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Performance of self-compacting concrete made with coarse and fine recycled concrete aggregates and ground granulated blast-furnace slag

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Abstract. This paper reports the effects of coarse and fine recycled concrete aggregates (RCA) on fresh and hardened properties of self-compacting concrete (SCC) containing ground granulated blast-furnace slag (GGBFS) as cement replacement. For this purpose, three SCC mixes groups, were produced at a constant water to binder ratio of 0.38. Both fine and coarse recycled aggregates were used as natural aggregates (NA) replacement at different substitution levels of 0%, 25%, 50%, 75% and 100% by volume for each mix group. Each group, included 0, 15% or 30% GGBFS as Portland cement replacement by weight. The SCC properties investigated were self-compactability parameters (i.e., slump flow, T500 time, V-funnel flow time, L-box passing ability and sieve stability), compressive strength, capillary water absorption and water penetration depth. The results show that the combined use of RCA with GGBFS had a significant effect on fresh and hardened SCC mixes. The addition of both fine and coarse recycled aggregates as a substitution up to 50% of natural aggregates enhance the workability of SCC mixes, whereas the addition from 50 to 100% decreases the workability, whatever the slag content used as cement replacement. An enhancement of workability of SCC mixes with recycled aggregates was noticed as increasing GGBFS from 0 to 30%. RCA content of 25% to 50% as NA replacement and cement replacement of 15% GGBFS seems to be the optimum level to produce satisfactory SCC without any bleeding or segregation. Furthermore, the addition of slag to recycled concrete aggregates of SCC mixes reduces strength losses at the long term (56 and 90 days). However, a decrease in the capillary water absorption and water permeability depth was noticed, when using RCA mixes with slag.

Keywords: self-compacting concrete; recycled coarse aggregates; granulated ground blast furnace slag; workability; strength; capillary water absorption; water permeability

1. Introduction

Self-compacting concrete (SCC) is a concrete that has good flowability and high resistance to

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segregation and can be used in heavily reinforced concrete elements without vibration (Akram *et al*. 2009). SCC was developed in Japan in the late 1980s and has recently been used in many countries for different applications (Kou and Poon 2009, Siddique 2011). SCC mixes usually incorporate supplementary cementitious materials (SCM), such as fly ash (FA), ground granulated blast-furnace slag (GGBFS) and silica fume (SF) to improve its rheological properties and stability at the fresh state and decreases its cost and reduces its environmental adverse effects (Boukendakdji *et al*. 2009, Melo and Carneiro 2010, Liu 2010, Craeye *et al*. 2010, Ahari *et al*. 2015).

GGBFS is one of the most widely used SCM as partial cement or aggregates replacement in SCC mixtures. GGBFS is widely available and its annual production worldwide is estimated at about 250 million tones. Nearly, one third of GGBFS goes as addition to the production of concrete for the building sector (Boukendakdji *et al*. 2009). Extensive studies have been conducted to investigate the effect of GGBFS on the properties of SCC and it was reported that the addition of GGBFS improved the rheological properties of concrete (Megat *et al*. 2011, Boukendakdji *et al*. 2012, Wang and Lin 2013, Zhao *et al*. 2015, Sethy *et al*. 2016, Rakesh and Bibhuti 2016). The use of GGBFS reduces the dosage of superplacizer needed to obtain a similar slump flow to concrete made with Portland cement only (Wang and Lin 2013). The incorporation of industrial slag in high volumes gives satisfactory SCC fresh properties (Sethy *et al*. 2016). However, Zhao *et al*. (2015) reported that the use of FA and GGBFS did not affect the flowability and stability of SCC. Park *et al*. (2005) reported that use of GGBFS reduces the yield stress and the viscosity of the cement paste. An enhancement of 10% of the rheological properties of self-compacting mortars with 30% of GGBFS as cement replacement was also reported (Adjoudj *et al*. 2014). In the same way, Sethy *et al*. (2016) illustrated that the increase of the slag content decreases the plastic viscosity and very low yield stress was found for all the replacements investigated. However, the introduction of GGBFS to the SCC lowered mechanical properties at early ages. This reduction could be overcome after a curing period of 28 days (Megat *et al*. 2011, Mucteba and Mansur 2011, Boukendakdji *et al*. 2012, Beycioglu *et al*. 2014, Zhao *et al*. 2015). Moreover, the use of GGBFS in SCC also improved the drying shrinkage, chloride ion penetration, water absorption, sulfate attack resistance and corrosion resistance of SCC (Bouikni *et al*. 2009, Erhan *et al*. 2010, TopcuIlker and Boga 2010, Mucteba *et al*. 2012, Deepankar *et al*. 2016, Yahiaoui *et al*. 2017).

In SCC mixtures, aggregates occupy 60-70% of the total volume and hence play a substantial role in its performance in the fresh and hardened states (Okamura and Ouchi 2003). Another cost-effective and environment-friendly method to produce SCC might be the use of RCA for SCC production. RCA from construction and demolition waste could be used as a substitute for NCA to reduce the environmental impact of concrete construction but their physical and mechanical properties are usually lower than virgin aggregates mainly due to the relatively soft and porous adhered mortar to their surface (Grdic *et al*. 2010). The question arises as to whether the key characteristics defining self-compacting ability, specified by EFNARC recommendations (EFNARC 2012), can be compromised if recycled concrete aggregates are used as the only aggregates for the production of SCC. Güneyisi *et al*. (2016b) reported that the self-compactibility characteristics of concrete are remarkably improved by the replacement of coarse and fine recycled concrete aggregate, while others researchers (Kebaïli *et al*. 2015) indicate that self-compacting ability criteria were not satisfied for the concrete mixes investigated, irrespective of the replacement level of NCA with RCA. The authors reported an increase in the rheological properties of concrete mixes and explained this by the angular shape and the rough surface texture of RCA as well as the high volume of coarse aggregates with a constant interstitial paste.

Later, Amer *et al*. (2016) found that the use of pre-saturated RCA aggregates is better to keep adequate superplasticizer dosage and relevant rheological parameters. With regard to mechanical properties, it has been well established by many researchers (Etxeberria *et al*. 2007, Kou and Poon 2009, Kou and Poon 2012, Choi and Yun 2013, Kou and Poon 2015, Señas *et al*. 2016, Tahar *et al*. 2016, Saha and Rajasekaran 2016) that the loss in compressive strength is decreased with increasing RCA content. Pereira *et al*. (2014) reported a loss of strength of only 3.3% with the maximum recycled aggregates incorporation. Gesoglu *et al*. (2015) also reported that SCC mixes with both fine and coarse aggregates showed the lowest compressive strength value compared to the corresponding control mixture. A reduction in strength up to 30.9% was found. Reduction in compressive strength could be explained by the weak interfacial transition zone due to the poor quality of the adhered mortar to RCA (Güneyisi *et al*. 2016a).

Concerning durability indicators, extensive research works (Sagoe *et al*. 2001, Grdic *et al*. 2010, Kou and Poon 2012) have been done on normal vibrated concrete (NVC) made with different replacement levels of NCA with RCA. According to these studies the incorporation of RCA as natural aggregates replacement adversely affect the durability properties of NVC. However, other studies (Pereira *et al*. 2014) have shown that, it is viable to replace NCA by RCA in self-compacting concrete without any detrimental effects on the permeability properties. The negative effect of RCA on the rheological, mechanical and durability properties of SCC could be mitigated by the addition of cementitious materials at an appropriate level due to their filler effect that increases the compactness and also due to their pozzolanic effect (Siddique 2003, Berndt 2009, Corinaldesi and Moriconi 2009, Kou *et al*. 2011, Kanish *et al*. 2016, Yaragal *et al*. 2016). Berndt (2009) found that recycled aggregate concrete mixtures containing 50% slag gave the best overall performance of vibrated concrete. Kou *et al*. (2007) reported that SCC with class F fly ash improves the mechanical and durability properties of recycled aggregate concrete. Kou and al. (2011) also reported that the replacement of 10% SF or 15% MK, improved both strength and durability performance, while a decrease in strength and an improvement in the durability of the recycled aggregate concretes were noticed for 35% FA and 55% GGBS as partial cement replacement. The addition of SF or MK at 10% by weight of cement is reported to compensate the loss of durability properties of SCC with 50% RCA as natural aggregates replacement (Kanish *et al*. 2016). Until now, there are few studies carried out on the effect of the simultaneous use of RCA and SCM on the properties of self-compacting concrete, mainly the combination of RCA and GGBFS as natural aggregates and cement replacement, respectively.

In this paper, the combined effects of coarse and fine recycled aggregates and GGBFS on the properties of self-compacting concrete is reported. Coarse and fine RCA are used to replace partially or totally virgin aggregates at levels of 0%, 25%, 50%, 75% and 100%, and GGBFS is used as a substitution to cement at 0%, 15% and 30%. The water- to-binder ratio was kept constant at 0.38 for all SCC mixtures. The fresh properties investigated include slump flow, T_{50} slump flow time, V-funnel flow time, L-box ratio and the segregation ratio whereas hardened properties include compressive strength, capillary water absorption and water permeability.

2. Experimental program

2.1 Materials

The cement used in all SCC mixes complied with EN-197/1 and labeled as CEM II/A 42.5. Its specific surface area by Blaine and specific weight were 3200 cm^2/g, and 3040 kg/m^3, respectively. The GGBFS used in this study was produced by locally available iron steel company. Its fineness and specific weight were 350 m^2/kg and 2850 kg/m^3, respectively. The chemical and physical properties of cement and GGBFS used are given in Table 1. The fine aggregates used were natural crushed sand and recycled concrete with maximum size of 4 mm. The coarse aggregates used for both natural and recycled concrete were two classes of either 8 mm or 16 mm maximum size. Recycled aggregates (fine and coarse) were obtained by crushing 1 m×1 m concrete slabs with a thickness of 10 cm. Slabs were manufactured in the laboratory and stored for 28 days in water curing. They were initially subjected to a preliminary manual crushing before a final processing using a mechanical crusher. The crushed material is passed through a sieve to obtain different fractions of recycled aggregates. The physical properties of natural and recycled aggregates are presented in Table 2. The grading sizes of coarse and fine aggregates are illustrated in Fig. 1. A polyether-polycarboxylate based superplasticiser was used, which has a solid content of 30%.

2.2 Mix proportions and mixing sequence of SCC

A total of fifteen SCC mixes, including control mixes were prepared with recycled aggregates and GGBFS. The water/binder (W/B) ratio and superplasticizer dosage were kept constant at 0.38 and 1.5% of binder by weight, respectively. Cement was partial replaced by GGBFS at the levels of 0%, 15% and 30%by weight.SCC mixes were designed in three groups, namely G1, G2 and G3. Each group had five concrete mixes, where the natural aggregates (fine and coarse) was partially replaced by recycled aggregates at 0%, 25%, 50%, 75% and 100%. Further details of mixes proportions are shown in Table 3. SCCR50L15code indicates self-compacting concrete mixes prepared with 50% recycled aggregates for both fine and coarse as natural aggregates replacement and 15%of GGBFS as cement replacement.

The mixing procedure and time are very important to design self-compacting concrete mixtures. In this study, the mixing sequence of the constituent materials of SCC mixes is based on

Table 1 Chemical analysis of cement and slag (%)

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LI	TiO_2	MnO	Cl
Cement	20.92	5.33	3.43	61.74	1.58	1.83	-	-	1.35	-	-	-
Slag	40.10	6.00	2.00	42.20	4.70	0.15	-	1.20		1.20	2.60	-

Table 2 Properties of the natural and recycled aggregates

Properties	Fine aggregates		Coarse aggregates			
	NFA*	RFA*	NCA* 3/8	NCA* 8/15	RCA* 3/8	RCA* 8/15
Specific density (kg/m^3)	2530	2266	2730	2700	2386	2400
Bulk density (kg/m^3)	1640	1258	1475	1465	1172	1154
Water absorption (%)	1.7	8.87	0.5	0.5	7.39	3.21
Sand equivalent (%)	76.15	79.50	-	-	-	-
Fineness modulus (%)	2.8	3.82	-	-	-	-
Humidity (%)	1.7	6.3	0.13	0.13	3.73	2.64

***NCA** natural coarse aggregate, ***RCA** recycled coarse aggregate, ***NFA** natural fine aggregates, ***RFA** recycled fine aggregates

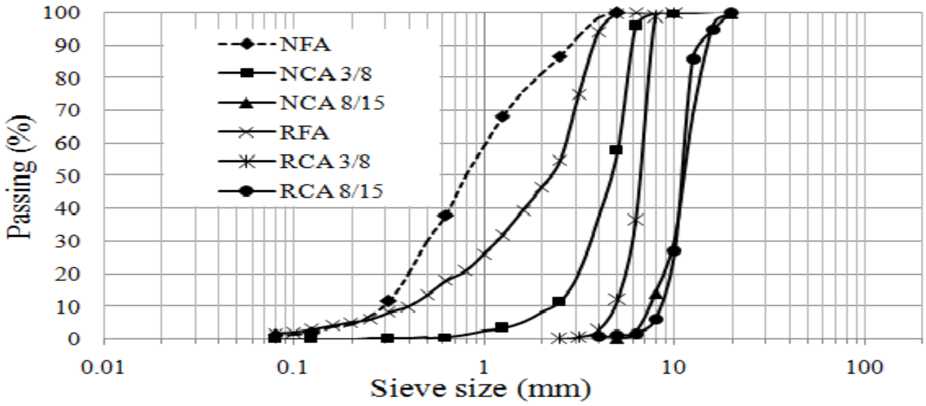

Fig. 1 Particle size distribution of the materials used

Table 3 Mix proportions of different SCC mixes (volume of concrete: 1 m^3)

	Mix group	Cement	Slag	NFA	RFA	NCA 3/8	NCA 8/15	RCA 3/8	RCA 8/15	Water	SP	W/B	V_{paste} (m^3)
G1	SCCR0L0	507	0	910	0	245	490	0	0	193	7.61	0.38	0.366
	SCCR25L0	507	0	682.5	203.75	183.75	367.5	54	107.75	193	7.61	0.38	0.366
	SCCR50L0	507	0	455	407.5	122.5	245	108	215.5	193	7.61	0.38	0.366
	SCCR75L0	507	0	277.5	611.25	61.25	122.5	162	323.25	193	7.61	0.38	0.366
	SCCR100L0	507	0	0	815	0	0	216	431	193	7.61	0.38	0.366
G2	SCCR0L15	434	73	910	0	245	490	0	0	193	7.61	0.38	0.367
	SCCR25L15	434	73	682.5	203.75	183.75	367.5	54	107.75	193	7.61	0.38	0.367
	SCCR50L15	434	73	455	407.5	122.5	245	108	215.5	193	7.61	0.38	0.367
	SCCR75L15	434	73	277.5	611.25	61.25	122.5	162	323.25	193	7.61	0.38	0.367
	SCCR100L15	434	73	0	815	0	0	216	431	193	7.61	0.38	0.367
G3	SCCR0L30	359	148	910	0	245	490	0	0	193	7.61	0.38	0.369
	SCCR25L30	359	148	682.5	203.75	183.75	367.5	54	107.75	193	7.61	0.38	0.369
	SCCR50L30	359	148	455	407.5	122.5	245	108	215.5	193	7.61	0.38	0.369
	SCCR75L30	359	148	277.5	611.25	61.25	122.5	162	323.25	193	7.61	0.38	0.369
	SCCR100L30	359	148	0	815	0	0	216	431	193	7.61	0.38	0.369

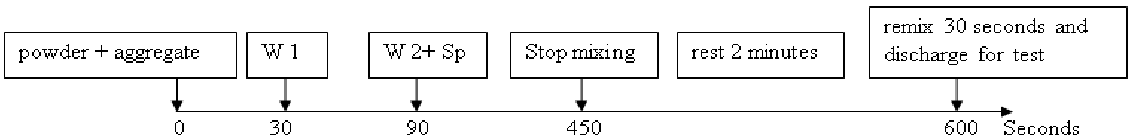

Fig. 2 Mixing procedure of SCC

the research work of Domone and Jim (1999) and is described in Fig. 2. The batching sequence adopted for all SCC mixes produced consisted of homogenizing the binder and aggregates for 30 s in a rotary planetary mixer, then adding 70% of water and mixed for one minute. Afterward, remaining water (30%) with SP was introduced, and the concrete was mixed for five minutes, then

Fig. 3 Slump flow for SCC with 100 RCA and 15 % of Slag

the mixing was stopped for two minutes and again the concrete was further mixed for 30 s before it was removed discharged from the mixer.

2.3 Testing

In the present investigation, the flowability (filling and passing ability) was performed on SCC mixes using slump flow, V-funnel and L-box tests. The resistance to segregation was measured by GTM sieve stability test (EFNARC 2012). The flow value of concrete mixes was evaluated by measuring the mean diameter in two perpendicular directions of SCC spread as shown in Fig. 3. The viscosity of SCC mixes was measured through the V-funnel flow time and the T_{50} slump flow time. The blocking ratio (H_2/H_1) for SCC mixes was determined by the L-box test, which gives an indication of the filling, passing, and visual segregation ability of the concrete. More details of the tests procedures are well documented elsewhere (EN 12350-8 2007, EN 12350-9 2007, EN 12350-11 2007) and were performed as per EFNARC guidelines for self-compacting concrete committee (EFNARC 2012).

For compressive strength test, from each concrete mixture, three cubes of 100 mm in size were cast. Specimens were left covered with a plastic sheet. After demoulding at the age of 24 hours, concrete specimens were immersed in water saturated with lime at 20±2℃ until the age of testing. The compression test was conducted at the age of 7, 28, 56 and 90 days according to NF P 18-406 (NF P 18-406 1981).

The sorptivity or rate of water absorption through self-compacting concrete surface was performed at 90 days as per recommended by ASTM (ASTM C1585-11 2012). The water capillary absorption test was carried out on the moulded side faces of the 100 mm cube specimens. In order to ensure that water flows in a single direction, specimens were sealed on the sides. The specimens were preconditioned in an oven at 80±2℃ until constant weight. After cooling, specimens were prepared and tested.

Water penetration depth under pressure for concrete mixes was determined in accordance to DIN 1048 (DIN 1048 2000). For this, a 500±50 kPa downward pressure was applied on a 150 mm cube specimen for 72 h to penetrate water through the specimen. At the end of the 72 hours period, the test specimens were split in the middle and the greatest penetration depth of pressurized water was measured in mm. The average of three test results is reported.

3. Results and discussion

3.1 Properties of fresh self-compacting concretes

Table 4 Fresh concrete test results

Mix group		Unit weight (kg/m^3)	Slump flow		V-funnel time (s)	L-box test Blocking ratio	Segregation ratio (%)
			Diameter (mm)	T_{50}(s)			
G1	SCCR0L0	2395	713	4.46	17.40	0.89	5.10
	SCCR25L0	2350	738	4.05	13.50	0.94	7.40
	SCCR50L0	2300	750	3.50	9.23	0.97	8.52
	SCCR75L0	2270	727	4.15	15.56	0.82	10.25
	SCCR100L0	2235	718	4.38	17.80	0.92	11.00
G2	SCCR0L15	2360	730	4.00	12.50	0.95	6.90
	SCCR25L15	2315	752	3.80	10.20	0.97	9.16
	SCCR50L15	2280	783	2.50	6.16	1.00	12.20
	SCCR75L15	2245	766	2.90	9.85	0.95	13.75
	SCCR100L15	2215	737	4.20	15.18	0.90	11.80
G3	SCCR0L30	2320	762	4.51	16.20	0.94	8.63
	SCCR25L30	2285	776	4.20	15.23	0.92	11.70
	SCCR50L30	2260	792	3.90	12.63	0.83	14.70
	SCCR75L30	2235	781	4.61	20.25	0.80	16.50
	SCCR100L30	2200	749	4.97	23.20	0.75	15.80

Test results for fresh density, filling ability (slump flow, T_{50} slump flow time, and V-funnel flow time), passing ability (Blocking ratio), and segregation resistance (segregation ratio) of all SCC mixes groups investigated in the present study are given in Table 4.

3.1.1 Fresh density

Fresh density of the different SCC mixes groups is presented in Fig. 4. The fresh density values varied in the range of 2200-2395 kg/m^3. It can be seen from this figure that fresh density of all SCC mixes groups decreases as increasing the replacement of GGBFS. This decrease was attributed to the lower value of the specific gravity of GGBFS compared to cement. On the other hand, and due to the porous old cement mortar adhered to RCA, specific gravity values of RCA mixes are lower than those for natural aggregates mixes. The fresh density of SCC mixes gradually decreases in terms of increasing RCA replacement levels, irrespective of the content of GGBFS used. The use of RCA at 25%, 50%, 75% and 100% replacement levels resulted in a decrease in the fresh density compared to control SCC mixes by about 1.25%, 4%, 5.20% and 6.70%, respectively. The lower values are given by SCC mixes with higher RCA and slag contents. This findings are in agreement with those obtained by many researchers (Grdic *et al*. 2010, Wang and Lin 2013, Güneyisi *et al*. 2016b).

3.1.2 Workability

Slump flow spread results achieved for all SCC mixes are given in Fig. 5. It can be seen that slump flow values for different SCC mixes groups were in the range of 713-792 mm and satisfy SCC fresh flow properties. According to EFNARC guidelines (EFNARC 2012), all SCC mixes groups are within the category of slump flow classes SF2 and SF3, which are generally suitable for applications, such as slabs and columns construction. The effect of RCA on the slump flow of SCC

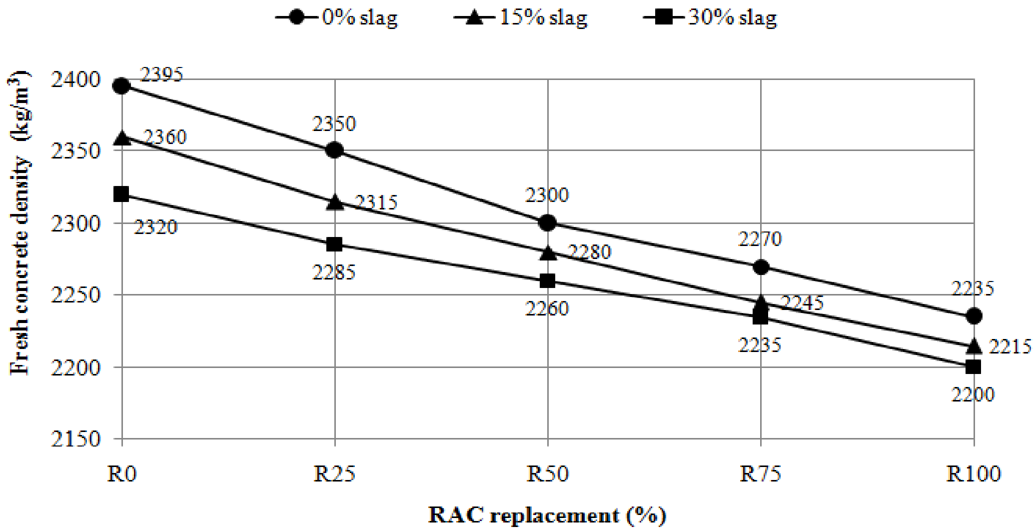

Fig. 4 Fresh density of SCC mixes

is evident from Fig. 5, as the percentage of RCA increases, the slump flow increases up to 50% of RCA. For high RCA replacement levels (75 and 100%), there was a drop in the slump flow confirming the results reported by Señas *et al*. (2016). In recycled SCC mixes with 15% and 30% GGBFS as cement replacement, the same trend was also observed. The higher slump values of 750 mm, 783 mm and 792 mm were obtained with SCC groups mixes, G1, G2 and G3 with 50% RCA, respectively. The results indicate clearly that the addition of GGBFS content from 15 to 30% improves the workability of concrete. This could be explained by the higher volume of paste due to the lower density of slag. Using a high volume of paste increases the distance between the aggregates, and the friction between the concrete components decreases. It can be concluded that the addition of GGBFS with a wide particle size distribution substantially enhances the rheology of the blended cements that facilitates particle packing and increases free water. Thus, the filling of small spherical slag particles between the largest cement particles as well as by the lower hydraulic activity leads to an improvement of the rheological parameters (Grzeszczyk and Janowska 2012). Moreover, increasing the amount of GGBFS content from 15 to 30% increased also the slump flow diameter of concretes gradually (Guneyisi and Gesoglu 2011). Metha (1983) suggested that slag increases workability because the specific gravity of furnace slag was slightly lower than that of cement. This results is similar to that found by Wang and Lin (2013) who reported that slump flow varied with the replacement ratio of Portland cement by slag. The slump flow for 15% slag sample was within the design value of 550-700 mm. The same tendency was reported by other research works (Boukendakdji *et al*. 2012, Beyciog˘lu *et al*. 2014).

In order to evaluate the viscosity of SCC mixes, the 500mm slump flow time (T_{50}) was also measured in the present study. As Fig. 5 reveals, it can be observed that all the mixes could be classified as VF2 (T_{50}>2s) in terms of viscosity according to EFNARC (EFNARC 2012). No segregation or water separation was noticed. The lowest values of T_{50} was given by SCC mixes with 50% RCA and 0%, 15% and 30 % GGBFS, which indicates a lack of cohesion. As a result, SCC mixes with 30% of GGBFS for different RCA became more viscous and provided a higher T_{50} slump flow time compared to other mixes.

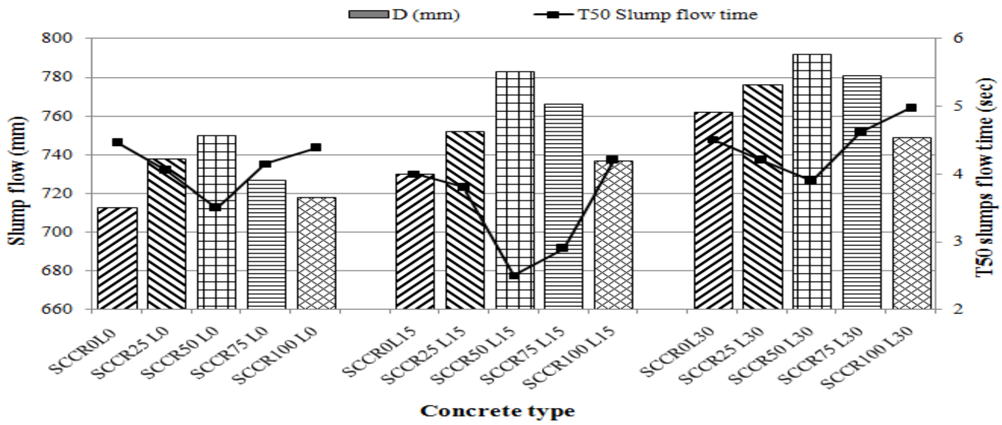

Fig. 5 Slump flow diameter and T_{50} time of SSC mixes

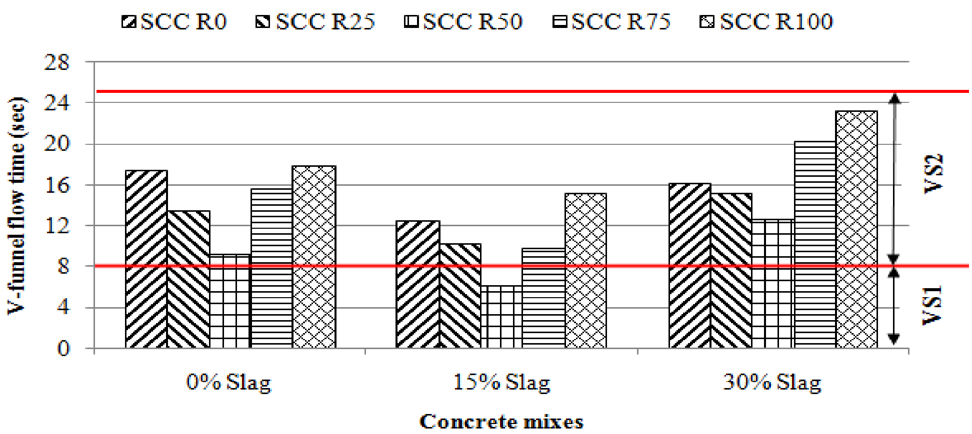

Fig. 6 V-funnel time of SCC mixes

V-funnel times results of different SCC mixes are presented in Fig. 6. From this figure, it can be seen that the V-funnel times for G1, G2 and G3 SCC groups were in the range of 9.23-17.80 s, 6.16-15.18 s and 12.63-23.2 s, respectively. V-funnel test results classify all the SSC mixes investigated as VF2 class (V-funnel flow time >9 s) except the mix SCCR50L15 which is VF1 class ($T \leq 8$s) (EFNARC 2012). The effect of RCA on the V-funnel flow time of SCC is evident as the flow time decreased for 25% and 50% RCA content but in turn significantly increased in the case of 75% and 100% RCA replacement. This may be attributed to the rougher surface texture of RCA particles compared to that of natural coarse aggregates. The shorter flow time indicates a greater flowing ability of concrete (Boukendakdji *et al*. 2012). However, a very small flow time does not necessarily give an indication of good flowing ability (EFNARC 2012). In the case of 100% RCA with and without slag addition, the flow became intermittent with a longer flow time of concrete. This could be explained by the accumulation of coarse aggregates in the tapered outlet of the V-funnel due to the lack of cohesiveness and the low flowing ability.

The results presented in Fig. 6 also indicate that, the incorporation of 15% to 30% of GGBFS increases the V-funnel flow time, for all SCC mixes compared to control mixes; the optimum time

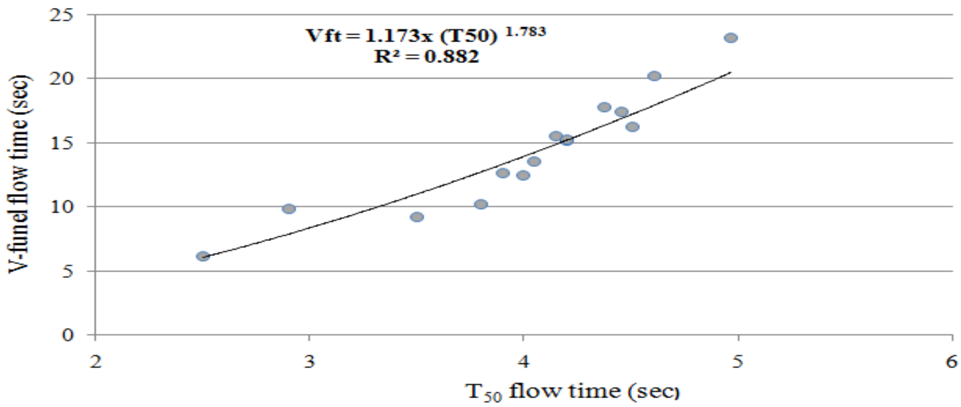

Fig. 7 Relationship between T_{50} and V-funnel time

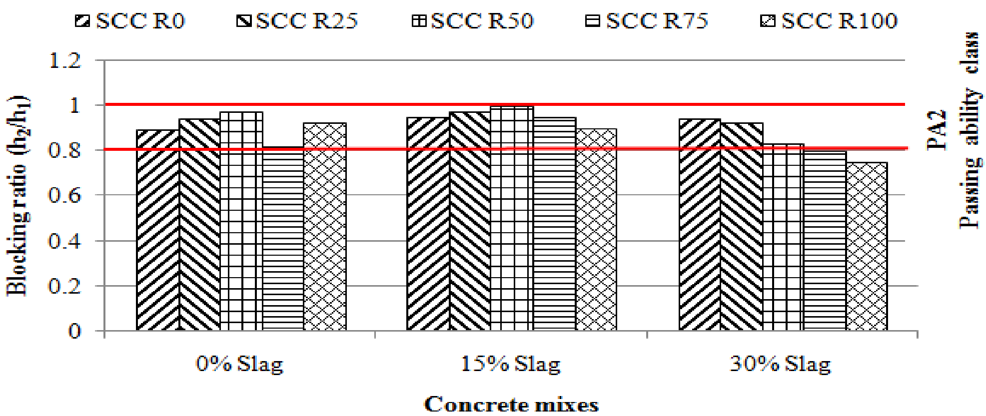

Fig. 8 Blocking ratio (h_2/h_1) of SSC mixes

is obtained for 15% of GGBFS content. In such a case, a longer flow time represents a higher viscosity of the mix that interrupted the continuous flow of concrete through the lower opening of the V-funnel and it directly relates to a better resistance to segregation (Kou *et al*. 2007). A good correlation (R^2=0.88) is obtained between the V-funnel flow time and the T_{50} flow time as illustrated in Fig. 7. Such a strong correlation implies that either T_{50} slump flow or V-funnel flow test is adequate to assess the relative viscosity and cohesiveness of SCC. Similar results were also reported by other researchers (Madandoust and Yasin 2012, Dinakar *et al*. 2013, Sethy *et al*. 2016).

L-box ratio test results of the SCC mixes groups are illustrated in Fig. 8. L-box height ratios of all SCC mixes with recycled aggregates and slag are within the range of 0.80-1.00, indicating good filling ability according to EFNARC recommendations (EFNARC 2012). As the test was conducted with three rebars they were ranked to the PA2 class; except the SCCR100L30 mixture, where the blocking ratio is lower than the minimum required and did not show any tendency of blockage between the rebars of the L-box device. This supports the point of view reported earlier by Sethy *et al*. (2016), which demonstrated that, even though the blocking ratio is greater than 0.65, SCC still has been accepted to achieve good passing ability. Fig. 8 reveals an improvement of the filling ability as increasing RCA content up to 50% for SCC mixes G1 and G2. In contrast,

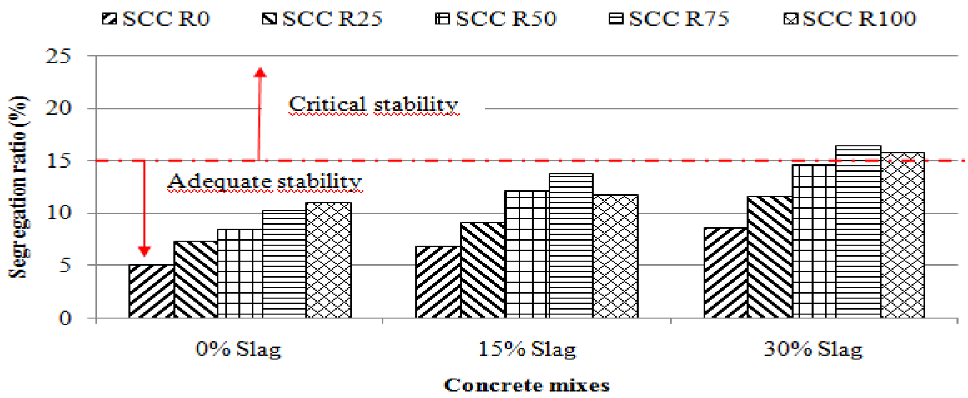

Fig. 9 Segregation ratio of SSC mixes

the L-box filling ratio decreased at 75% and 100% RCA levels, so indicating a lower passing ability. The higher filling ability is noticed for SCC mixes with 15% slag as compared to mixes without slag. Higher replacement of NCA by RCA made the concrete harsh and increased the blocking tendency of SCCR75S30 and SCCR100S30. It should be noticed that passing ability is more sensitive to the dosage of GGBFS. Increasing the GGBFS dosage decreased the passing ability of SCC mixes as can be seen in Fig. 8. However, SCC mix containing a partial substitution rate of approximately 15% of cement by GGBFS gives a favorable effect on the passing ability.

Fig. 9 shows the segregation resistance of all SCC mixes. The results show clearly that segregation index of the SCC mixes tend to increase with an increase of RCA and GGBFS contents. All SCC mixes exhibit adequate stability and satisfy the European specifications (EFNARC 2012); except mixes with 30% GGBFS and 75% or 100% RCA. Thus, the higher the replacement level of RCA and GGBFS in SCC, the higher the reduction in the segregation resistance. The results demonstrate that all SCC mixes in the present study were classified as SR2 class (< 15%) in terms of segregation resistance classes according to EFNARC (EFNARC 2012) except SCC mixes with 75% and 100% with 30% GGBFS are classified as SR1 class (<20%).

3.2 Properties of hardened concretes

3.2.1 Compressive strength

Fig. 10 shows the compressive strength test results of all self-compacting concrete mixes groups investigated in the present work at the age of 7, 56, 28 and 90 days of water curing. As shown in this figure, the compressive strength values increased with the age of concrete, whatever the RCA and GGBFS levels used. Compressive strength values range between 30.2 MPa and 53.5 MPa. As expected, increasing RCA levels in SCC mixes without slag resulted in a reduction in the compressive strength for all ages. The same tendency is noticed for all recycled SCC mixes with 15% and 30% GGBFS as cement replacement. At the age of 90 days, it can be seen that compressive strength of SCC mixes groups G1, G2 and G3 prepared with 100% RCA are reduced by 14.60%, 16.80% and 12.20%, respectively compared to SCC mix with natural aggregate (SCCR0L0). This reduction may be explained by the poor quality of the adhered mortar to recycled aggregates which weak the interfacial transition zone (ITZ) (Güneyisi *et al*. 2016a). In this study, the reduction in compressive strength values of SCC mixes containing RCA was

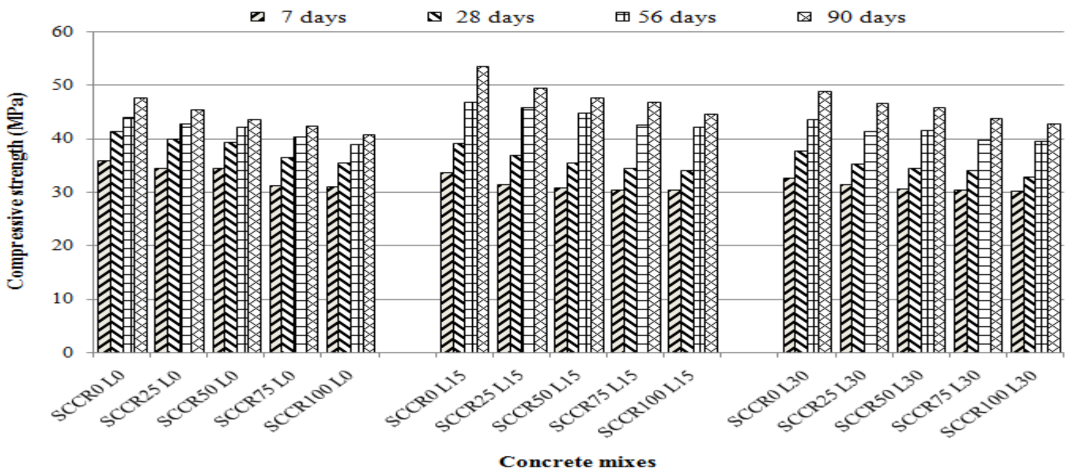

Fig. 10 Compressive strength of SCC mixes

comparatively higher than the values reported in the literature (Grdic *et al*. 2010, Pereira *et al*. 2014, Tuyan *et al*. 2014, Señas *et al* 2016). This may be attributed to the replacement of both fine and coarse recycled aggregates in the mixes. Kong *et al*. (2010) indicated that pores and cracks in RCA absorb water and lead to high water content in the new ITZ, thus, large calcium hydroxide crystals form and weaken the structure. On the other hand, Thomas *et al*. (2013) found that the new cement paste wraps the recycled aggregates, which are composed of old paste and natural aggregate. So, the new cement paste is more compact and denser than the one observed in the recycled aggregate.

The increase in the replacement level of GGBFS resulted in a reduction in the compressive strength of the SCC mixes with either natural or recycled aggregates at 7 and 28 days. This can be attributed to the low pozzolanic reaction activity of GGBFS at early age. However, at the ages of 56 and 90 days, there is an improvement in strength performance of SCC mixes groups G2 and G3 with 15% and 30 % GGBFS cement replacement, respectively compared to mix control (mix G1). It has been demonstrated that at later age, the calcium hydroxide (CH) resulting from the primary cement hydration reacted with GGBFS to produce a secondary hydration (Sethy *et al*. 2016). Also, because RCA are more porous than natural aggregates, the mineral admixtures and the hydration products could penetrate the pores and cracks of RCA and thus improve the interfacial transition zone (ITZ) bonding between the paste and the aggregates and hence improve the mechanical properties of concrete (Kou *et al*. 2007).

3.2.2 Capillary water absorption

The water capillary absorption test allows the characterization of the porous structure and is an indicator of the concrete durability. The amount of water absorbed per unit area denoted I, as function of square root of time for all SCC mixes with different levels of RCA and GGBFS, at the age of 90 days of water curing is shown in Figs. 11-13. It can be seen from these figures, an increase of water absorption with increase of the level of RCA in SCC mixes compared to control mixes, irrespective of the replacement content of GGBFS. The higher water absorption is noted for SCC mixes with higher RCA content. For example, water absorption value of SCCR100L0 is nearly more than twice the value of mix control (SCCR0L0). The higher absorption of SCC with

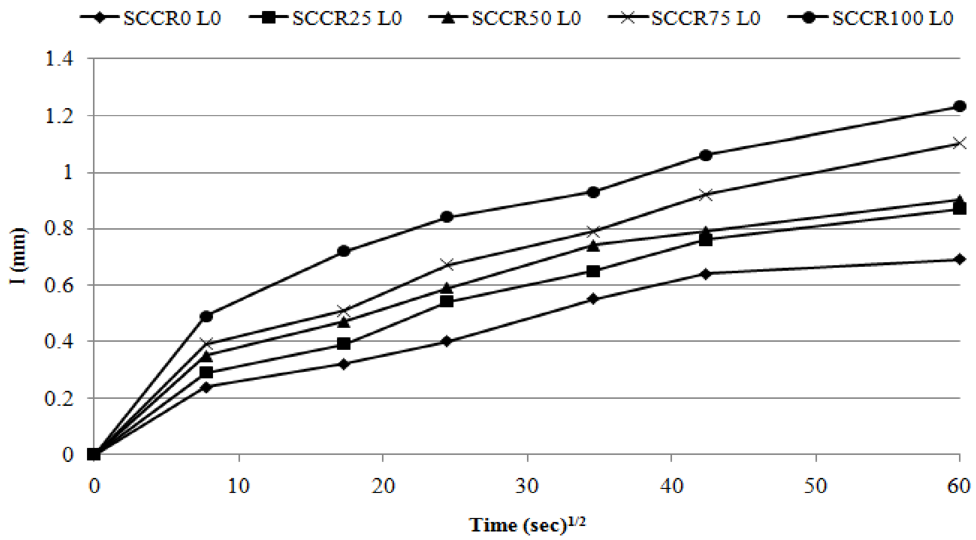

Fig. 11 Absorption for concretes containing varying amounts of RAC without slag

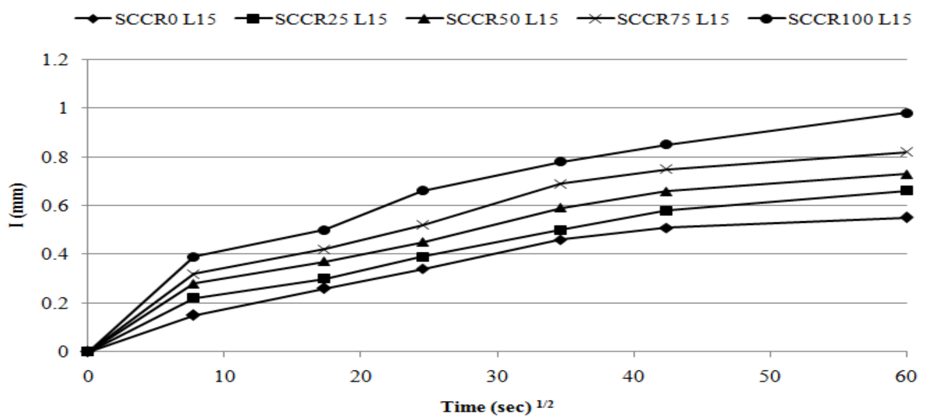

Fig. 12 Absorption for concretes containing varying amounts of RAC and 15% Slag

RCA can be explained by the high RCA water absorption coefficient and its effect on the pore system. Tuyan *et al*. (2014) showed that water absorption was more pronounced in mixes having 60% RCA substitution level. Comparing Fig. 11 with Figs. 11-13, a decrease in the amount of water absorption with the increase of cement replacement level of GGBFS is observed. Reduction in absorption by 20.23% and 13% is noticed for SCCR100L15 and SCCR100L30 mixes, respectively as compared to control mix (SCCR100L0).This enhancement can be explained by the more refined pore structure of GGBFS concrete. The positive effect of GGBFS on the capillary absorption of SCC has been mentioned in the literature not only for low slag content but especially for higher slag rates up to 50% (Guneyisi and Gesoglu 2008, Vejmelkova *et al*. 2009, Ahari *et al*. 2015). This improvement is justified by the CSH gel, produced by the hydration of slag and modification of the distribution and dimensions of capillary porosity (Jiang and Grandet 1989). The relationship between sorptivity and compressive strength of SCC is plotted in Fig. 14. In

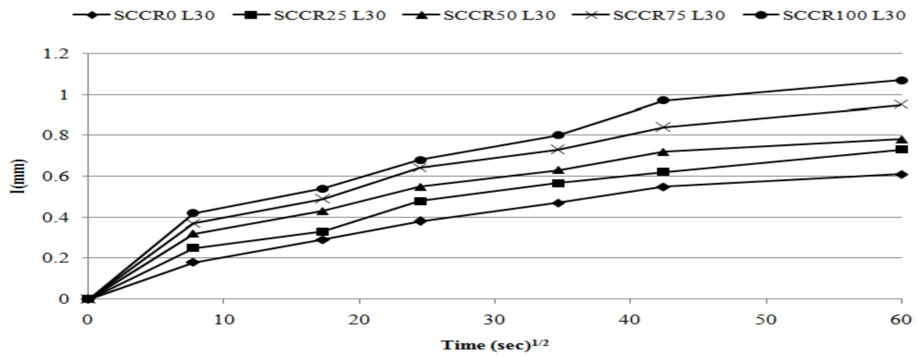

Fig. 13 Absorption for concretes containing varying amounts of RAC and 30% Slag

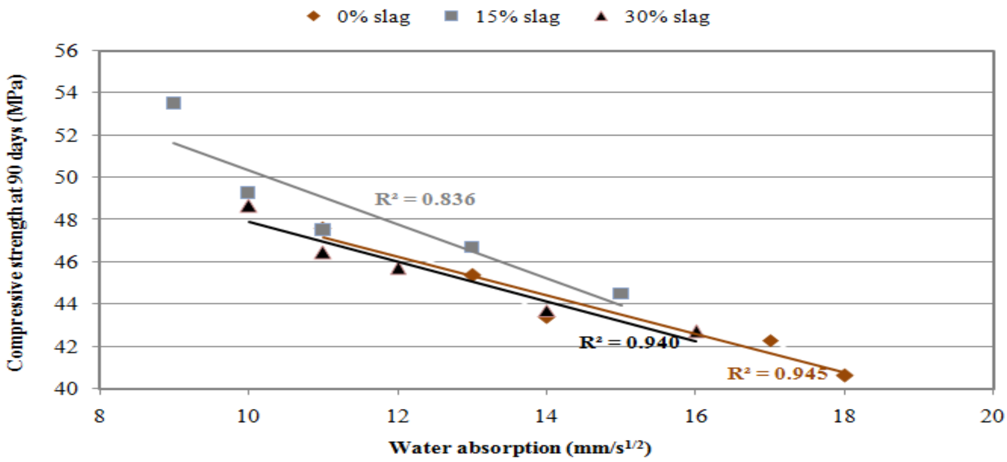

Fig. 14 Correlation between compressive strength and water absorption

general, a positive correlation has been obtained between the sorptivity and the compressive strength values. The coefficient of regression is about 0.94, 0.83 and 0.94 for recycled SCC mixes with 0%, 15% and 30% GGBFS, respectively, i.e., as the strength of SCC increased due to hydration, the sorptivity reduced significantly indicating a denser microstructure.

3.2.3 Water penetration depth

Water penetration depth results at the age of 56 and 90 days water curing for SCC mixes groups G1, G2 and G3 are illustrated in Fig. 15. A similar tendency in the water penetration depth results is observed as that of capillary water absorption coefficient results. Water penetration increased as RCA content increased. The higher permeability of the RCA mixes is probably associated with the residual mortar in the RCA. However, at the same recycled aggregate replacement level, the incorporation of slag significantly increased the resistance to water penetration. Moreover, the resistance to water penetration in G3mixes was lower than in G2 mixes. At 90 days, SCCR0 with 15 and 30% of GGBFS showed a decrease in water depth penetration about 42.40% and 19.80% compared to those without GGBFS, respectively. This can be explained by the positive effect of GGBFS at long-term and hence a decrease of the pore size structure as well as the permeability of

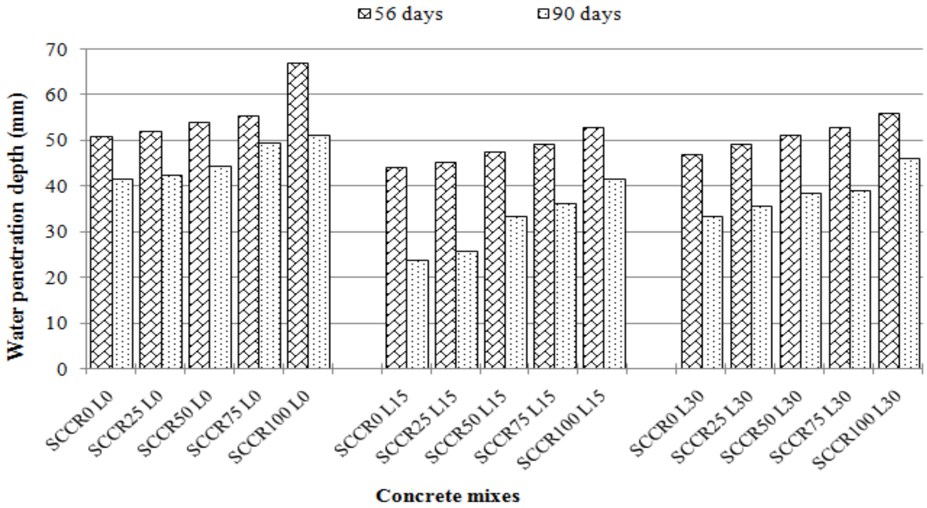

Fig. 15 Water penetration depth of SCC mixes

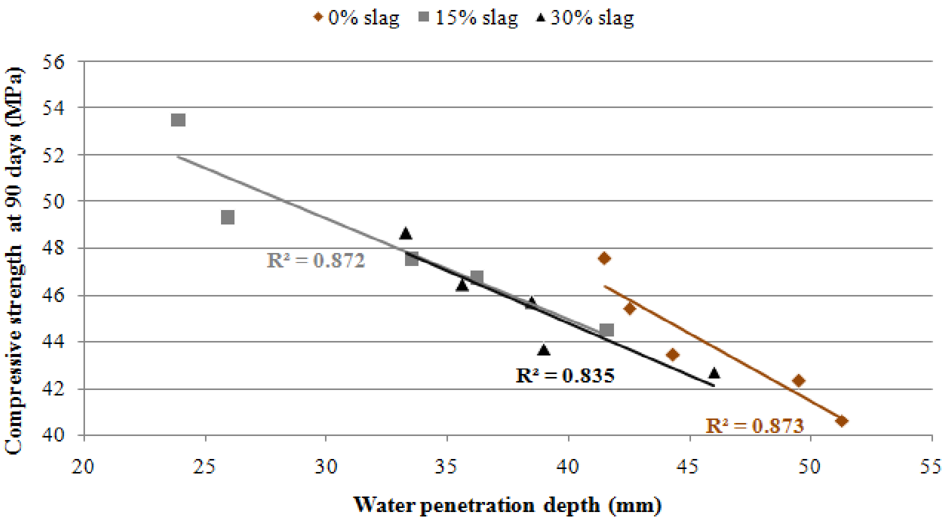

Fig. 16 Correlation between compressive strength and water penetration depth

SCC mixes with GGBFS. The fact that, the incorporation of slag improves the resistance to water penetration of concrete has been confirmed by other studies (ACI 2000, Cheng *et al*. 2005). Fig. 16 presents the correlation between compressive strength and average maximum penetration of water under pressure for the three SCC mixes groups at 90 days. Although, there is tendency for the water penetration depth to decrease with the increase in strength. The correlation coefficients are not high (0.872, 0.835 and 0.873 for 0, 15% and 30% of GGBFS, respectively). The relatively low correlation is probably because water permeability does not depend only on the compressive strength but also on the specific surface area, the size and tortuosity of the pores structure with which is connected and on the average length of the journey that a particle fluid takes from one end to the other.

5. Conclusions

Based on the results of this experimental investigation and the materials used, the following conclusions may be drawn:

- Fresh density of SCC mixes gradually decreases with the increase of RCA level as natural aggregates replacement. The simultaneously use of RCA and GGBFS decreases the fresh density of SCC. This loss may be attributed to the low specific gravity values of the RCA and GGBFS, as compared with natural aggregates and cement, respectively.
- RCA can be used in SCC mixes as NA replacement, without affecting the key fresh properties, such as filling ability, passing ability, and segregation resistance of concrete. An improvement of workability was observed with an optimum of 25% and 50% RCA. The same tendency is noticed when GGBFS is used as replacement of cement at levels of 15% and 30% in SCC mixes with RCA. Successful SCC mixes were obtained without any sign of bleeding or segregation with an optimum content of 15% GGBFS.
- Compressive strength of all SCC mixes decreased with increase of RCA. At the same RCA level replacement level, the use of GGBFS as cement replacement decreased the compressive strength at early age, but at later ages (56 and 90 days) the strength is comparable or higher to that of reference concrete. SCC mixes with 15% GGBFS content provided the highest compressive strength.
- The capillary water absorption of SCC increases with RCA replacement level. The use of GGBFS as cement replacement significantly decreases the water absorption of SCC mixes for both natural and recycled concrete aggregates.
- The resistance to water penetration of SCC mixes decreases with increasing RCA content. However, the resistance was improved by the addition of GGBFS in SCC mixes.
- In summary, comparing the results of this experimental investigation, successfully SCC mixes could be produced by using combined RCA (fine and coarse) up to 50% and GGBFS with 15 to 30% levels as natural aggregates and cement replacements, respectively.

References

ACI (2000), ACI Committee Report 233R-95, Ground Granulated Blast Furnace Slag as a Cementitious Constituent in Concrete, American Concrete Institute.

Adjoudj, M., Ezziane, K., Kadri, E.H., Ngo, T.T. and Kaci, A. (2014), “Evaluation of rheological parameters of mortar containing various amounts of mineral addition with polycarboxylate superplasticizer”, *Constr. Build. Mater.*, **70**, 549-559.

Ahari, R.S., Erdem, T.K. and Ramyar, K. (2015), “Permeability properties of self-consolidating concrete containing various supplementary cementitious materials”, *Constr. Build. Mater.*, **79**, 326-336.

Akram, T., Memon, S.A. and Obaid, H. (2009), “Production of low cost self-compacting concrete using bagasse ash”, *Constr. Build. Mater.*, **23**(2), 703-712.

Amer, A.A.M., Ezziane, K., Bougara, A. and Adjoudj, M. (2016), “Rheological and mechanical behavior of concrete made with pre-saturated and dried recycled concrete aggregates”, *Constr. Build. Mater.*, **123**, 300-308.

ASTM C1585-11 (2012), Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic- Cement Concretes.

Berndt, M.L. (2009), “Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate”, *Constr. Build. Mater.*, **23**, 2606-2613.

Beycioglu, A., Aruntas, H. and Wang, H.Y. (2014), "Workability and mechanical properties of self-compacting concretes containing LLFA, GBFS and MC", *Constr. Build. Mater.*, **73**, 626-635.

Bouikni, A., Swamy, R.N. and Bali, A. (2009), "Durability properties of concrete containing 50% and 65% slag", *Constr. Build. Mater.*, **23**(8), 2836-2845.

Boukendakdji, O., Kadri, E.H. and Kenai, S. (2012), "Effect of granulated blast furnace slag and superplasticizer type on the fresh properties and compressive strength of self-compacting concrete", *Cement Concrete Compos.*, **34**(4), 583-590.

Boukendakdji, O., Kenai, S., Kadri, E.H. and Rouis, F. (2009), "Effect of slag on the self-compacted concrete", *Constr. Build. Mater.*, **23**(7), 2593-2598.

Cheng, A., Huang, R., Jiann, K.W. and Cheng, H.C. (2005), "Influence of GGBS on durability and corrosion behavior of reinforced concrete", *Mater. Chem. Phys.*, **93**, 404-411.

Choi, W.C. and Yun, H.D. (2013), "Long-term deflection and flexural behavior of reinforced concrete beams with recycled aggregate", *Mater. Des.*, **51**,7 42-750.

Corinaldesi, V. and Moriconi, G. (2009), "Influence of mineral additions on the performance of 100% recycled aggregate concrete", *Constr. Build. Mater.*, **23**, 2869-2876.

Craeye, B., Schutter, G.D., Desmet, B., Vantomme, J., Heirman, G. and Vandewalle, L. (2010), "Effect of mineral filler type on autogenous shrinkage of self-compacting concrete", *Cement Concrete Res.*, **40**, 908-913.

Deepankar, K.A., Bhupinder, S. and Surender, K.V. (2016), "The effect of attack of chloride and sulphate on ground granulated blast furnace slag concrete", *Adv. Concrete Constr*., **4**(2), 107-121.

DIN 1048 (2000), Testing Method for Concrete: Determination of the Depth of Penetration of Water Under Pressure.

Dinakar, P., Sethy, K.P. and Sahoo, U.C. (2013), "Design of self-compacting concrete with ground granulated blast furnace slag", *Mater. Des.*, **43**, 161-169.

Domone, P.L.J. and Jin, J. (1999), "Properties of mortar for self-compacting concrete", *Proceedings of RILEM International Symposium on Self-Compacting Concrete*, Stockholm, Paris.

EFNARC (2012), "The European guidelines for self-compacting concrete", *Cement Concrete Compos*., **34**, 583-590.

El Amiri, A. (1988), "Durability of concrete in hot climate", PhD Thesis, Leeds University, England.

EN 12350-11 (2007), Testing Fresh Concrete - Part 11: Self-Compacting Concrete - Sieve Segregation Test.

EN 12350-8 (2007), Testing Fresh Concrete - Part 8: Self-Compacting Concrete - Slump-Flow Test.

EN 12350-9 (2007), Testing Fresh Concrete - Part 9: Self-Compacting Concrete - V Funnel Test.

Erhan, G., Mehmet, G. and Erdogan, O. (2010), "Strength and drying shrinkage properties of self-compacting concrete incorporating multi-system blended mineral admixtures", *Constr. Build. Mater.*, **24**(10), 1878-1887.

Etxeberria, M., Vázquez, E., Mari, A. and Barra, M. (2007), "Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete", *Cement Concrete Res.*, **37**(5), 735-742.

Gesoglu, M., Güneyisi, E., Ö znurÖ z, H., Taha, I. and Taner, Y.M. (2015), "Failure characteristics of self-compacting concretes made with recycled Aggregates", *Constr. Build. Mater.*, **98**, 334-344.

Grdic, Z.J., Toplicic, C.G.A., Despotovic, I.M. and Ristic, N.S. (2010), "Properties of self-compacting concrete prepared with coarse recycled concrete aggregate", *Constr. Build. Mater.*, **24**(7), 1129-1133.

Grzeszczyk, S. and Janowska,R.E. (2012), "The influence of small particle on the fluidity of blast furnace slg cementpaste containing superplasticizers", *Constr. Build. Mater.*, **26**, 411-415.

Guneyisi, E. and Gesoglu, M. (2008a), "A study on durability properties of high-performance concretes incorporating high replacement levels of slag", *Mater. Struct.*, **40**(3), 479-493.

Guneyisi, E. and Gesoglu, M. (2011b), "Properties of self-compacting portland pozzolana and limestone blended cement concretes containing different replacement levels of slag", *Mater. Struct.*, **44**, 1399-1410.

Güneyisi, E., Gesog'lu, M., Kareem, Q. and Ipek, S. (2016a), "Effect of different substitution of natural aggregate by recycled aggregate on performance characteristics of pervious concrete", *Mater. Struct.*, **49**(1), 521-536.

Güneyisi, E., Gesoglu, M., Algin, Z. and Yazici, H. (2016b), "Rheological and fresh properties of self-compacting concretes containing coarse and fine recycled concrete aggregates", *Constr. Build. Mater.*, **113**, 622-630.

Jiang, S.P. and Grandet, J. (1989), "Evolution comparée des porosités des mortiers de ciment au laitier et des mortiers de ciment portland", *Cement Concrete Res.*, **19**, 487-495.

Kanish, K.M.E., Singh, S.P. and Singh, B. (2016), "Durability of self-compacting concrete made with Recycled Concrete, Aggregates and mineral admixtures", *Constr. Build. Mater.*, **128**, 67-76.

Kebaïli, O., Mouret, M., Arabi, N. and Cassagnabere, F. (2015), "Adverse effect of the mass substitution of natural aggregates by air-dried recycled concrete aggregates on the self-compacting ability of concrete: evidence and analysis through an example", *J. Clean. Prod.*, **87**, 752-761.

Kong, D., Lei, T., Zheng, J., Ma, C., Jiang, J. and Jiang, J. (2010), "Effect and mechanism of surface coating pozzalanics materials around aggregate on properties and ITZ microstructure of recycled aggregate concrete", *Constr. Build. Mater.*, **24**(5), 701-708.

Kou, S.C. and Poon, C.S. (2009), "Properties of self-compacting concrete prepared with coarse and fine recycled concrete aggregates", *Cement Concrete Compos.*, **31**, 622-627.

Kou, S.C. and Poon, C.S. (2012), "Enhancing the durability properties of concrete prepared with coarse recycled aggregate", *Constr. Build. Mater.*, **35**, 69-76.

Kou, S.C. and Poon, C.S. (2015), "Effect of the quality of parent concrete on the properties of high performance recycled aggregate concrete", *Constr. Build. Mater.*, **77**, 501-508.

Kou, S.C., Poon, C.S. and Agrela, F. (2011), "Comparisons of natural and recycled aggregate concretes prepared with the addition of different mineral admixtures", *Cement Concrete Compos.*, **33**, 788-795.

Kou, S.C., Poon, C.S. and Chan, D. (2007), "Influence of fly ash as cement replacement on the properties of recycled aggregate concrete", *Mater. Civil Eng.*, **19**(9), 709-717.

Liu, M. (2010), "Self-compacting concrete with different levels of pulverized fuel ash", *Constr. Build. Mater.*, **24**, 1245-1252.

Madandoust, R. and Yasin, M.S. (2012), "Fresh and hardened properties of self-compacting concrete containing metakaolin", *Constr. Build. Mater.*, **35**, 752-760.

Megat, J.M.A., Brooks, J.J., Kabir, S. and Rivard, P. (2011), "Influence of supplementary cementitious materials on engineering properties of high strength concrete", *Constr. Build. Mater.*, **25**, 2639-2648.

Melo, K.A. and Carneiro, A.M.P. (2010), "Effect of Metakaolin's finesses and content in self-consolidating concrete", *Constr. Build. Mater.*, **24**, 1529-1535.

Metha, P.K. (1983), "Pozzolanic and cementitious by productions as mineral admixturesfor concrete - a critical review", *First International Conference on the Use of Fly Ash, Silica Fume, Slag and Other Mineral By - Products in Concrete,* Canada.

Mucteba, U. and Mansur, S. (2011), "Performance of self-compacting concrete containing different mineral admixtures", *Constr. Build. Mater.*, **25**(11), 4112-4120.

Mucteba, U., Kemalettin, Y. and Metin, I. (2012), "The effect of mineral admixtures on mechanical properties, chloride ion permeability and impermeability of self-compacting concrete", *Constr. Build. Mater.*, **27**(1), 263-270.

NF P 18-406 (1981), Bétons-Essais de Ccompression.

Okamura, H. and Ouchi, M. (2003), "Self-compacting concrete", *J. Adv. Concrete Technol.*, **1**(1), 5-15.

Park, C.K., Noh, M.H. and Park, T.H. (2005), "Rheological properties of cementitious materials containing mineral admixtures", *Cement Concrete Res.*, **35**(5), 842-851.

Pereira, O.L.A., Nepomuceno, M.C.S., Castro, G.J.P. and Vila, M.F.C. (2014), "Permeability properties of self-compacting concrete with coarse recycled aggregates", *Constr. Build. Mater.*, **51**,113-120.

Rakesh, K.P. and Bibhuti, B.M. (2016), "Fresh and hardened properties of concrete incorporating ground blast furnace slag-a review", *Adv. Concrete Constr.*, **4**(4), 283-303.

Sagoe, C.K.K., Brown, T. and Taylor, A.H. (2001), "Performance of concrete made with commercially produced coarse recycled concrete aggregate", *Cement Concrete Res.*, **31**(5), 707-712.

Saha, S. and Rajasekaran, C. (2016), "Mechanical properties of recycled aggregate concrete produced with Portland Pozzolana Cement", *Adv. Concrete Constr.*, **4**(1), 27-35.

Señas, L., Priano, C. and Marfil, S. (2016), "Influence of recycled aggregates on properties of self-consolidating concretes", *Constr. Build. Mater.*, **113**, 498-505.
Sethy, K.P., Pasla, D. and Sahoo, U.K. (2016), "Utilization of high volume of industrial slag in self-compacting concrete", *J. Clean. Prod.*, **112**, 581-588.
Siddique, R. (2003), "Effect of fine aggregate replacement with class F fly ash on the mechanical properties of concrete", *Cement Concrete Res.*, **33**(4), 539-547.
Siddique, R. (2011), "Properties of self-compacting concrete containing class F fly ash", *Mater. Des.*, **32**, 1501-1507.
Tahar, Z., Kadri, E.L., Ngo, T.T., Bouvet, A. and Kaci, A. (2016), "Influence of recycled sand and gravel on the rheological and mechanical characteristic of concrete", *J. Adhes. Sci. Technol.*, **30**(4), 392-411.
Thomas, C., Setién, J., Polanco, J.A., Alaejos, P. and Sánchez, J.M. (2013), "Durability of recycled aggregate concrete", *Constr. Build. Mater.*, **40**, 1054-1065.
TopcuIlker, B. and Boga, A.R. (2010), "Effect of ground granulated blast-furnace slag on corrosion performance of steel embedded in concrete", *Mater. Des.*, **31**(7), 3358-3365.
Tuyan, M., Mardani, A. and Ramyar, K. (2014), "Freeze-thaw resistance, mechanical and transport properties of self-consolidating concrete incorporating coarse recycled concrete aggregate", *Mater. Des.*, **53**, 983-991.
Vejmelkova, E., Pavlikova, M., Keršner, Z., Rovnanikova, P., Ondracek, M. and Sedlmajer, M. (2009), "High performance concrete containing lower slag amount: a complex view of mechanical and durability properties", *Constr. Build. Mater.*, **23**(6), 2237-2245.
Wang, H.Y. and Lin, C.C. (2013), "A study of fresh and engineering properties of self-compacting high slag concrete (SCHSC)", *Constr. Build. Mater.*, **42**, 132-138.
Yahiaoui, W., Kenai, S., Menadi, B. and Kadri E.H. (2017), "Durability of self-compacted concrete containing slag in hot climate", *Adv. Concrete Constr.*, **5**(3), 271-288.
Yaragal, S.C., Teja, D.C. and Shaffi, M. (2016), "Performance studies on concrete with recycled coarse aggregates", *Adv. Concrete Constr.*, **4**(4), 263-281.
Zhao, H., Sun, W., Wu, X. and Gao, B. (2015), "The properties of the self-compacting concrete with fly ash and ground granulated blast furnace slag mineral admixtures", *J. Clean. Prod.*, **95**, 66-74.

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