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# Durability of self compacted concrete containing slag in hot climate

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**Abstract.** This paper aims to investigate the effects of replacing cement with ground granulated blast furnace slag (GGBFS) in self compacting concrete in the fresh and hardened state. The performance of SCC in moderate climate is well investigated but few studies are available on the effect of hot environment. In this paper, the effect of initial water-curing period and curing conditions on the performance of SCC is reported. Cement was substituted by GGBFS by weight at two different levels of substitution (15% and 25%). Concrete specimens were stored either in a standard environment (T=20°C, RH=100%) or in the open air in North Africa during the summer period (T=35 to 40°C; R.H=50 to 60%) after an initial humid curing period of 0, 3, 7 or 28 days. Compressive strength at 28 and 90 days, capillary absorption, sorptivity, water permeability, porosity and chloride ion penetration were investigated. The results show that the viscosity and yield stress are decreased with increasing dosage of GGBFS. The importance of humid curing in hot climates in particular when GGBFS is used is also proved. The substitution of cement by GGBFS improves SCC durability at long term. The best performances were observed in concrete specimens with 25% GGBFS and for 28 days water curing.

**Keywords:** self-compacting concrete, slag, rheology, hot climate, compressive strength, durability

## 1. Introduction

Concrete is the most widely used material in construction industry and the knowledge of its behavior in the fresh and hardened state is of great interest. Recent developments in concrete technology led to the development of self-compacting concrete (SCC) that could be made without vibration.

SCC is characterized by its high paste content and hence various cementitious materials such as slag, natural pouzzolana, limestone and metakaolin are added to the mix. The performance of SCC in moderate climate is well investigated (Boukendakdji *et al.* 2009, Belaidi *et al.* 2012, Benabed *et al.* 2012, Boukendakdji *et al.* 2012). Several studies have been conducted on the performance of

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vibrated concrete in hot climate (Kenai and Amrane 1996, Kenai and Lachemat 1995). However, few studies are available on the effect of hot and dry environment. Hot weather conditions create several problems for both fresh and hardened concrete. Reduced durability is one of the major problems in concrete prepared under hot weather conditions.

Under hot weather conditions, concrete has to be cured for an extended period of time compared to normal weather conditions in order to achieve acceptable strength and durability (Ibrahim *et al.* 2013). The characteristics of hardened vibrated and self-compacting concrete made of slag depend on the nature and proportions of the constituents but also on the storage conditions that affect the hydration reactions. A comprehensive review on the effects of ground granulated blast furnace slag (GGBFS) on fresh and hardened properties of concrete demonstrated that slag improves workability and strength at long term if the replacement ratio is limited to 40% to 50% (Rakesh-Kumar and Bibhuti-Bhushen 2016). The use of slag also improves the durability of concrete under chloride and sulphate attack (Deepankar *et al*. 2016). Curing and environmental conditions also affect the hydration reactions and hence the performance of concrete. The ambient temperature is one of the most important environmental factors. Temperature could reach up to 40℃ in summer coupled with relatively low humidity (30% to 60%) and hence high and rapid loss of water by evaporation. The loss of water is particularly significant at concrete surfaces and hence causes shrinkage, creates severe thermal stresses in concrete and increases risk of cracking.

The increase in water curing duration increases the compressive strength whereas air curing decreases the compressive strength (Ferhat and Tohumcu 2013). Concretes that received no curing showed the poorest performance in terms of strength development, porosity, and resistance to chloride-ion penetration (Zhao *et al.* 2012). Moist cured concrete for only two days showed significant improvement in strength, and other characteristics, as compared to concretes without any curing (Ramezanianpour 1995). Other studies (Ozer and Ozkul 2004, Kefeng and Gjorv 1996) illustrated that, initial water-curing period has some effect on the compressive strength development of ordinary Portland and pozzolanic cement concretes and recommended to apply water-curing for at least seven days for the development of the pozzolanic activity. The elevated temperatures also cause the hydration products to precipitate more rapidly, leading to a denser hydration product shell that forms around the unhydrated clinker particles. It also results in a microstructure with a more heterogeneous distribution at early age. In recent years, using mineral admixtures and a subsequent curing treatment are used to overcome these problems (Shuai *et al*. 2016). Self-curing compounds are also used to enhance the performance of self-compacting mortar mixes (Sri-Rama *et al.* 2016). High temperature modified the structure of C-S-H gel in cement pastes and mortar (Aparicio *et al.* 2016a) and compressive strength increases rapidly at early ages but reaches lower values at long term compared to curing at 20℃ (Aparicio *et al.* 2016b). The effect of heat curing on electric arc furnace oxidizing slag (EOS) concrete was investigated and the results showed that to limit the rate of expansion, EOS should be in the range of 20% to 30% (Chun-Ya 2016).

In this study, a local medium hydraulicity GGBFS was used as a substitution to Portland cement and its effect on the rheological, mechanical and transport proprieties of SCC are evaluated. The effect of initial water-curing period on the compressive strength, capillary absorption, water permeability, porosity and chloride ion penetration is also investigated.

## 2. Materials

Table 1 Chemical compositions of ground granulated blast furnace slag

| Element | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | MnO | $K_2O$ | $SO_3$ | $TiO_2$ |
|---|---|---|---|---|---|---|---|---|---|
| % | 40.10 | 6.00 | 2.00 | 42.20 | 4.70 | 2.60 | 1.20 | 0.15 | 1.20 |

Table 2 Mix proportions details of SCC used

| Mix composition (kg/m$^3$) | Cement | Slag | CA 3/8 | CA 8/15 | Sand | Water | SP |
|---|---|---|---|---|---|---|---|
| SCC 0% Slag | 491.1 | 0 | 247 | 495 | 920 | 198 | 7.85 |
| SCC 15% Slag | 417.5 | 73.6 | 247 | 495 | 920 | 198 | 7.85 |
| SCC 25% Slag | 368.4 | 122.7 | 247 | 495 | 920 | 198 | 7.85 |

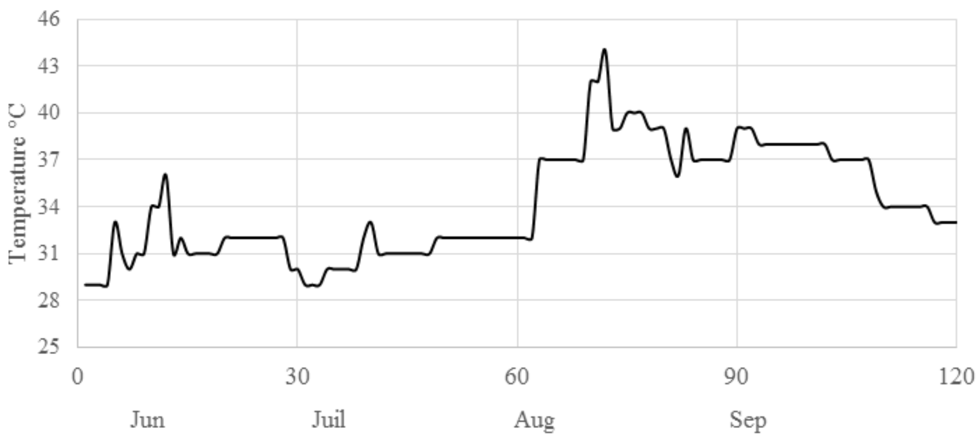


Fig. 1 Variation in maximum temperatures in the region during the test period

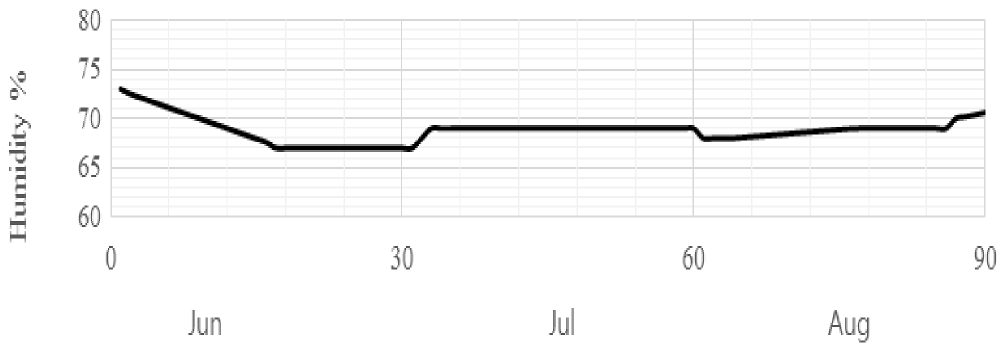


Fig. 2 Variation in humidity in the region during the test period

The cement used is a blended cement type CEM IIA 42.5 with a specific surface of Blaine of 304 m²/kg. GGBFS from a local steel factory was ground in the laboratory at a fineness of 350 m²/g and was used as a substitution by weight of cement. This slag is known of its low to medium activity (Hadj-Sadok *et al.* 2012, 2011). The chemical compositions of GGBFS is summarized in Table 1. The sand used was a mixture of two sands: a river sand and a dune sand. Two types of gravel were used (3/8 and 8/15) and a polycarboxylate superplasticizer named MEDAFLOW 30 was used to reduce the water/cement ratio.

Fig. 3 Water permeability test

## 3. Methods

The water/binder ratio was kept constant at 0.40 in this study. The dosage of superplasticizer was optimized on mortar to obtain a homogeneous and stable self-compacting mortar (without bleeding) and was kept constant in all mixes (1.6% of cement by weight). Concrete mix design was based on the Okamura general method (Okamura and Ouchi 1999, Okamura and Ouchi 2003). Three formulations were studied, namely a SCC mix without addition chosen as the reference concrete and two other SCC mixes with 15% and 25% slag as cement replacement by weight. Details of the mix proportions of SCC are given in Table 2. After an initial moist curing of 0, 3, 7 or 28 days, the specimens were cured in two different environments:

• Water at (20±2)℃

• In the open air, on the laboratory roof in summer, (T=30℃ to 45℃ and R.H=65% to 70%) (Figs. 1 and 2).

The slump flow test of fresh SCC was conducted according to EFNARC (EFNARC 2012). The initial slump flow value of fresh SCC is represented by the mean diameter (measured in two perpendicular directions) of concrete after lifting the standard slump cone. The L-box test was performed in accordance with EFNARC standards. During the test, fresh SCC was allowed to flow upon the release of a trap door from the vertical section to the horizontal section by a few reinforcement bars of L-shape box. The height of concrete at the end of the horizontal section was compared to the height of concrete remaining in the vertical section (EFNARC 2012).

The stability test method was used to assess the segregation resistance of fresh SCC. The method consisted of taking (4.8±0.2) liters of SCC and allowing the concrete to stand for 15 min in bucket covered with a lid to prevent evaporation, then, SCC mixture was poured on to 5 mm sieve, which sat on a sieve pan on a weighing scale. After 2 min, the mass of mortar passed through the sieve was measured and expressed as a percentage of the weight of the original sample on the sieve (EFNAC 2012).

The rheological parameters were investigated using a rheometer composed of an agitator with a steel vane (15 cm in height and 10 cm in diameter), a cylindrical container (30 cm in height and 30 cm in diameter) and a computer. After filling of the container with concrete, the vane is immersed in concrete and centered in the middle so that the upper part of the vane is in the erase of the concrete. The agitator is driven by a computer. The measurements are performed with an imposed speed profile. Finally, the plastic viscosity ($\mu$) and yield stress ($\tau 0$) are determined from the experimental measurements (Adjoudj *et al.* 2014, Soualhi *et al.* 2014).

The concrete compressive strength was measured on cubic specimens 100×100×100 $mm^3$ for each concrete mix at the age of 28 and 90 days. The compressive strength tests were performed on a 3000 kN compressive machine at a loading speed of 0.5 kN/s according to NF P 18-406 standards (NF P 18-455 2003).

The capillary absorption tests are performed on molded cubic specimens (100×100×100 mm) according to ASTM C1585-04 procedure at the age of 90 days (ASTM 1585-11 2012). The specimens were stored in a ventilated oven at a temperature of (50±2)°C and RH of (8±3)% for 3 days until constant weight. The side faces of the specimens were coated by a resin to ensure unidirectional flow and prevent the evaporation of the absorbed water. The specimens were immerged in the water container at a maximum height of 5 mm. Before each weight measurement, the specimens were removed from the container, wiped and then weighed. Measurements were taken at: 1 min, 5 min, 10 min, 20 min, 30 min, 1 h, 2 h, 3 h, 4 h, 5 h, 6 h.

The water penetration test was carried out according to German Standard DIN 1048 (DIN 1048 2000) on concrete specimens of 150×150×150 mm, at the age of 90 days. The test cell assembly being used had the provision for testing three cubes at a time. Once the specimens were assembled in the test cells, a water pressure of 5 bars was applied for 72 hours. Water pressure is applied by means of an arrangement consisting of a water tank connected to an air compressor through a valve, to adjust the pressure. Basic procedure of such a test is to apply water under pressure to one surface of the specimen for a specific time and then split the specimen perpendicular to the injected face and the water penetration depth measured (Fig. 3).

Accessible porosity test was determined by weighing a specimen of concrete after immersion in water after saturation under vacuum (CPC11.3 1984). The specimen were dried in an oven at a temperature of (105±5)°C until the difference between two successive weightings, did not exceed 0.1%. The sample was placed in a closed chamber (dryer), under a constant pressure for 4 hours. Then the water was introduced gradually until filling and the specimen was covered by about 20 mm of water. The specimen was maintained in saturation during (18±2) h. Specimens were then weighed in water and in air with a hydrostatic balance. Accessible porosity to water, $\varepsilon$, is expressed as percentage by volume according to Eq. (1).

$$\varepsilon = \frac{M_{air} - M_{dry}}{M_{air} - M_{water}} \times 100 \tag{1}$$

$M_{water}$: weight in water of saturated sample
$M_{air}$: weight in air of saturated sample
$M_{dry}$: weight of oven-dried sample.

## 4. Results and discussion

### *4.1 Properties of fresh SCC*

The properties of fresh SCC are presented in Table 3. For all SCC mixes, the slump flow was

Table 3 Results of fresh properties of SCC

| Tests | SCC 0% Slag | SCC 15% Slag | SCC 25% Slag |
|---|---|---|---|
| Slump flow diameter (mm) | 635 | 720 | 780 |
| Blocking ratio ($h_2/h_1$)(%) | 86 | 90 | 96 |
| Segregation ratio (%) | 5.50 | 7.90 | 10.95 |

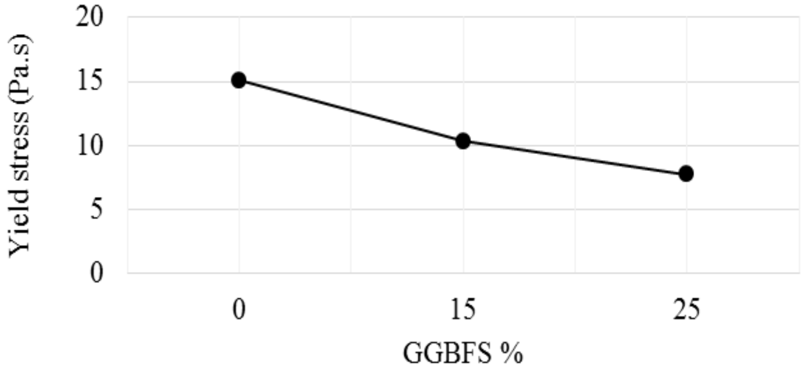


Fig. 4 Effect of slag content on yield stress

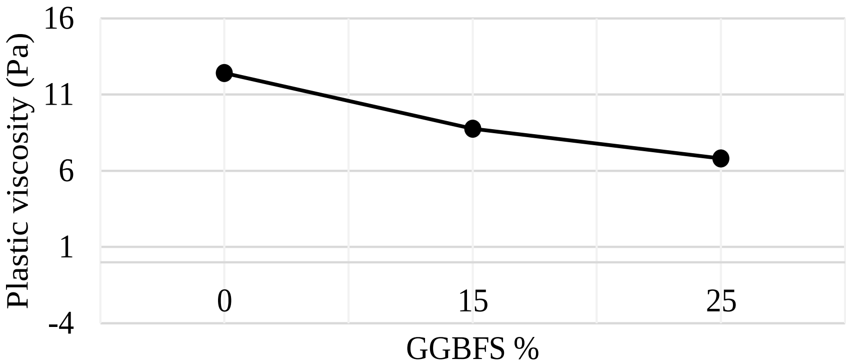


Fig. 5 Effect of slag content on plastic viscosity

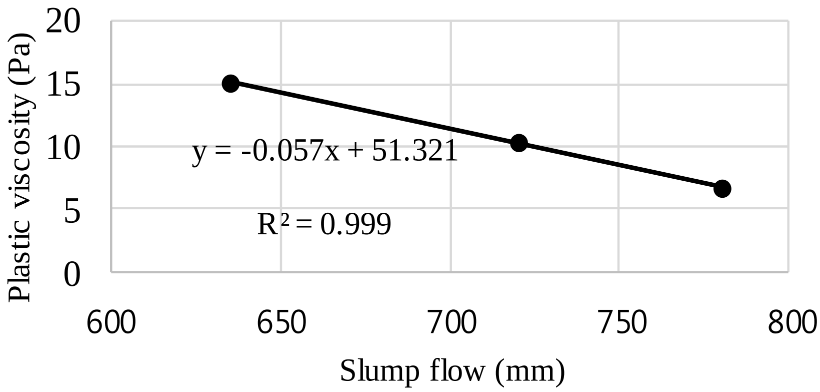


Fig. 6 Correlation between plastic viscosity and slump flow

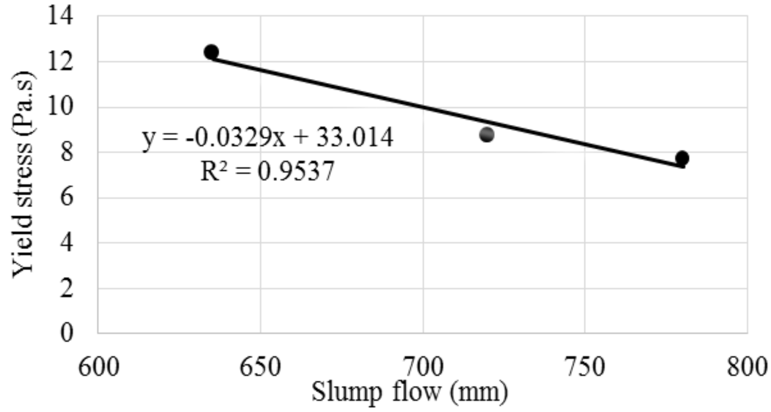


Fig. 7 Correlation between yield stress and slump flow

between 635 and 780 mm, which is an indication of good deformability. The effect of GGBFS on the flow is remarkable. The slump flow of SCC-R is less than that of SCC containing slag. However all SCC mixes showed slump flow diameter values in the range of 550-850 mm and hence are in conformity with SCC requirements. The increase in slag substitution level increases the slump flow and the optimum slag dosage seems to be 15%.

The L-box ratio characterizes the filling and passing ability of SCC and no blocking risk was observed for all mixes as the L-box blocking ratio was above 0.8. Table 3 shows that the segregation ratio of SCC mixtures are considered satisfactory. All the studied SCC mixes are stable (laitance<15%). Boukendakdji *et al.* (2012) showed that for concrete mixes with 10% and 15% slag content, and for two types of superplasticizers, the segregation resistance is satisfied, but for higher substitutions levels than 15%, bleeding and segregation were observed. The incorporation of slag in mortar has been found by other researchers to improve its workability and its properties in the fresh state (Li and Ding 2003, Her-Yung and Chih-Chung 2013). The use of other mineral additions such as silica fume, fly ash and slag has also been found to improve the workability properties of SCC and increases the L-Box (H2/H1) ratio, indicating improved filling and passing capacity of SCC (Mucteba and Mansur 2011, Gesoglu *et al.* 2009).

### *4.2 Effect of GGBFS on rheological parameters*

Figs. 4 and 5 show the effect of the slag on the rheology of SCC. The incorporation of slag improves the workability of SCC and leads to a decrease in the yield stress. The yield stress decreases from 15.09 Pa.s to 10.37 Pa.s and 7.74 Pa.s for 15% and 25% of slag, respectively. Fig. 5 shows that the viscosity decreases with the increase of slag content. It decreases from 12.4 for mixes without slag to 8.75 and 6.81 for mixes with 15% and 25% of slag, respectively. (Adjoudj *et al*. 2014) showed that the yield stress value of cement mortar increases with the increase of the substitution rate of blast furnace slag and natural pozzolan whereas the viscosity is reduced. (Boukendakdji *et al.* 2012) also found that the higher the slag contents the lower the yield stress and the lower the plastic viscosity when two types of superplasticizers were investigated.

The correlation between viscosity and slump flow is illustrated in Fig. 6 with a high correlation coefficient of 0.999. A decrease in viscosity is observed with increasing slump flow. Fig. 7 shows the relationship between the yield stress and the slump flow of SCC with a correlation coefficient

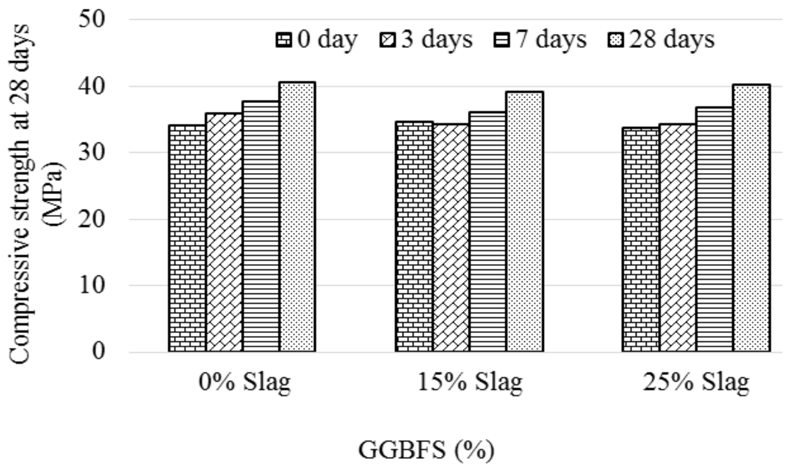


Fig. 8 Effect of slag content and duration of water curing on the 28 days compressive strength of concrete

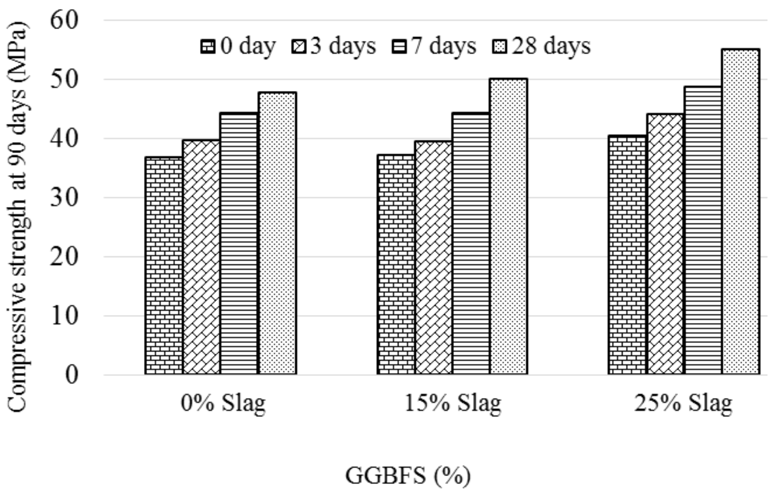


Fig. 9 Effect of slag content and duration of water curing on the 90 days compressive strength of concrete

$R^2$ of 0.953. The correlation confirms the presence of an inverse type of relationship between them; the lower yield stress of SCC containing slag, the higher the slump flow, i.e., the yield stress decreases linearly with an increasing slump flow of SCC. Other researchers have also established a good correlation between the slump flow and the yield stress (Aïssoun *et al.* 2016).

### *4.3 Compressive strength*

Figs. 8 and 9 show the variation of the compressive strength of SCC with slag and duration of moist curing (T=20°C, RH=100%). Compressive strength was measured at 28 and 90 days after a period of humid curing for 0, 3, 7 and 28 days and then storage on the roof of the laboratory during summer period. It can be clearly seen that the compressive strength is greatly affected by the curing period and the slag content. Air curing resulted in compressive strength reductions for all mixes. The compressive strength values obtained at 28 days of 0% are 84%, 89% and 93% of 0, 3

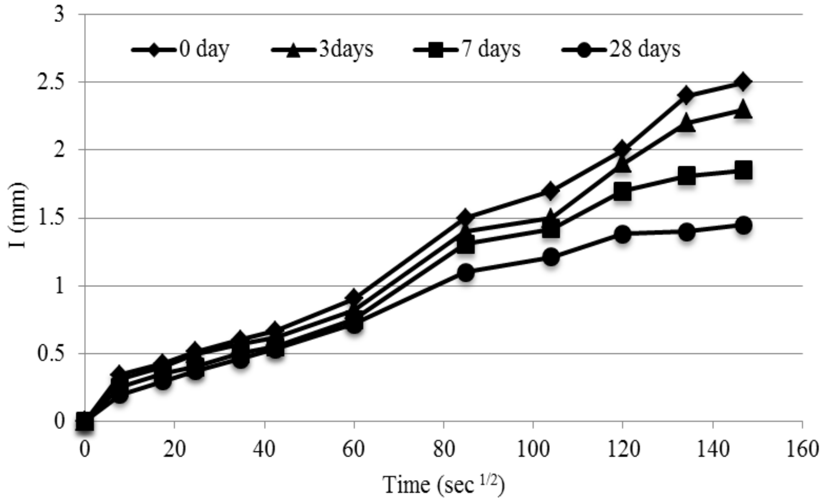


Fig. 10 Capillary absorption for 0% slag

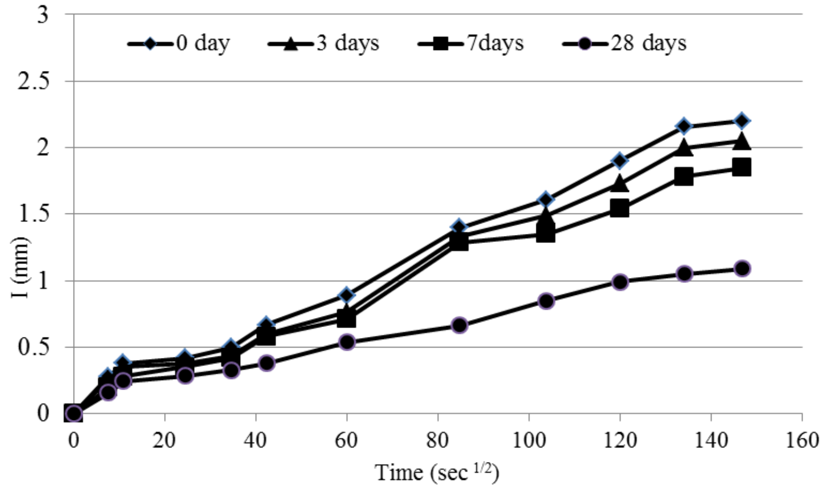


Fig. 11 Capillary absorption for 15% of slag

and 7 days of humid curing, respectively compared with standard cured (28 days water curing) specimens. These values for 15% slag are 89%, 88% and 92% for 0, 3 and 7 days of humid curing, respectively. The compressive strength values obtained at 28 days for 25% slag are 84%, 85% and 92% for 0, 3 and 7 days of humid curing, respectively. Similar results were obtained at 90 days of age.

As expected, the longer the duration of water curing the higher the compressive strength at 28 days of age. Specimens without any water curing presented a loss of compressive strength of only 16%, 11% and 16% of the value obtained at the same age after 28 days of water curing for 0%, 15% and 25% of slag. Curing in water seems to be more effective for short term periods of curing (3 and 7 days). As compared to specimens without water curing, seven days water curing gave an increase in compressive strength of 3.52 MPa, 1.47 MPa and 3.01 MPa of 0%, 15% and 25% slag, while 28 days curing gave a gain in compressive strength of 6.44 MPa, 4.42 MPa and 6.38 MPa

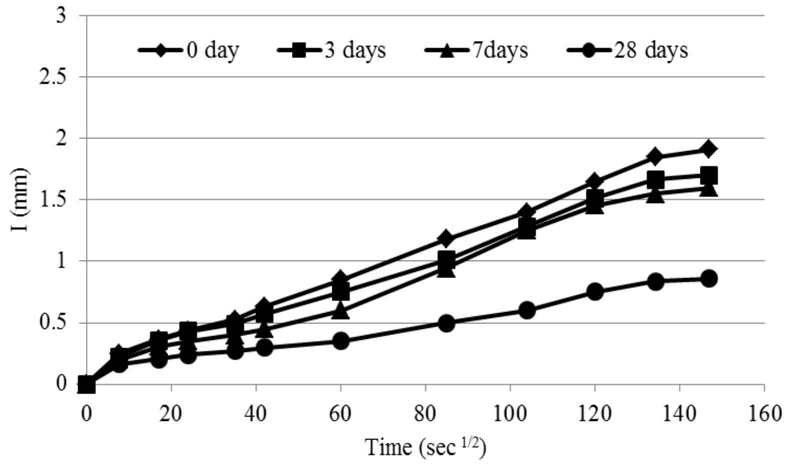


Fig. 12 Capillary absorption for 25% of slag

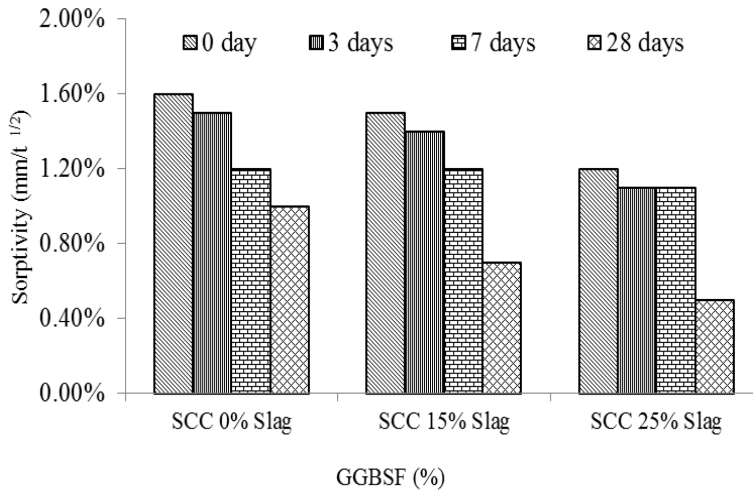


Fig. 13 Effect of slag content and duration of water curing on the 90 days sorptivity of SCC

for 0%, 15% and 25% slag, respectively. Hence an optimal period of humid curing of 3 to 7 days could be recommended. It should be noted that in practice duration of curing higher than 7 days is unlikely.

The increase in the substitution level of slag from 15% to 25% resulted in a compressive strength at 28 days comparable to that of cement without slag, irrespective of the period of curing. For example, for 28 days of curing, the compressive strength values are 40.57 MPa, 39.15 MPa and 40.21 MPa for slag contents of 0%, 15% and 25% respectively. However, at 90 days of age, specimens containing GGBFS have slightly higher compressive strength in comparison with specimens without slag at all humid curing durations. The values of compressive strength at 90 days ranged from 37 MPa to 44 MPa, 37 MPa to 50 MPa and 40 MPa to 55 MPa for slag contents of 0%, 15% and 25%, respectively. A slight increase of 1.5% to 13% and 9.4% to 21% in the compressive strength at 90 days is observed when slag cement is increased from 15% to 25% respectively. The increase in long-term compressive strength with the duration of curing is more

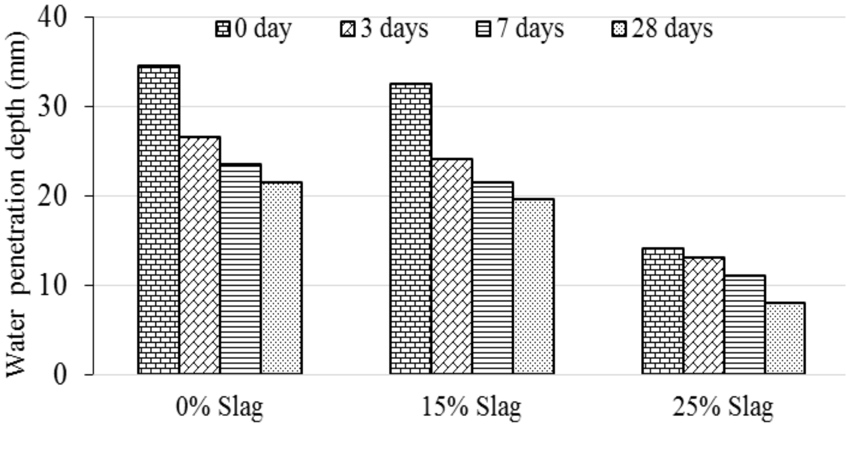


Fig. 14 Effect of slag content and curing period on the water penetration depth

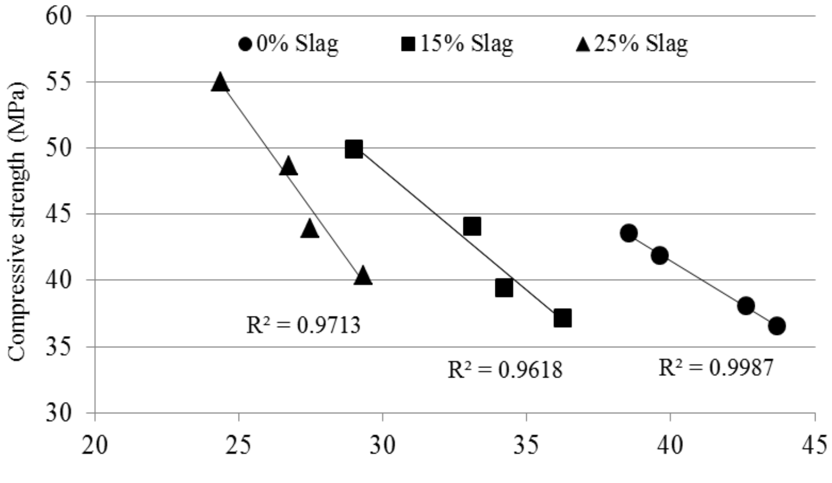


Fig. 15 Correlation between compressive strength and water penetration depth

pronounced with higher levels of substitution by slag as the hydration of slag takes place slowly but steadily. These results are consistent with those obtained by other researchers who worked on SCC with mineral additions (Heba 2011, Ibrahim *et al.* 2013).

(Zhao *et al.* 2012) showed that that the initial water-curing period has a significant effect on compressive strength of SCC. The initial water-curing period of 7 days gave the maximum 28-days compressive strength. The compressive strength of self-compacting high-slag concrete (SCHSC) containing 15% furnace slag is apparently higher than that of the control group by about 13% (Chih-Chung 2013). The initial steam curing could significantly increase the compressive strength. Higher temperature causes higher initial compressive strength, which is due to promoted hydration, C-S-H gel, and CH crystalline formation. However, ultimate compressive strengths at the age of 90 days were comparatively the same (Ramezanianpour *et al.* 2014). (López-Gayarre *et* *al.* 2014) showed that the compressive strength of concrete samples was higher when they were cured under standard conditions with controlled temperature and humidity. (Ferhat and Tohumcu 2013) reported that the highest compressive strength values were obtained from standard cured specimens (cured in water for 28 days). The increase in water curing duration resulted in increases in compressive strength. The lowest compressive strength values were obtained from air-cured specimens. Lime-saturated cured samples gave higher compressive strength than dry cured samples of concrete (Turkmen and Kantarci 2007).

### 4.4 Capillary absorption

Figs. 10 to 12 show that the capillary absorption decreases with the duration of water curing. It can be seen that the capillary absorption at 28 days of water curing has the lowest absorption coefficient. The longer the duration of curing in water, the lower is the absorption coefficient. The absorption coefficients obtained after 28 days of water curing are 80%, 61% and 41% of those obtained when no water curing was applied for respectively 0%, 15% and 25 % of slag. Water curing was most effective at 3 and 7 days showing the importance of a minimum period of curing. A period of 7 days of curing reduces the water absorption coefficient by 15%, 18% and 35% for 0%, 15% and 25% slag mixes, respectively. However, the incorporation of slag generated a slight decrease in water capillary absorption for both SCC mixes with 15% and 25% slag. Capillary absorption is related to the development of hydration and the filling of pores with hydration products which is developed by 90 days of age.

The results of sorptivity tests are summarized in Fig. 13. It can be seen that SCC containing slag had a lower sorptivity than the reference concrete. Sorptivity varied between 1.32 to 1.10, 1.30 to 0.8 and 1.20 to 0.50 for 0%, 15% and 25% of slag, respectively. However, the sorptivity increased significantly for specimens cured in the hot environment of the laboratory roof. Other researchers have also reported a decrease in the sorptivity values in self-cured self-compacting mortars as compared to no cured self-compacting mortars (Sri-Rama *et al.* 2016).

The incorporation of slag has been reported to have reduced remarkably the capillary water absorption in concrete mixtures, particularly, concrete with 40% of slag as compared to the highest capillary water absorption of 3.32 $kg/m^2$ observed for control concrete mixture (Deboucha *et al.* 2015).

### 4.5 Water permeability

The water penetration depth of SCC mixes decreases with increasing period of water curing (Fig. 14). Specimens kept on the roof in hot dry environment showed an increase of 13.3%, 8.7% and 20.4% in water permeability compared to 28 days water cured specimens of 0%, 15% and 25% of slag respectively. Seven days of water curing resulted in a decrease in water penetration depth of 10.5% compared to uncured specimens of 0% slag. As compared to no water curing, the increase of water curing duration to 3, 7 and 28 days decreases the water penetration depth by 8.7%, 9.5% and 2.5% for 15% slag and 20.4%, 12.7% and 9.7% for 25% slag, respectively.

The low penetration depth for 28 days cured specimens is due to the filling of pores by the hydration products due to the continuous hydration of cement in water. The conservation of specimens in a hot climate produced a higher percentage of large and less uniform pores. All mixes containing slag presented a lower water penetration depth as compared to mixes without slag. The decrease in water depth penetration for 28 days cured specimens compared to the reference mix without slag was of the order of 14.41% and 23.37% for SCC mixes with 15% and 25% of slag,

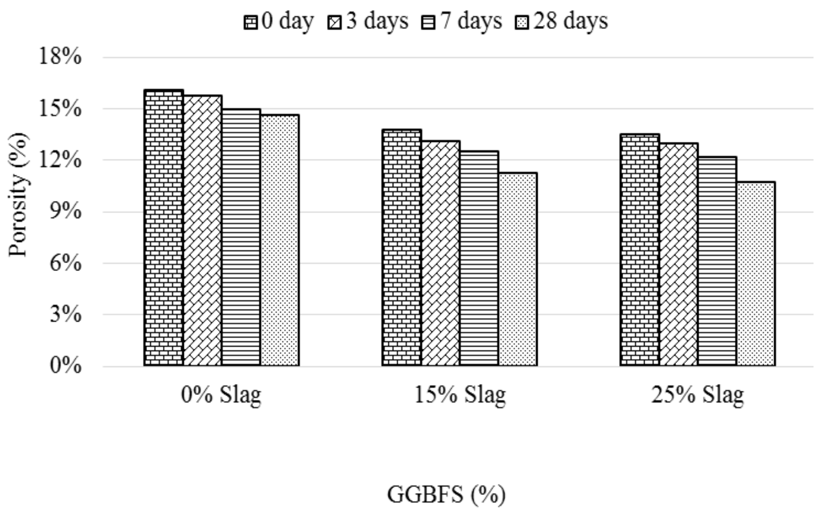


Fig. 16 Effect of slag content and curing period on porosity

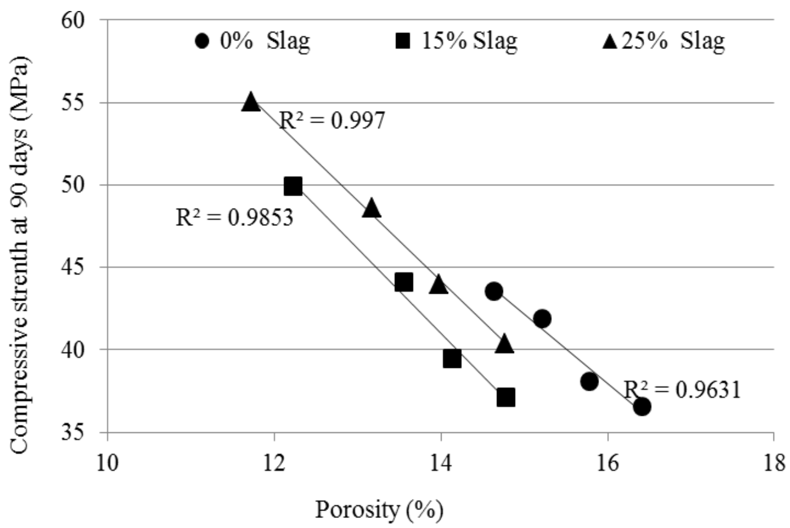


Fig. 17 Correlation between compressive strength and porosity

respectively. This can be explained by the positive effect of slag at long-term as the test was conducted at 90 days of age and hence resulted in a decrease of the pore size structure as well as a decrease of the permeability of SCC slag mixes. These results indicate a high compacity of the paste matrix and a poorly interconnected pore system (Silva and De-Brito 2015).

An increase in the depth of water penetration of 37%, 49%, and 84%, respectively was observed as the water-curing of slabs was reduced from 28 to 7, 3, and 1 days (Al-Khaiat and Haque 1998). The permeability increases by 13% to 62% when the temperature was raised from 20℃ to 50℃ and by 3% to 55% by an additional increase to 80℃ (Jooss and Reinhardt 2002). The water permeability results are in agreement with the water capillary absorption results as water permeability and capillarity being more related to the size and type of pores than to total porosity.

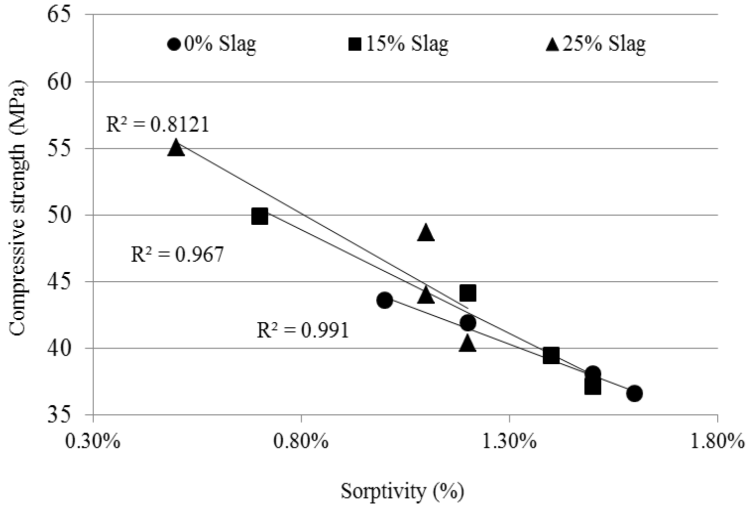


Fig. 18 Correlation between compressive strength and sorptivity

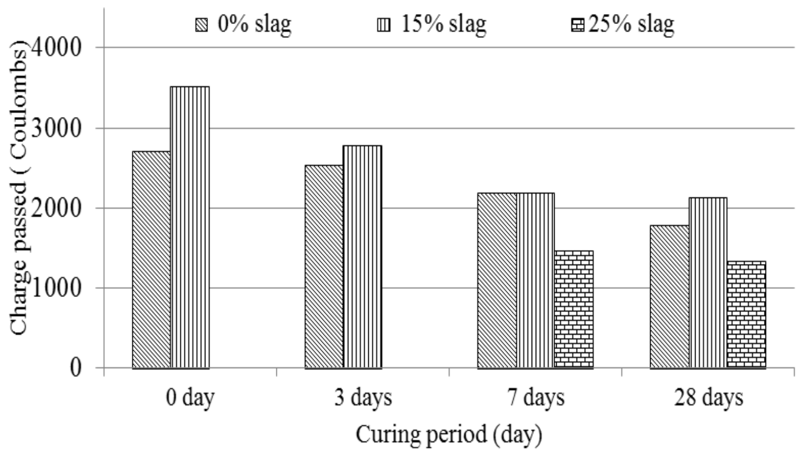


Fig. 19 Chloride penetration according to the curing time and the slag content *Tests unsuccessful for 25% slag at 0 and 3 days of curing

In order to establish a relationship between compressive strength and depth penetration for SCC under different initial water-curing periods, a linear regression (Eq. (2)) was applied (Fig. 15)

$$Y = a\,X + b \tag{2}$$

A good correlation is observed, the correlation coefficients are (0.998, 0.961 and 0.971 for 0%, 15% and 25% of slag, respectively).

### *4.6 Porosity*

Fig. 16 presents the results of the porosity according to the curing duration and slag content. Concrete mixes which received no humid curing after demoulding showed the worst performance in terms of porosity. It can also be observed that the initial water curing period has a significant effect on porosity of SCC. As the curing period increased, there was a reduction in the porosity in all concrete specimen. Porosity decreases from 16.1% to 14.6% and 13.8% to 11.2% and from 13.5% to 10.7% when the curing period increases from 0 to 28 days for a slag content of 0%, 15% and 25% respectively. The lowest porosities were noted in concrete specimen cured for 28 days. Water curing modifies the porous network, reduces the average pore diameter of concrete and results in denser microstructure especially at long term as hydration progresses in the presence of mineral additions (Ramezanianpour 1995).

(Oliveira *et al*. 2015) showed that the average pore diameter is lower in specimens subjected to additional curing period of 7 days. (Al-Otaibi 2008) reported an increase in porosity in the early age up to 28 days but when the comparison was done on equal slump, slag concrete eventually had lower porosity after 28 days.

Fig. 17 illustrates the relationship between the compressive strength at 90 days and the porosity of slag-based SCC. This correlation confirms that the compressive strength is related to the porosity accessible to water (the slope of the trend lines is identical and their correlation coefficient are high). Fig. 18 presents a good correlation between the compressive strength at 90 days and the sorptivity of slag-based SCC.

### *3.7 Chloride ion penetration*

Fig. 19 presents the results of the chloride-penetration according to the humid curing period and the slag content. The SCC mixtures were assessed as moderate chloride permeability concretes as per ASTM C 1202-94 assessment criteria, with less than 3000 coulombs of total charge passing. The mixtures with 25% slag and 7 days and 28 days of water curing presented less than 2000 coulombs of charge and could be considered as low ion chloride penetrability.

The results indicates that the initial curing affects remarkably the chloride penetration as moist cured samples have significantly lowered the chloride penetration values as compared to air-cured samples. At 28 days of water curing, the chloride penetration decreases by 34%, 29.5% and 18.5% compared to 0, 3 and 7 days of curing, respectively. However, the addition of slag has slightly increased the chloride ion penetration. For example, for 15% of slag an increase of 39%, 23% and 3% is observed as compared to mixes without slag for initial curing periods of 0, 3 and 7 days, respectively. Lower chloride ion diffusion of SCC with initial water curing periods of 3, 7 and 14 days are also reported elsewhere with the least diffusion observed at 7 days of water curing (Zhao *et al.* 2012).

## 5. Conclusions

Based on the results of this experimental investigation, the following conclusions can be drawn:

• The incorporation of the slag as a mineral addition leads to the reduction of the viscosity and the yield stress compared with the reference concrete.

• The substitution of cement by slag leads to comparable compressive strength at 28 days of age and higher strength at 90 days of age with 28 days of water curing.

• Capillary water absorption of specimens without water curing has the highest absorption coefficient while the lowest coefficient is observed for concrete specimens cured for 28 days.

• The water penetration decreased with increasing slag content and an increase in the duration of water curing.

• Increasing slag content decreases the chloride ion penetration and specimens stored in open air presented the highest chloride ion penetration.

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