7, 28, and 90 days. Three saturated 100 × 200 mm cylinders were tested at each age. The test was carried out by the four-point Wenner array probe technique.

2.4.3 Water penetration test

Water penetration test, specified by BS EN-12390-8, is commonly used to evaluate the penetrability of concrete. In this test, water is applied on one face of the 150-mm concrete cubes specimen under a 0.5 MPa pressure, which is maintained for 72 hours. Then, the specimens are removed and split open into two halves. The water penetration profile on the concrete surface is then marked and the maximum depth of water penetration is recorded and considered as the test result (Ramezanianpour *et al*. 2011).

2.4.4 Capillary absorption test

Capillary absorption occurs in fine pores (10 *n*m-10 μm) where forces arising from surface tension are in the same range as gravity forces present in the liquid. It is the principal mechanism when the material is just partially wetted (Hanžič *et al*.2010).

The capillary absorption was measured on 100 mm concrete cubic specimens, which were dried at slightly elevated temperature (50°C- to avoid internal micro-cracking (Kolias and Georgiou 2005)) for 14 days. Then, the specimen was rested on rods to allow free access of water to the surfaces and the tap water level was kept at 5 ± 1 mm above the base of the specimen. The mass of the specimens was measured after 0, 3, 6, 24 and 72 h of absorption. The sorptivity coefficient (S) according to BS EN-480-5:1997 was obtained using the following expression

$$Q/A = c + S\sqrt{t} \tag{2}$$

where (Q) is the amount of adsorbed water in m^3; (A) is the cross section of the test specimen in m^2; (t) is the time in seconds; (c) is the constant coefficient; and S is the sorptivity coefficient ($m/s^{0.5}$).

3. Results and discussion

3.1 Mortar mixes

The slag cement mortars were prepared according to the tests conditions determined by the Taguchi method and the compressive strength was measured at the ages of 7 and 28 days, as presented in Table 7. Applying the number of experimental repetitions and the measurements (the compressive strength of slag cement mortar) into Eq. (1), the S/N ratio of each test condition was determined (Table 7). The boldface in the table refers to the maximum value of S/N ratio at each age among 9 tests. Subsequently, the values of the S/N ratio were substituted into Eq. (2) and the mean of the S/N ratios of a certain factor in the *i*th level, $(M)_{Factor=I}^{Level=i}$, was obtained. In Table 8 the boldface refers to the maximum value of the mean of the S/N ratios of a certain factor among three levels, which indicates the optimum conditions for the compressive strength of slag cement mortar at each age.

Table 7 S/N ratio of the tests

				7-day results				28-day results			
	Factor			Yi (MPa)			S/N	Yi (MPa)			S/N
	A	B	C	Y1	Y2	Y3		Y1	Y2	Y3	
Test 1	0.4	3500	10	25.8	26.6	27.0	28.45	31.4	33.0	31.1	30.05
Test 2		4000	20	24.1	23.5	26.5	27.82	38.0	39.7	40.3	**31.89**
Test 3		4500	35	25.8	24.1	23.6	27.76	36.0	37.8	36.9	31.34
Test 4	0.485	3500	20	21.9	24.4	24.8	27.45	34.2	35.9	34.7	30.86
Test 5		4000	35	22.6	21.1	20.8	26.63	33.8	33.6	34.7	30.63
Test 6		4500	10	27.0	27.4	28.1	**28.78**	34.3	35.1	35.0	30.83
Test 7	0.55	3500	35	19.2	18.8	17.8	25.38	28.1	26.8	27.9	28.81
Test 8		4000	10	24.5	24.1	23.3	27.59	31.2	32.4	31.0	29.97
Test 9		4500	20	21.8	21.8	23.1	26.93	35.0	33.9	34.3	30.73

Table 8 S/N ratio response values

Factor/level	7-day results				28-day results			
	j = 1	*j* = 2	*j* = 3	M	*j* = 1	*j* = 2	*j* = 3	M
A/1	28.45	27.82	27.76	**28.01**	30.05	31.89	31.34	**31.09**
A/2	27.45	26.63	28.78	27.62	30.86	30.63	30.83	30.77
A/3	25.38	27.59	26.93	26.63	28.81	29.97	30.73	29.84
B/1	28.45	27.45	25.38	27.09	30.05	30.86	28.81	29.91
B/2	27.82	26.63	27.59	27.35	31.89	30.63	29.97	30.83
B/3	27.76	28.78	26.93	**27.83**	31.34	30.83	30.73	**30.96**
C/1	28.45	28.78	27.59	**28.27**	30.05	30.83	29.97	30.28
C/2	27.82	27.45	26.93	27.40	31.89	30.86	30.73	**31.16**
C/3	27.76	26.63	25.38	26.59	31.34	30.63	28.81	30.26

From

Table 8 it can be inferred that the optimum mix proportions of slag cement mortar leading to the highest 7-day compressive strength are as follows: (1) The w/cm ratio of 0.4; (2) the slag fineness of 450 m^2/kg; and (3) the replacement level of 10%. In addition, the optimum mix proportions to achieve the highest 28-day compressive strength using Iranian slag are: (1) The w/cm ratio of 0.4; (2) the slag fineness of 450 m^2/kg; and (3) the replacement level of 20%. Then, the verification experiments were carried out according to the aforementioned optimum conditions; the compressive strength of slag cement mortars were recorded, and the S/N ratio was calculated (Table 9).

As shown in Table 9, the values of the S/N ratio under the optimum conditions for the 7-day compressive strength (29.03) and the 28-day compressive strength (32.08) slightly exceed those of Test 6 (28.78) and Test 2 (31.89), respectively. Lowest w/cm ratio in the optimum mixture is the main reason for improvement in compressive strength.

Then, the contribution percentage was calculated for each factor. Initially, $\overline{Y}_k^F$ (the average value of the measurement results of a certain factor in the *k*th level) was obtained from Y_i in Table 7 and the values are listed in Table 10. By substituting $\overline{Y}_k^F$ and Y_T = 23.68 into Eq. (6), the factorial sum of squares, SS_F, for each factor was calculated individually and these are listed in Table 10. Using Eq. (4), the total sum of squares, SS_T, was determined. By substituting SS_F and SS_T = 189.194 in the Eq. (7), the variance of error, V_{Er}, was obtained. Finally, by the substitution of SS_F, SS_T = 189.194, V_{Er} = 1.156, and DOF_F = 2 in the Eq. (3), the contribution percentage of each factor, ρ_f, was determined sequentially; and these values are presented in Table 10.

According to their magnitudes, the rank order of the contribution percentage of each factor on the 7-day compressive strength is as follows: (1) the replacement level (45.90%), (2) the w/cm ratio (32.13%), and (3) the slag fineness (7.30%). Obviously, the GGBFS replacement level is the most influential factor on the early age compressive strength of slag cement mortar. However,

Table 5 S/N ratios of the optimum conditions and confirmation tests

	Test condition	A	B	C	Y1	Y2	Y3	S/N
7-day	Test 6	0.485	450	10	27.0	27.4	28.1	28.78
	Optimum condition	0.40	450	10	29.3	27.6	28.0	29.03
28-day	Test 2	0.40	400	20	38.0	39.7	40.3	31.89
	Optimum condition	0.40	450	20	40.2	39.5	40.8	32.08

Table 10 $\overline{Y}_k^A$, $\overline{Y}_k^B$, $\overline{Y}_k^C$,SS_F and ρ_f

Factor	7-day results					28-day results				
	$\overline{Y}_k^A$	$\overline{Y}_k^B$	$\overline{Y}_k^C$	SS_F	ρ_f	$\overline{Y}_k^A$	$\overline{Y}_k^B$	$\overline{Y}_k^C$	SS_F	ρ_f
A	25.22	22.92	25.97	63.1	32.1	36.02	31.45	32.72	111.4	38.7
B	24.23	23.38	23.54	16.1	7.3	34.58	34.96	36.22	83.3	28.8
C	21.60	24.74	21.53	89.2	45.9	31.17	35.36	32.84	71.1	24.5

after 28 days of curing, the influence of the three factors changes significantly, since w/cm ratio affects the compressive strength the most (38.7%), the slag fineness which was a minor factor at early age, has a contribution percentage of 28.8%, and finally replacement level has a moderate contribution of 24.5% on the development of 28-day compressive strength.

The contribution percentages of the three investigated parameters show that for the mixes with higher amounts of slag, the strength reduction is considerable at early ages, while the strength loss is decreased after 28 days of curing. Furthermore, it is proved that increasing slag fineness is not an efficient way to achieve higher early age strength in slag cement mortars, while it improves the 28-day compressive strength.

Based on the obtained results in this stage, 20% was considered as the appropriate GGBFS replacement level for concrete mixtures, while the highest fineness level seemed to be necessary to decrease the strength loss. Also, as a feasibility study of inclusion of higher percentage of GGBFS in high-strength concrete mixtures, 30% replacement level was studied.

3.2 Concrete test results

3.2.1 Compressive strength results

The compressive strength test was conducted on 100-mm cube specimens at different ages and the results are summarized in Fig. 1. It is observed that concrete compressive strength values are consistent with the trends observed in the first stage (GGBFS incorporated mortars). At the age of 7 days, GGBFS inclusion caused compressive strength reduction which was more significant at 30% replacement level. For instance, 30% decrease was occurred in G0-0.4 early age strength due to GGBFS addition by 30%.

After 28 days of curing, the strength decrease in 20% GGBFS incorporated mixtures (comparing to their companion plain mixtures) is less evident. However, the strength loss as a result of 30% local GGBFS inclusion is obvious at this age (8% and 14% strength loss at *w*/*c* of 0.4 and 0.35, respectively).

Another interesting finding is that the negative effect of local GGBFS on the compressive strength of high-strength mixtures was not disappeared even after 90 days of water curing (except for G20-0.35). This is in contrary to the findings of previous studies by various researchers, where the similar strength properties were measured for plain and slag concrete mixtures since 28 or 56 days age onwards (Binici H and Kose 2007, Gopalakrishnan and Bharatkumar 2001, Johari *et al*. 2011).

Considering the “compressive strength” as the only assessment criterion, the mentioned findings approve the low reactivity of the local GGBFS used in this study, which hardly satisfies the minimum requirements for Grade 80 slag (ASTM C989/C989M-12a 2012).

3.2.2 Durability tests results

Electrical resistivity test was conducted on all mixtures at the ages of 7, 28 and 90 days and the results are summarized in Table 11. At 7 days age, the lowest electrical resistivity values were obtained for the mixtures containing 30% GGBFS. This is in consistent with the previous results and approves the fact that minor hydration reactions of local GGBFS during the first 7 days of curing cannot compensate for the dilution effects resulting from clinker replacement.

The lowest electrical resistivity values were measured for G0-0.4 since 28 days age, while slag incorporated mixtures developed higher electrical resistivity values after 28 days of curing. For instance, GGBFS replacement of 20% and 30% at w/c = 0.4 resulted in considerable increases of

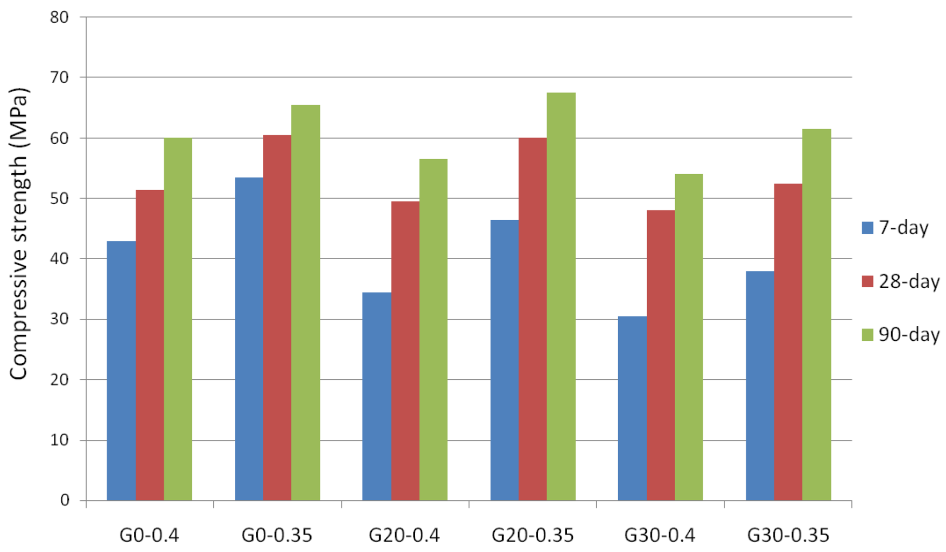

Fig. 1 Compressive strength of concrete mixtures at different ages

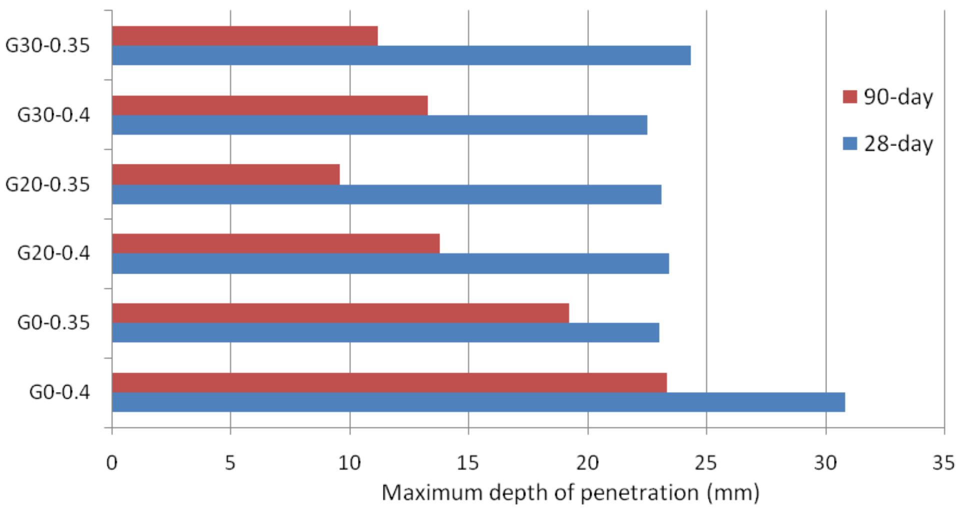

Fig. 2 Results of water penetration test at 28 and 90 days age

Table 6 Surface resistivity of concrete mixtures at different ages (kΩ.cm)

Mix ID	7-day	Permeability class	28-day	Permeability class	90-day	Permeability class
G0-0.4	7.7	High	12	Moderate	16.9	Moderate
G0-0.35	8.9	High	13.9	Moderate	22.1	Low
G20-0.4	8.2	High	12.5	Moderate	23.7	Low
G20-0.35	8	High	15.5	Moderate	29.2	Low
G30-0.4	7.1	High	13.7	Moderate	26.4	Low
G30-0.35	7.4	High	16.7	Moderate	28.1	Low

40% and 56% in resistivity values at the age of 90 days. It could be justified by a finer pore size distribution (Feng and Zang 1990) and decreased ionic concentration as a result of GGBFS consumption (Ahmadi and Shekarchi 2010, Feng and Hao 1998).

According to the chloride ion permeability classes defined by FM 5-578 (2004), G0-0.4 mixture permeability is rated as “moderate” after 90 days of curing, while the other mixtures achieved “low” permeability rating at the same age (see Table 11).

These findings imply the positive effect of low-reactivity slag on electrical resistivity of high-strength concrete, which is evident after 28 days of water curing and is more significant at 30% replacement level.

Water penetration test results for all concrete mixtures are presented in Fig. 2. The maximum depth of water penetration is reported as an indication of water penetrability of high-strength concrete mixtures. After 28 days of curing, 31 mm was measured as the penetration depth of G0-0.4 specimens. It was higher than penetration depths measured for other five mixtures, which were all about 23 mm. In fact, increasing GGBFS content from 20% to 30% of cementitious materials, did not lead to higher resistance to water penetration at this age.

Considering the 90-day results, which could be a better evaluation basis for durability performance of slag concrete, it is observed that GGBFS incorporated mixtures demonstrated higher resistance to water penetration, compared to control specimens. However, no significant difference was observed between mixtures with 20% and 30% GGBFS inclusion. Also, lowering w/c from 0.4 to 0.35 led to 2-4 mm decrease in penetration depth, which is far less significant in comparison to the improvement caused by GGBFS addition.

The mass of absorbed water after 3, 6, 24 and 72 hours and also sorptivity coefficients for high-strength concretes are listed in Table 12. It is observed that after 28 days of curing, the lowest sorptivity value was measured for G30-0.35 mixture, while the highest value was obtained by G0-0.4, as expected. It is observed that inclusion of higher GGBFS content (30%) reduced the sorptivity coefficients since 28 days age, indicating that the presence of GGBFS decrease the absorption by capillary rise. Considering the 90-day results, it is inferred that the positive effect of GGBFS on the capillary absorption of concrete is similar at both w/c ratios which were studied herein. In fact, an average 32% decrease was obtained for high-strength mixtures with either w/c ratio.

Similar to water penetration and electrical resistivity test results, it is observed that the positive effect (lower capillary absorption) imparted by GGBFS inclusion is greater than that of lowering w/c by 5%.

Table 7 Water mass uptake values and sorptivity coefficients (m/s$^{0.5}$) at 28 and 90 days

	28-day results					90-day results				
Mix ID	3h (g)	6h(g)	24h(g)	72h(g)	S (cm/s$^{0.5}$)	3h(g)	6h(g)	24h(g)	72h(g)	S (cm/s$^{0.5}$)
G0-0.4	22	29	45	52	10.2	17.5	26.5	40.5	46.5	9.1
G0-0.35	17	22	30.5	33	8.3	15.5	22.5	29	31.5	7.9
G20-0.4	21.5	28	42	42.5	7.7	15	23.5	36	40.5	7.5
G20-0.35	14.5	18.5	24.5	27	6.5	14.5	17	23	25	6.2
G30-0.4	20.5	27	37.5	39	5.3	13	20	32.5	38	4.9
G30-0.35	14	17.5	24	25	4.9	12	16.5	21	23.5	4.6

4. Conclusions

From the experimental investigations and analysis which were carried out in this study, the following conclusions are drawn, which are relevant for the materials used and range of parameters studied:

•The contribution percentage of the three considered parameters on the mortar 7-day compressive strength is as follows: (1) Replacement level (45.90%), (2) w/cm ratio (32.13%), and (3) Slag fineness (7.30%). However, at 28 days age, the influence of the three factors changes significantly, since w/cm affects the compressive strength the most (38.7%), the slag fineness which was a minor factor at early age, has a contribution percentage of 28.8%, and finally replacement level has a moderate contribution of 24.5% on the development of 28-day compressive strength.

•The results obtained by Taguchi test conditions proved that increasing slag fineness is not an efficient way to achieve higher early age strength in mortars containing local GGBFS, while it improves the 28-day compressive strength.

•The negative effect of local GGBFS on the compressive strength of high-strength mixtures was not disappeared even after 90 days of water curing (except for G20-0.35).

•The results of durability tests indicated that increasing the GGBFS content from 20% to 30% of Portland cement (by weight) has positive effect on electrical resistivity and sorptivity of high-strength concrete, while it has minor effect on water penetrability.

•The results of durability tests indicated that the positive effect (higher surface resistivity and lower capillary absorption and penetrability) imparted by 20% GGBFS inclusion is greater than that of lowering *w/c* by 5%.

•This study indicated that use of low-reactivity GGBFS as a cement replacement material (at moderate levels such as 20% and 30%) can enhance the durability of high-strength concrete, while it reduces the compressive strength (especially at early ages).

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