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Combined effect of mineral admixture and curing temperature on mechanical behavior and porosity of SCC

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Abstract. In order to provide sufficient stability and resistance against bleeding and segregation during transportation and placing, mineral admixtures are often used in self-compacting concrete mixes (SCC). These fine materials also contribute to reducing the construction cost and the consumption of natural resources. Many studies have confirmed the benefits of these mineral admixtures on properties of SCC in standard curing conditions. However, there are few published reports regarding their effects at elevated curing temperatures. The main objective of this study is to investigate the effect of three different mineral admixtures namely limestone powder (LP), granulated blast furnace slag (GS) and natural pozzolana (PZ) on mechanical properties and porosity of SCC when exposed to different curing temperatures (20, 40, 60 and 80℃). The level of substitution of cement by mineral admixture was fixed at 15%. The results showed that increasing curing temperature causes an improvement in performance at an early age without penalizing its long-term properties. However the temperature of 40℃ is considered the optimal curing temperature to make economical and high performance SCC. On the other hand, GS is the most suitable mineral admixture for SCC under elevated curing temperature.

Keywords: SCC; mineral admixture; curing temperature; mechanical strength; modulus of elasticity; porosity

1. Introduction

Self-compacting concrete offers some economical, technical and environmental advantages and hence it is widely used in many countries for different applications and structural configurations (Okamura and Ouchi 2003). This type of concrete can flow through and fill the gaps of reinforcement and corners of molds under its own weight without any need for vibration and compaction during the placing process with no segregation or excessive bleeding. These characteristics make it suitable for precast applications and heavily reinforced sections. Therefore, the self-compaction characteristics of SCC result in a more reliable quality in concrete placement

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and a more homogeneous material structure; minimize the concrete void spaces and have uniform surface texture, improved durability, high strength, and faster construction (Persson 2001).

SCC are characterized by high paste content and for economic and environmental reasons, mineral admixtures are often used in this concrete. Limestone powder (LP), granulated blast furnace slag (GS), fly ash (FA) and naturel pozzolana (PZ) are the most frequently used mineral admixture in SCC. Several studies have confirmed that the incorporation of these fine materials which are generally waste or industrial by-product (reactive or inert) can not only reduces total material cost, but also result in considerable benefits to the environment. In addition, they can enhance the workability and rheological properties of SCC, reduce heat of hydration, contribute to the strength development of concrete and make it more durable (Chore and Joshi 2015, Kangkang *et al.* 2015, Deepankar *et al.* 2016, Rakesh and Bibhuti 2016, Lenka and Panda 2017, Yahiaoui *et al.* 2017).

Boukendakdji *et al.* (2012) reported that, replacing 15% of cement content by GS in SCC increases the workability, reduces the need of superplasticizer (SP) necessary to obtain a similar slump flow compared with the concrete containing only cement as binder and gives a similar long-term strength as reference concrete. Moreover, Hadjsadok *et al.* (2011) found that mechanical properties and durability of slag concrete is improved at long term for low water/binder ratio (0.42) concrete and the sulfate attack resistance is achieved by slag replacement up to 30%.

Limestone powder (LP) is one of the extensively materials studied in literature. It has shown that it improves the workability and viscosity of SCC, as well as reduces its porosity with excellent densification of concrete microstructure (Hallal *et al.* 2010). Furthermore, the study on durability of concrete incorporating LP by Menadi *et al.* (2009) found a reduction in water permeability for concrete containing 15% of limestone fines as replacement of crushed sand.

The effect of PZ as a mineral admixture in SCC was also studied by several researchers; it is well established that due to its pozzolanic activity, this mineral admixture shows a beneficial contribution in improving the durability characteristics and ultimate strength of concrete (Belaidi *et al.* 2012). Ghrici *et al.* (2007) found an enhancement in acid and sulfate attack resistance as well as resistance to chloride ion penetration for cement mortar with natural pozzolana. The resistance of concrete with natural pozzolana in sodium sulfate and acid attacks has also been proved by Siad *et al.* (2013).

On the other hand, mixing mineral admixtures as ternary or catenary blended cement in concrete lead to better performances as reported by several researchers. Results of Ghrici *et al.* (2007) showed that the use of ternary blended cement (C+20% LP+30% PZ) improves the compressive and flexural strengths at early age and at long-term. Durability was also enhanced where better resistances to sulfate, acid and chloride ions penetration were shown. Mallikarjuna and Gunneswara (2017) reported also the improvement in compressive strength by using a combination of fly ash and GS as binder in geopolymer concrete.

However, SCC may be exposed to elevate curing temperatures whether in extreme weather conditions, in massive concrete structures or as a curing process in prefabrication. It is widely reported that a high curing temperature achieves high mechanical properties at early age, but can adversely affects the strength at later ages (Pihlajavaara 1972, Kim *et al.* 2000, Kanstad *et al.* 2003). This loss in strength at later age could be due to high temperature producing hydration products with non-uniform distribution (Neville 2000, Escalante and Sharp 2001) forms an open and unfilled pore structure in concrete (Lothenbach *et al.* 2007).

The kinetic of hardening of SCC with low water/binder ratio and high mineral admixture replacement is not always equivalent to that of ordinary concrete (Ba *et al.* 2011). Research results will differ between a reduction, stabilization and even an increase in strength at later age than curing at 20℃; which may be affected by the concrete composition, type and rate of admixtures and curing temperature. Gidion and Marios (2015), Derabla and Larbi (2014); reported that increasing curing temperature lead to smaller loss in later strength of SCC. Moreover, the study of Reinhardt and Stegmaier (2006) showed that there is no negative effect of elevated temperature on the high strength SCC, while the heat curing leads to coarser pores without increasing the total pore volume. This result is confirmed by other researchers (Aparicio 2016) who found a stabilization on microstructural and mechanical parameters after seven days for high curing temperature of SCC.

The beneficial effect of mineral admixtures on SCC properties at elevated temperatures has been shown by several investigators. It has been confirmed that the strength of concrete with mineral admixtures was higher than that of concrete without admixtures in heat curing conditions (Yazici *et al.* 2009, Bingol and Tohumcu 2013, Ramezanianpour *et al.* 2014, Juenger and Siddique 2015, Boubekeur *et al.* 2017). Moreover, other studies proved that increasing curing temperature can significantly improve the reactivity of GS and FA in concrete (Ho *et al.* 2003, Liu *et al.* 2005). Kanstad *et al.* (2003) report that high strength concretes (70 MPa) with pozzolanic admixtures i.e. silica fume (SF), FA and PZ, show no negative effect in strength while curing temperature rises from 20 to 55℃.

Other researchers studied the effect of several curing temperatures on properties of SCC. Bingöl and Tohumcu (2013) demonstrated that the optimum temperature of heat curing in SCC is 70℃. However, Ramezanianpour *et al.* (2013) found that the application of cycles with maximum temperature of 70℃ decreases the durability properties of SCC, such as surface resistivity and capillary absorption. It was reported that the optimum temperature of heat curing was near 60℃ considering strength and more pre-curing can increase the strength and durability as well since it may increase pozzolanic activity (Ho *et al.* 2003). As reported by Bougara *et al.* (2009), the temperature of 40℃ presents the optimum curing temperature for strength development of the slag cement.

Therefore, the objective of this study is to examine the effect of substitution of 15% of the cement weight, by different mineral admixtures such as slag, pozzolana and limestone powder on mechanical properties and porosity of SCC cured under temperatures ranging between 20 and 80℃.

2. Experimental program

2.1 Materials

Local Ordinary Portland Cement type CEM I 42.5 was used. Three types of mineral admixtures were used: natural pozzolana (PZ) from a local volcanic deposit, limestone powder (LP) from a cement manufacturing quarry and granulated blast furnace slag (GS) from local steel factory. These mineral admixtures were ground in order to obtain a fine powder similar to that of common cements (SSB≈3500 cm^2/g). Table 1 describes the chemical compositions and physical properties of Portland cement and mineral admixtures used in this study. The activity index (*i*), was determined by mechanical method according to European standard EN 196-1 on standardized mortar with 15% mineral admixture.

Two sands and two gravels were used: a siliceous fine dune sand (S1), a crushed limestone

Table 1 Chemical and physical analysis of cement and mineral admixtures

Chemical Constituent (%)	Cement	Limestone powder (LP)	Granulated slag (GS)	Natural pozzolana (PZ)
CaO	63.57	53.08	42.20	10.50
SiO_2	20.18	1.42	40.10	47.97
Al_2O_3	3.75	0.91	6.00	17.54
Fe_2O_3	4.74	0.56	2.00	10.50
MgO	2.12	0.43	4.70	3.80
MnO	-	0.50	2.6	-
SO_3	2.67	0.60	0.13	0.40
K_2O	0.55	0.52	1.17	1.50
TiO_2	-	-	1.10	-
Na_2O	0.69	0.08	-	3.40
Cl	0.01	-	-	-
Loss on ignition (%)	1.72	41.90	-	4.39
Activity index at 7 days ($\boldsymbol{i_7}$)	-	0.84	0.83	0.85
Activity index at 28 days ($\boldsymbol{i_{28}}$)	-	0.88	0.91	0.88
Activity index at 90 days ($\boldsymbol{i_{90}}$)	-	0.89	0.96	0.91
Physical properties				
Specific gravity (g/cm^3)	3.150	2.544	2.857	2.590
Blaine fineness (cm^2/g)	3370	3560	3450	3490

Table 2 Physical and mechanical properties of fine and coarse aggregates

Properties	Sand		Gravel		Standard
Fraction size	S1 (0/1)	S2 (0/4)	G1 (3/8)	G2 (8/15)	
Fineness Modulus	1.06	3.45	-	-	NF EN 933-1
Specific gravity (kg/l)	2.59	2.63	2.66	2.67	NF EN 1097-6
Bulk density (kg/l)	1.42	1.53	1.37	1.34	NF EN 1097-3
Sand equivalent (%)	61.13	75.63	-	-	NF EN 933-8
Water absorption (%)	0.04	0.38	0.19	0.52	NF EN 1097-6
Los-Angeles (%)	-	-	27.92	24.60	NF EN 1097-2

sand (S2), a 3/8 gravel (G1) and an 8/15 gravel (G2) from the same quarry. The physical and mechanical properties of fine and coarse aggregates are summarized in table 2. Fig. 1 gives the grading sizes of these aggregates. In this study a polyether-polycarboxylate based superplasticizer was used with a solid content of 30% and specific density of 1.065 g/cm^3.

2.2 Mix proportions

In order to determine the quantities of materials: cement, aggregate, water and superplasticizer, the formulations are based on the Japanese method (general method) proposed by Okamura and Ouchi (2003), with some modifications being made to the level of the sand content in the mortar

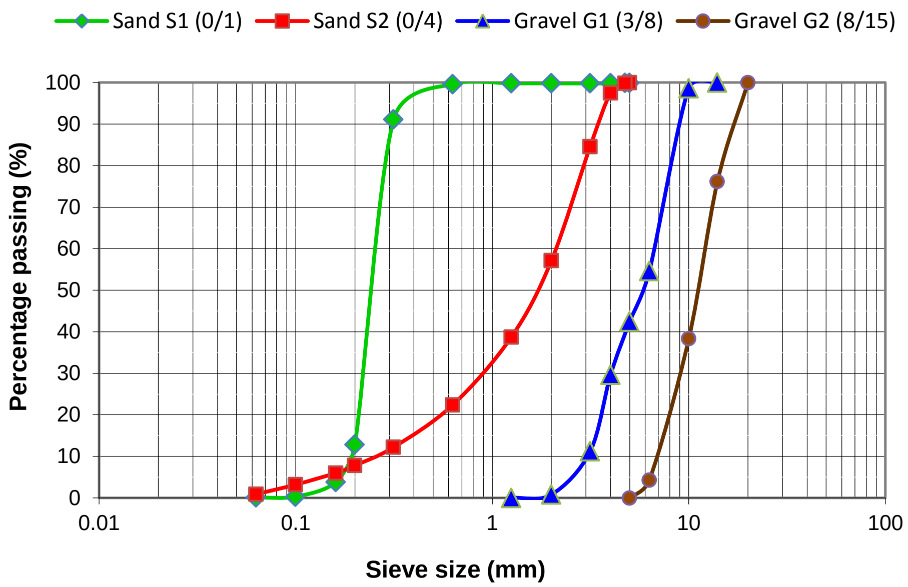

Fig. 1 Grading curves of fine and coarse aggregates used

(S/M), the water-powder weight ratio (W/P) and the superplasticizer-powder weight ratio (Sp/ P) in order to take into account the requirements of the local materials and to obtain good fresh properties of SCC.

Four self-compacting concrete mixes were made with a total powder content of 470 kg/m^3 (Portland cement and mineral admixture), while keeping constant the W/P ratio at 0.42, S/M ratio at 0.50, paste volume at 34.4% (including air content of 1%) and Sp/P ratio at 1.6%. For SCC with mineral admixture, the cement was substituted by weight with 15% of mineral admixture to obtain a self-compact paste for each SCC mixture as recommended by the French Association of Civil Engineering (AFGC 2002) (the paste volume was kept constant). The 15% substitution rate was chosen as it is the average rate used in most local cement manufacturing companies and also based on previous work which showed that this is the optimal rate (Itim *et al.* 2011, Boukendakdji *et al.* 2012, Belaidi *et al.* 2012). The mix proportions of the produced mixtures (for 1 m^3 by weight) are shown in Table 3.

2.3 Manufacturing and tests

All concrete batches are manufactured in the laboratory environment by a rotary planetary mixer with the capacity of 50 dm^3 and all components of SCC mixture were batched by weight. In order to ensure a good homogeneity of concrete mixes and a better dispersion of fine particles by the superplasticizer, mixing process for SCC was longer than that for conventional concrete mixes, and superplasticizer were diluted in water before added to the concrete (Chopin *et al.* 2004). Therefore, the following mixing procedure consisted in mixing the coarse and fine aggregates with the cement and mineral admixture together for half a minute (30 s), then the amount of 60% of mixing water and mixed for 1 min before adding the remaining 40% of water containing the superplasticizer during another 1 min. The mixing is continued for another 5 minutes and then

Table 3 Mix proportions for studied SCC mixes

Constituent (kg/m^3)	SCC-R	SCC-LP	SCC-GS	SCC-PZ
Cement	467	404	400	403
LP	-	57	-	-
GS	-	-	64	-
PZ	-	-	-	58
Sand S1 (0/1)	360	360	360	360
Sand S2 (0/4)	541	541	541	541
Gravel G1 (3/8)	401	401	401	401
Gravel G2 (8/15)	401	401	401	401
Water	196	194	195	194
Superplasticizer	7.47	7.37	7.43	7.39

stopped for 2 minutes before remixing for just half a minute (30 s) and unloading. After the mixing process was completed and to ensure the self-compacting properties of concretes with admixtures of different natures, a variety of tests were carried out to determine properties of fresh SCC.

2.3.1 Fresh concrete tests

Before casting, the properties of SCC mixes such as filling ability, passing ability and segregation resistance, were verified according to tests recommended by the AFGC (2002) such as slump flow diameter (D), time taken to reach a slump diameter of 500 mm (T_{500}), V-funnel flow time ($t_{V\text{-}Funnel}$), L-box height ratio (H_2/H_1) and sieve stability (S%).

2.3.2 Manufacturing, curing and testing of specimens

After testing SCC in fresh state, a number of specimens were then cast without any vibration and compaction in lubricated molds in order to measure compressive strength (R_c), flexural tensile strength (R_t), ultrasonic pulse velocity (UPV), modulus of elasticity (E) and porosity (P). Table 4, gives the different types of mold corresponding to tests at the hardened state used in this study. In order to study the effect of water-curing temperature on SCC properties, the samples were divided into four equal groups and subjected to different curing regimes as summarized below.

For normal curing mode, specimens were kept in water at 20±3°C until age of tests. For heat treated curing, each set of specimens was kept in heated water for 7 days and thereafter the curing was continued in water at normal temperature (20°C) until age of tests. Three different temperatures for heating water were employed in this study: 40, 60 and 80°C. The maximum heating temperature is limited by 80°C according to the temperature applying in precast concrete manufacturing (Neville 2002, Bingol and Tohumcu 2013). The heated curing duration was fixed at 7 days according to the findings of other researchers who proved that an initial water-curing of 7 days is more beneficial for compressive strength development of SCC than that for 3, 14 and 28 days (Ozer and Ozkul 2004, Zhao *et al.* 2012, Salhi *et al.* 2017).

The characterization of SCC in the hardened state was carried out by the following methods and according to the standards given in table 4. For each type of SCC, the tests were carried out on three specimens for each testing age and the average values are reported.

- For each SCC mixture, 100 mm cube specimens were used to determine the ultrasonic pulse velocity and compressive strength at 3, 7, 28, and 90 days in accordance with NF EN 12504-4 and NF EN 12390-3 respectively. The ultrasonic pulse velocity test was performed in both directions by direct transmission method so that the direction of measurement of the transit time is perpendicular to the direction of manufacture, and then the test result ultrasound for each sample is the median value of two measurements in both directions.

- Flexural tensile strength was determined using 70×70×280 mm^3 beam samples at the ages of 3, 7, 28 and 90 days in accordance with NF EN 12390-5 standard.
- The modulus of elasticity test was conducted according to the specifications given in European standard NF EN 1352 by using 160 mm×320 mm cylinders at the age of 28 days.
- The test of the porosity accessible to water was carried out at the age of 28 days for half prism specimens of 70×70×280 mm^3 and the porosity was calculated according to NF P 18-459 standard.

Table 4 Description of different specimens and tests realized for SCC mixes in hardened state

Test	Age (day)	Specimen		Standard
		Form (cm)	Number	
Compressive strength	3, 7, 28 and 90	Cub (100×100×100)	192	NF EN 12390-3
Flexural tensile strength	3, 7, 28 and 90	Beam (70×70×280)	192	NF EN 12390-5
Ultrasonic pulse velocity	3, 7, 28 and 90	Cub (100×100×100)	192	NF EN 12504-4
Modulus of elasticity	28	Cylinder (∅160×320)	16	NF EN 1352
Porosity	28	½ Beam (70×70×280)	16	NF P 18-459

3. Experimental results and descussion

3.1 Characterization of SCC in fresh state

The test results of fresh properties SCC are illustrated in Figs. 2 and 3. As seen in Fig. 2, the slump flow diameters of all mixtures were in the range of 650 and 800 mm, which is an indication of good deformability and conforming AFGC recommendations (AFGC 2002). The effect of mineral admixture on the flow is remarkable in terms of its nature (Fig. 2). An improvement in slump flow diameter is observed by SCC-LP and SCC-GS which may be attributed to the spherical shape of LP and GS (Neville 2000). Unlike SCC-PZ which presented the lowest slump flow diameter, a decrease of 4% in comparison to the SCC-R is observed and it may be due to the angular shapes and rough surface texture of PZ (Belaidi *et al.* 2012), in addition to the pozzolanic activity of this admixture which needs a higher water amount (Juenger and Siddique 2015). These results confirm those found by other researchers (Belaidi *et al.* 2012, Boukendakdji *et al.* 2012, Derabla and Larbi 2014, Yahiaoui *et al.* 2017).

According to the t_{500} results, Fig. 2 shows that the slump flow times for all SCC mixes were less than 5 s and met the requirements of the AFGC recommendations (AFGC 2002). A decrease on t_{500} is observed by SCC-LP and SCC-GS compared to SCC-R, while the SCC-PZ had the highest value (4.5 s), which indicate the significant effect of mineral admixtures on flow time of SCC.

Based on the *V*-funnel test results (Fig. 2), all the SCC mixes performed well in terms of stability because all mixes exhibited a *V*-funnel flow time less than the recommended value (10 s)

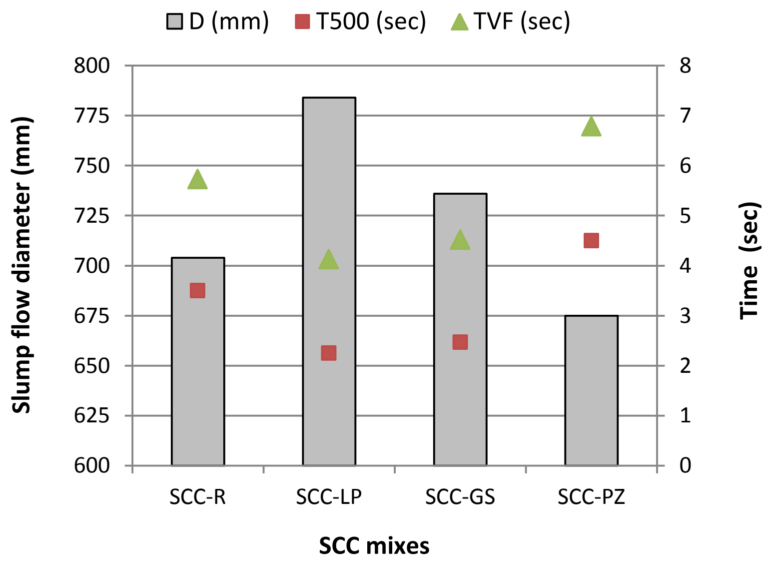

Fig. 2 Results of slump flow and *V*-Funnel test for SCC mixes

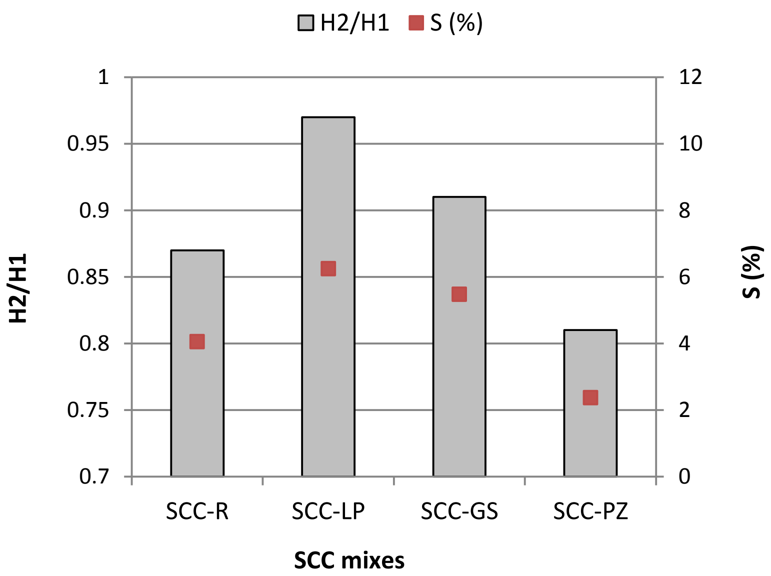

Fig. 3 Results of *L*-Box and sieve stability test for SCC mixes

by AFGC to obtain a good filling ability and sufficient viscosity of SCC (AFGC 2002). The lowest *V*-funnel flow time of 4.1 s was measured for SCC-LP, while the SCC-PZ had the highest flow time of 6.8 s. Therefore, PZ makes SCC more viscous compared to SCC made with LP or GS which confirms the results obtained by Diamantonis *et al.* (2010).

With regard to the filling capacity estimated by the H_2/H_1 ratio measured through the *L*-box test, all self-compacting concretes had H_2/H_1>0.8 meeting the AFGC limitations (AFGC 2002).

The highest values were observed for SCC-LP mixes and the lowest values for SCC-PZ mixes (Fig. 3). Therefore, LP and GS remarkably improved the filling and passing ability of SCC, compared to PZ.

According to AFGC recommendations (AFGC 2002)**,** a value of segregation index less than 15% is an indicator of a good resistance to segregation. As seen in Fig. 3, all the studied SCC mixes presented values between 2% and 7% which proved a satisfactory resistance to segregation (laitance <15%). SCC-PZ is characterized by high stability (laitance of 2.3%) and consequently a high resistance to segregation and to bleeding which confirms the result obtained by other researchers (Hammat 2012, Kenai *et al.* 2014). The SCC-GS and SCC-LP mixes are homogeneous but less stable. Researchers in (Hammat 2012, Aparicio *et al*. 2016) found also that LP and GS, allow increasing the fluidity of SCC mixture but they affect negatively its stability.

It can be concluded from these tests, that all workability results were in the range established by AFGC (2002) indicating a good filling and passing ability as well as segregation resistance. Therefore, it can be said that for all mineral admixtures, the chosen composition ensures good fluidity and cohesiveness of SCC.

3.2 Characterization of SCC in hardened state

3.2.1 Compressive strength

The results of compressive strength according to water curing temperature and age of specimens for all SCC mixes are presented in Fig. 4. The strength development depends greatly on curing temperature as it does with vibrated concrete. At early age (3 days), all mixes showed an increase in compressive strength with increasing curing temperature as initially expected. This strength gain is more important from 20 to 40℃ that from 40 to 60 or 80℃. Except SCC-GS which shows a linear increase in strength, with a gain of 71%; 92%; and 124% at 40; 60 and 80℃ respectively.

Beyond 7 days, the optimum curing temperature was 40℃ for all SCC mixes, which led to significant increase in strength at early age without decreasing it at later age. The increase was

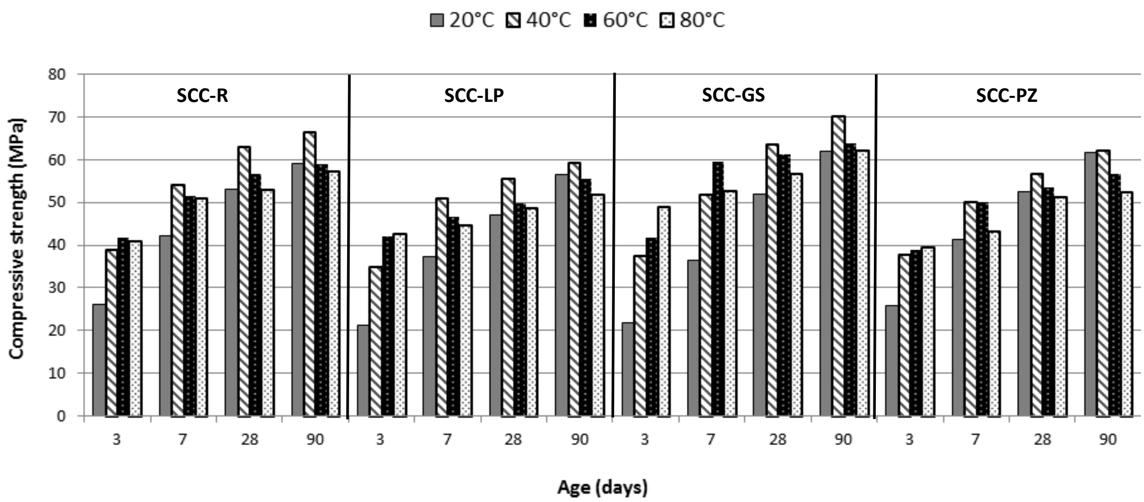

Fig. 4 Compressive strength of SCC mixes at different ages and water curing temperature

48%, 62%, 71% and 45% at 3 days and 12%, 5%, 13% and 1% at 90 days for SCC-R, SCC-LP, SCC-GS and SCC-PZ, respectively. This strength gain at later age for all mixes is due to extended hydration which is promoted under this temperature. Similar results were reported by other researchers (Bougara *et al.* 2009), who found that the curing temperature of 40℃ seems to be optimum for strength development of concrete with mineral admixtures.

Increasing curing temperature to 60℃ causes an improvement in strength at early age for all SCC mixes without penalizing it at later age, while comparable strengths were observed to 20℃ at 90 days for SCC-R, SCC-LP and SCC-GS. Except SCC-PZ which shows a loss of 8% at 90 days.

Temperature of 80℃ which has the highest energy cost, does not improve the strength of SCC-R, SCC-LP and SCC-PZ at early and later age compared to 60℃. A similar strength was observed for 60℃ at 3 days (40 MPa) and a loss of 3%; 8% and 15% at 90 days as compared to 20℃ at the same age. Furthermore, SCC-GS shows the highest strength at 3 days at 80℃ (49 MPa) and had the same strength as that in standard curing (20℃) at 90 days with a value of 62 MPa.

By taking into account the effect of mineral admixtures, it can be seen that under standard curing conditions (20℃) and compared to SCC-R, the highest strengths are observed by SCC-PZ at all ages with an increase of about 5% at 90 days. This could be due to the higher pozzolanic activity of PZ which promotes the hydration according to Table 1 (activity index). GS with its slow hydraulic and pozzolanic reaction shows an increase in strength of SCC at early age than at later age (90 days) which confirms the results obtained by other researchers for concrete with 15% GS (Hadj-sadok *et al.* 2011, Boukendakdji *et al.* 2012). In contrary, limestone powder remains inert without any activation, with a loss in strength of SCC-LP compared to SCC-R at all ages. Ye *et al.* (2007) have also found that limestone powder used as filler in SCC does not participate in chemical reaction.

In heat treated SCC, LP is more active at early age if temperature exceeds 40℃ than in standard curing with a gain in strength about 0.82 and 3.85% at 60℃ and 80℃ compared to SCC-R in the same temperature. From 7 days, limestone leads to a strength loss of SCC for all curing temperatures. According to Ramezanianpour *et al.* (2014), this can be explained by the fact that limestone particles act as nucleation sites and hence increase the early hydration of cement which may lead to a more disoriented crystallization of CH and strength loss at later age. For all ages, SCC with 15% GS exposed to elevated temperature exhibited significant increase in strength as compared to other SCC under the same temperature which agrees with the conclusions of other studies (Derabla and Larbi 2014, Gidion and Marios 2015). Moreover, SCC-PZ gained less strength compared to reference SCC (SCC-R) without any mineral admixture at elevated curing temperature for all ages.

3.2.2 Flexural tensile strength

The flexural tensile strength tests carried out on the different SCC mixes at 3, 7, 28 and 90 days are summarized in Fig. 5. In standard curing condition (20℃), and up to 28 days of age, the results indicate a negative effect of the three mineral admixtures on flexural strength of SCC with losses of 16%, 32% and 39% were observed at 3 days for SCC-LP, SCC-GS and SCC-PZ respectively compared to SCC-R. At 90 days, the highest strength was observed for SCC-GS with a value of about 9 MPa which exceeds that of SCC-R by 9%, whereas both SCC-LP and SCC-PZ show a decrease of about 3% and 4% respectively. This decrease in strength of SCC with LP was confirmed by other researchers (Parra *et al.* 2011), while the increase in flexural tensile strength for SCC with GS was also reported by Boukendakdji (2010) for SCC with 15% of granulated slag at 90 days.

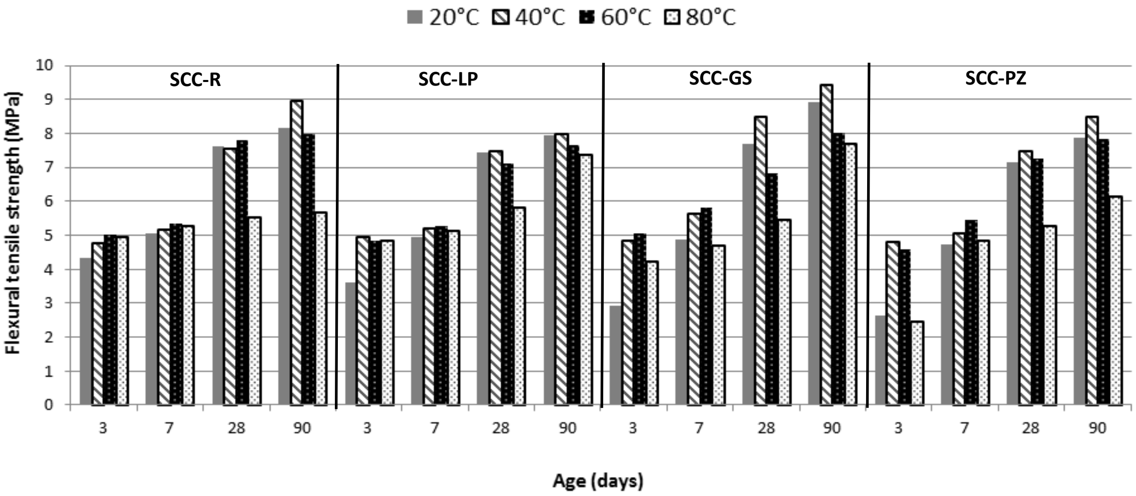

Fig. 5 Flexural tensile strength of SCC mixes at different ages and curing temperatures

At early age (up to 7 days) and like compressive strength, the flexural tensile strength of all mixes (Fig. 5) tended to increase as the curing temperature increases. Beyond this age and for temperature over 40℃ a decrease was clearly observed in strength of SCC-LP and SCC-GS compared to those at 20℃, while similar strength between 20℃ and 60℃, are observed for SCC-R and SCC-PZ at 28 and 90 days. Compared to other temperatures, increasing curing temperature to 80℃, does not improve the strength of all SCC mixes at all ages. This is probably due to the formation of micro-cracks above 60℃.

As compared to SCC-R an improvement of the efficiency of mineral admixtures is observed at early age as temperature increases and comparable strengths to SCC-R were observed for all SCC mixes. But at later age both SCC-LP and SCC-PZ mark a decrease in tensile strength at high temperatures, while SCC-LP marked the highest loss. However, SCC-GS presented the best behavior at 40℃ and similar strength to SCC-R at 60℃ in 90 days. Yazýcý *et al.* (2009) found also that the use of mineral admixtures such as FA and GS reduced the negative effect of high curing temperature on flexural strength and toughness of concrete.

From these experimental results it can be concluded that the best curing temperature to achieve the highest tensile strength of SCC was 40℃ as was the case for compressive strength. Furthermore, for all curing temperatures, the highest strengths at later age were observed for SCC with GS.

3.2.3 Modulus of elasticity

The modulus of elasticity (E) test was carried out at age of 28 days, the test results are presented as a function of curing temperature and mineral admixture type in Fig. 6. A significant effect of mineral admixture type on modulus of elasticity is noticed. In standard curing condition (20℃), the values of E ranged between 35 GPa and 43 GPa, where the highest value is given by SCC-GS. Whereas, the modulus of elasticity of SCC-LP and SCC-PZ fell by about 9% and 6% respectively compared to SCC-R.

Increasing curing temperature up to 40℃ causes an improvement in modulus of elasticity for all mixes, where the highest modulus for all concretes was observed at this temperature which is in

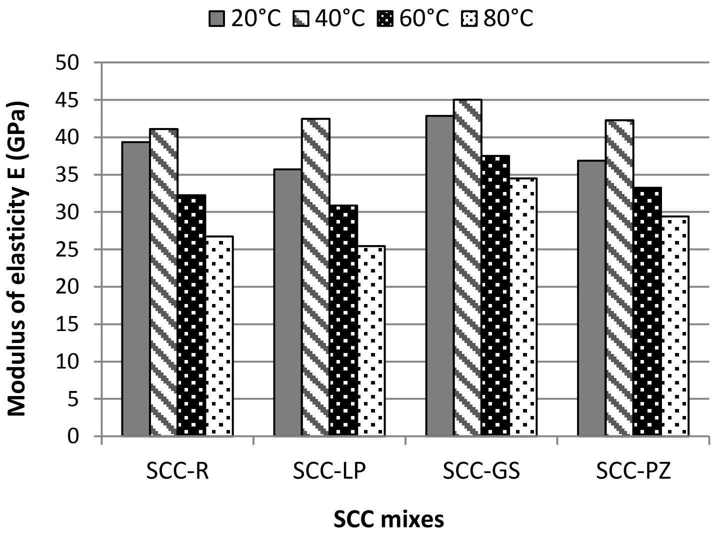

Fig. 6 Modulus of elasticity versus curing temperature and mineral admixture type

agreement with the results obtained for compressive strength. Beyond this temperature, the modulus of elasticity decreases as curing temperature of SCC mixes increases compared to those in standard curing

It is clearly observed from Fig. 6, that the incorporation of GS is very beneficial for high curing temperature allowing SCC mixes to acquire a higher modulus of elasticity at elevated curing temperature. A gain of about 9%, 10%, 16% and 29% was observed by SCC-GS at 20℃, 40℃, 60℃ and 80℃ respectively compared to SCC-R at the same temperatures, and the highest modulus for each curing temperature is shown by SCC-GS. In Contrary, limestone powder and natural pozzolana show no significant effect on the modulus of elasticity for curing temperature over 40℃.

3.2.4 Ultrasonic pulse velocity

Ultrasonic pulse velocity (UPV) allows to evaluate not only the quality of concrete (homogeneity, presence of cracks and voids), but also to determine the compressive strength of an existing structure and in precast concrete. The test results of UPV for all SCC mixes are correlated with their corresponding compressive strengths as a function of curing temperature according to the following proposed models (Fig. 7).

$$f_c = 0.0463\mathbf{e}^{1.5306\mathbf{V}}\ ;\ (R^2 = 0.9645) \quad \text{for } 20℃ \tag{1}$$

$$f_c = 0.1545\mathbf{e}^{1.2461\mathbf{V}}\ ;\ (R^2 = 0.9611) \quad \text{for } 40℃ \tag{2}$$

$$f_c = 5.6001\mathbf{e}^{0.4852\mathbf{V}}\ ;\ (R^2 = 0.8044) \quad \text{for } 60℃ \tag{3}$$

$$f_c = 3.0421\mathbf{e}^{0.6026\mathbf{V}}\ ;\ (R^2 = 0.8089) \quad \text{for } 80℃ \tag{4}$$

It can be noticed that even with the increase in curing temperature, a good correlation could be found between UPV and corresponding compressive strength for SCC mixes (R^2>0.8). Furthermore, all the proposed correlations have exponential form relationships with different

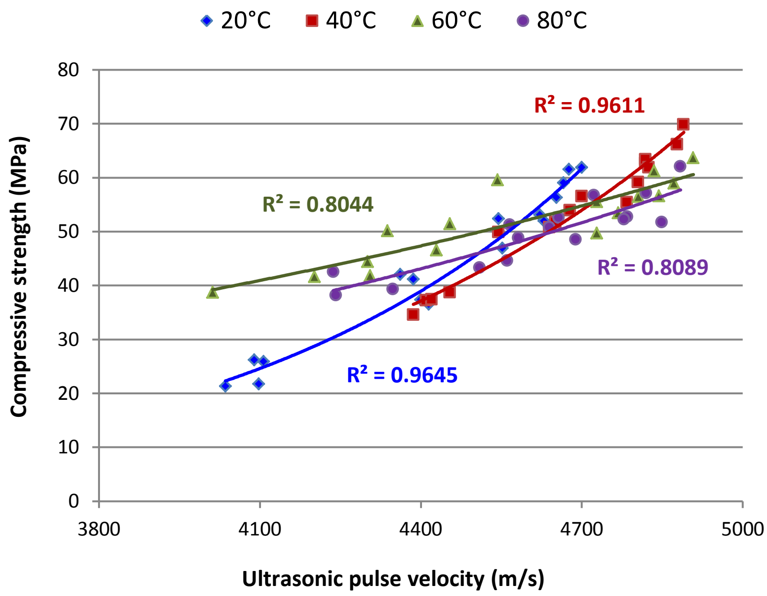

Fig. 7 Relationship between compressive strength and ultrasonic pulse velocity

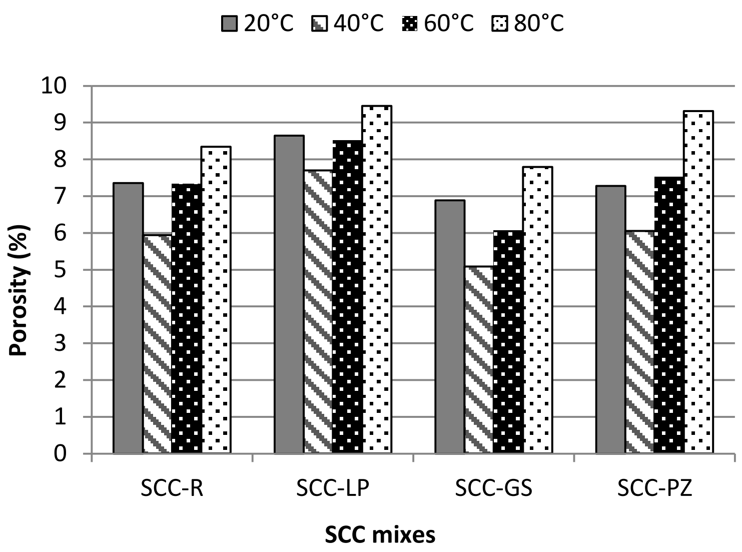

Fig. 8 Porosity of SCC mixes versus curing temperature and mineral admixture type

constant, which agree with the form obtained by other researchers for concrete with mineral admixtures (Zulfu *et al.* 2008). The correlation coefficient for SCC mixes at 20℃ and 40℃ is of the order of 0.96 and decreases to 0.80 at 60℃ and 80℃. The relation between UPV and compressive strength is affected by curing temperature of SCC mixes and hence must be calibrated for each specific concrete.

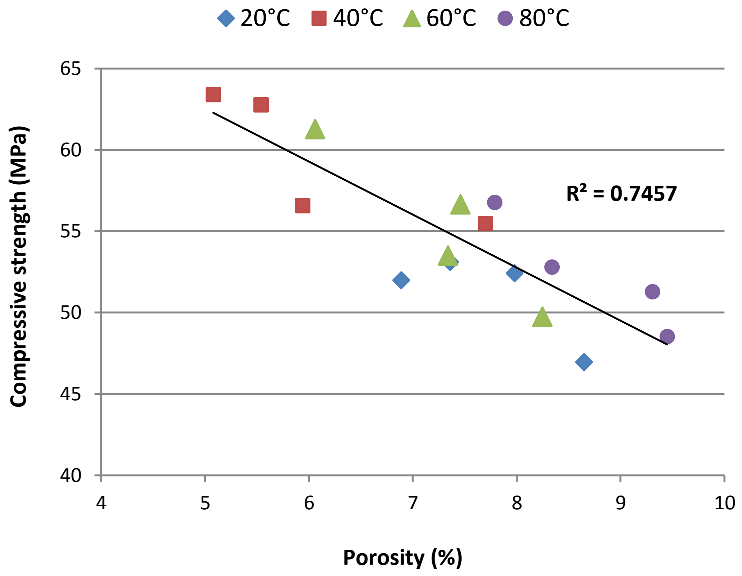

Fig. 9 Relationship between compressive strength and porosity of SCC mixes

3.2.5 Porosity

Concrete durability depends greatly on its porosity, which determines the intensity of interaction of concrete with aggressive agents. The porosity test results obtained for 28 days age SCC mixes, at different curing temperatures are shown in Fig. 8.

In standard curing conditions, the results indicate the important effect of mineral admixtures on porosity of SCC. Indeed, GS and PZ by their hydraulic or pozzolanic activity, lead to the lowest porosities, with reductions of 6% and 1%, confirming the results of compressive strength at the age of 28 days. Furthermore, a greater increase (17.5%) was noted in the porosity of SCC-LP compared to SCC-R. Derabla and Larbi (2014), reported higher reduction of porosity (40%) when incorporating about 20% of GS. Boucetta (2014) also reported a decrease in the porosity of SCC with slag compared to those with LP.

Increasing curing temperature to 40℃ decreases SCC porosity for all mixes, while a loss of 25%, 11%, 26% and 17% is observed for SCC-R, SCC-LP, SCC-GS and SCC-PZ, respectively compared to those found at 20℃. Furthermore, the same porosities are shown for all SCC mixes between 20℃ and 60℃, except SCC-GS which shows a reduction of 12% at this temperature. A good performance and better durability for heat treated SCC can be obtained under temperature up to 60℃ by adding GS. Beyond this temperature, the porosity becomes higher with the increase of curing temperature, so that the higher values are measured at 80℃ for all SCC mixes.

The most porous SCC for all curing temperature is SCC-LP mix, which presents porosities exceeding those of SCC-R by about 18%, 30%, 16% and 13% at 20℃, 40℃, 60℃ and 80℃, respectively. Similar results were observed by Derabla and Larbi (2014) for SCC with 20% LP. Furthermore an increase in porosity compared to SCC-R, is also observed by SCC-PZ for temperature beyond 40℃. The SCC mixes with GS are the less porous for all temperatures; while, a reduction of 6%, 15%, 17% and 7% is observed compared to SCC-R at 20℃, 40℃, 60℃ and 80℃, respectively and confirming the results of compressive strength.

Porosity may be directly related to the compressive strength; indeed, Fig. 9 shows the relationships between 28 days compressive strength and porosity of SCC mixes depending on curing temperatures. It can be clearly seen that compressive strength is highly dependent on porosity of concrete caused by increasing curing temperature.

5. Conclusions

The main aim of this study is to investigate the effect of curing temperature and mineral admixtures, i.e., LP, GS, and PZ, on mechanical properties and porosity of SCC. Based on the experimental results, the following conclusions can be drawn:

- It is possible to have self-compacting concrete properties when the cement is substituted by 15% of local mineral admixtures. Furthermore, an improvement in fluidity and deformability measurements was observed by LP and GS, unlike PZ which has developed a less workable SCC but with high segregation resistance.
- In standard curing conditions, SCC-PZ presents the highest performances for all ages. Furthermore, GS with its slow hydraulic activity presents its efficiency at later age (90 days). Conversely, LP remains inert without any activation. Hence its use can be justified only by particular economic and ecological considerations.
- Increasing curing temperature leads to considerable improvement in hydration and strength of SCC mixes. While, the optimum curing temperature to obtain a high performances SCC at early and later age, is 40℃ for SCC-PZ, 60℃ for SCC-R and SCC-LP and 80℃ for SCC-GS (49 and 62 MPa at 3 days and 90 days respectively). Granulated slag is considered the most effective mineral admixture, where its use produces the more resistant and less porous heat treated SCC mixes.
- Based on the results found for mechanical strengths, elastic deformation and porosity; all SCC mixes are considered satisfactory for application in structural elements and the effects of high curing temperature are not harmful to SCC properties as is the case for vibrated concrete.

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