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Properties of self-compacting concrete prepared with coarse and fine recycled concrete aggregates

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ABSTRACT

In this study, the fresh and hardened properties of self-compacting concrete (SCC) using recycled concrete aggregate as both coarse and fine aggregates were evaluated. Three series of SCC mixtures were prepared with 100% coarse recycled aggregates, and different levels of fine recycled aggregates were used to replace river sand. The cement content was kept constant for all concrete mixtures. The SCC mixtures were prepared with 0, 25, 50, 75 and 100% fine recycled aggregates, the corresponding water-to-binder ratios (W/B) were 0.53 and 0.44 for the SCC mixtures in Series I and II, respectively. The SCC mixtures in Series III were prepared with 100% recycled concrete aggregates (both coarse and fine) but three different W/B ratios of 0.44, 0.40 and 0.35 were used. Different tests covering fresh, hardened and durability properties of these SCC mixtures were executed. The results indicate that the properties of the SCCs made from river sand and crushed fine recycled aggregates showed only slight differences. The feasibility of utilizing fine and coarse recycled aggregates with rejected fly ash and Class F fly ash for self-compacting concrete has been demonstrated.

1. Introduction

The use of self-compacting concrete has gained a wider acceptance in recent years. It not only reduces noise due to a vibration-free environment but also shortens the duration of construction. The term *Self-Compacting Concrete* (SCC) refers to a new type of high performance concrete mixture which flows under its own weight while maintaining sufficient resistance to segregation.

Segregation resistance plays an important role for SCC because poor segregation resistance would cause poor deformability, blockage around congested reinforcement and non-homogeneous properties of the hardened concrete [1]. In order to increase the segregation resistance of SCC, a high powder (i.e. limestone powder, fly ash) content is normally required. Alternatively, a viscosity agent is often employed to ensure a high resistance to segregation [2]. A preliminary study on the utilization of rejected fly ash (r-FA) as a replacement of the viscosity agent in the production of SCC has shown that the incorporation of r-FA in SCC shortened the flow time to reach the desired slump flow, lowered the air content, increased compressive strength and elastic modulus, and improved bleeding and segregation resistances [3].

Recycled aggregates are produced from the re-processing of mineral waste materials, with the largest source being construction and demolition (C&D) waste. The coarse portion of the recycled aggregates has been used as a replacement of the natural aggregates for concrete production. The potential benefits and drawbacks of using recycled aggregates in concrete are well understood and extensively documented [4–10]. In general, the quality of recycled aggregates is inferior to those of natural aggregates. The density of the recycled aggregates is lower than the natural aggregates and the recycled aggregates have a greater water absorption value compared to the natural aggregates. As a result, a proper mix design is required for obtaining the desired qualities for concrete made with recycled aggregates [11,12].

In addition to the coarse recycled aggregates, fine recycled aggregates (<5 mm) can also be used to replace natural fine aggregates in the production of concrete. Khatib [13] reported that when natural fine aggregates in concrete were replaced by 0%, 25%, 50%, 75% and 100% fine recycled aggregates and the free water/cement ratio was kept constant for all the mixes, the 28-day strength of the concrete developed at a slower rate. Furthermore, the concrete mixtures containing fine recycled aggregates had higher shrinkage than the natural aggregates concrete. Evangelista and de Brito [8] indicated that the use of fine recycled concrete aggregates up to 30% replacement ratios would not jeopardize the mechanical properties of concrete.

2. Experimental details

2.1. Materials

Ordinary Portland cement and fly ash (FA) were used as the cementitious materials in the SCC mixtures. ASTM Type I Portland

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Table 1
Chemical component of the material used in the experiment.

	SiO_2 (%)	Fe_2O_3 (%)	Al_2O_3 (%)	TiO_2 (%)	CaO (%)	MgO (%)	SO_3 (%)	K_2O (%)	Na_2O (%)	LOI (%)
f-FA	47.62	7.35	27.4	1.23	8.11	3.55	0.57	0.88	0.87	3.90
r-FA	47.23	8.42	24.54	0.99	8.28	1.62	0.39	–	–	8.06
Cement	19.61	3.32	7.33	–	63.15	2.54	2.13	–	–	2.97

cement, with a fineness of 3520 cm^2/g and density of 3150 kg/m^3 was used. Two fly ashes were used in this study. The first one was a fine fly ash (f-FA) which complied with BS 3892 [14] with most of the particles passing through the 45-μm sieve. The other one was the rejected fly ash (r-FA) with most of the particles >45-μm. Both of fly ashes corresponded to ASTM low-calcium Class F fly ash and were produced as by-products during the generation of electricity from a local coal-fired power plant. The chemical and physical properties of the cement and fly ashes are given in Tables 1 and 2, respectively.

In this study, the coarse and fine recycled aggregate sourced from a local Construction and Demolition (C&D) waste recycling facility was used. The nominal sizes of the coarse recycled aggregates were 20 mm and 10 mm. River sand with a fineness modulus of 2.11 was used as the fine natural aggregates while the recycled aggregates with a particle size of <5 mm was used as fine recycled aggregates. The particle size distributions of all the aggregates used conformed to the requirements of BS 812 [15]. The corresponding physical and mechanical properties of the aggregates are shown in Table 3 and the particle size distribution of fine recycled aggregates and river sand are shown in Table 4.

The chemical admixtures used were a superplasticizer (Grace, ADVA-109) and a viscosity agent (Grace, V -MAR 2) commercially available in Hong Kong.

Table 2
Physical properties of the material used in the experiment.

Material	Fineness (cm^2/g)	Density (kg/m^3)
f-FA	3996	2280
r-FA	1190	2190
Cement	3520	3150

Table 3
Properties of recycled aggregates and river sand.

Material	Nominal size (mm)	Density (kg/m^3)	Water absorption (%)		10% fine values (kN)
			10 min	24 h	
River sand	–	2620	0.36	0.88	–
Recycled aggregate	10	2490	2.84	4.26	126
	20	2570	2.63	3.52	
	<5	2300	6.05	11.86	–

Table 4
Particle size distribution of fine recycled aggregates and river sand.

Size of BS test sieve (mm)	5	2.36	1.18	0.6	0.3	0.15	0.075
	Percentage passing (%)						
River sand	100	96	87	70	26	2	0.1
Fine recycled aggregate	100	85	62	53	30	8.1	3.6

2.2. Mixture proportions

Three series of SCC mixtures with different fine recycled aggregate contents and water-to-binder (W/B) ratios were prepared. In the paper, only the OPC and f-FA are treated as binder, while the r-FA is treated as a filler. r-FA has been demonstrated by the authors to be able to replace the viscosity agent normally required in SCC mixes to control segregation [3]. In all the concrete mixtures, the cement and r-FA contents were kept constant at levels of 340 kg/m^3 and 200 kg/m^3, respectively. The recycled coarse aggregates were used as the only source of coarse aggregates.

In Series I, five SCC mixtures were prepared and a W/B ratio of 0.53 was used for all the concrete mixtures. No f-FA was added. The fine recycled aggregates were used as 0, 25, 50, 75 and 100% by volume replacements of the river sand.

In Series II, five SCC mixtures were prepared with a W/B ratio of 0.44. 70 kg/m^3 of f-FA was added to increase the cementitious materials content. Similarly, the fine recycled aggregates were also used as 0, 25, 50, 75 and 100% by volume replacements of the fine natural aggregates. In Series III mixtures, 100% fine recycled aggregates were used to replace river sand and three W/B ratios of 0.44, 0.40 and 0.35 were employed. The mix proportions of the mixtures in Series I, II and III are summarized in Tables 5 and 6, respectively. The mixture proportions reported in Tables 5 and 6 are based on all the aggregates being in a saturated surface dry condition. The amounts of water added to the mixes were higher due to the high water absorption of the recycled aggregates. The actual added water in the mixtures is shown in Table 7.

2.3. Specimens casting and curing

All the concrete mixtures were mixed for 5 min in a laboratory mixer. Before casting, a variety of tests were conducted on the concrete mixtures to determine their fresh properties including the slump flow, flow time, segregation resistance, blocking ratio and wet density. For each concrete mixture, fifteen 100 × 100 ×

Table 5
Mix proportion of RA-SCC mixtures in Series I.

Mix code	W/C	Recycled fine agg. (%)	Proportions (kg/m^3)							SP ADVA-109 (l/m^3)	Viscosity agent (l/m^3)
			Water	Cement	r-FA	Sand	RF	Recycled agg. coarse			
								10 mm	20 mm		
Control-1		0				695	0				1.0
RF25		25				521	153				1.5
RF50	0.53	50	180	340	200	348	305	560	335	8.5	1.5
RF75		75				174	458				1.5
RF100		100				0	610				1.5

Table 6
Mix proportion of RA-SCC mixtures in Series II and III.

Mix code	W/B	Recycled fine agg. (%)	Proportions (kg/m^3)								SP ADVA-109 (l/m^3)
			Water	Cement	f-FA	r-FA	Sand	RF	Recycled agg. coarse		
									10 mm	20 mm	
Series II											
Control-2		0					662	0			
RCF25		25					497	145			
RCF50	0.44	50	180	340	70	200	331	291	530	320	8.5
RCF75		75					166	436			
RFC100		100					0	581			
Series III											
RF100A	0.44		180	340			0	581			8.5
RF100B	0.40	100	165	340	70	200	0	616	530	320	9.0
RF100C	0.35		145	340			0	662			9.5

Table 7
Actual water content in RA-SCC mixtures.

Series I		Series II		Series III	
Mix code	Actual added water (kg/m^3)	Mix code	Actual added water (kg/m^3)	Mix code	Actual added water (kg/m^3)
Control-1	182	Control-2	182	RCF100A	241
RF25	198	RCF25	197	RCF100B	229
RF50	213	RCF50	212	RCF100C	213
RF75	229	RCF75	226	–	–
RF100	244	RCF100	241	–	–

100 mm cubes were cast for the determination of compressive strength, seventeen 100 × 200 mm cylinders were cast for the determination of splitting tensile strength and the resistance to chloride-ion penetration. Furthermore, three 70 × 70 × 285 mm prisms were cast for measuring the drying shrinkage. After casting, all the specimens were covered with plastic sheets and water-saturated burlaps before being air cured in the laboratory at 20 ± 3 °C for 24 h. The specimens were then demoulded and three cubes were immediately used to determine the 1-day compressive strength of the SCC mixtures. The rest of the specimens were then transferred to a standard water curing tank at 27 °C until the time of testing.

2.4. Test methods

The slump flow test was used to evaluate the free deformability and flowability of the SCC in the absence of any obstruction. A standard slump cone was used for the test and the concrete was poured in the cone without compaction. The slump flow value is represented by the mean diameter (measured in two perpendicular directions) of concrete after lifting the standard slump cone. The measurements were repeated 1 h after the initial mixing (during the 1 h rest period, the concrete mixture was not agitated, but the mixture was remixed for about 1 min using the initial mixing speed before the second slump test was preformed) to evaluate the slump loss properties of the SCC mixtures.

The GTM screen stability test method, developed by the French contractor (GTM) [16] was adopted to assess the segregation resistance of the fresh SCC mixtures. The method consisted of taking 10 l of concrete and allowing the concrete to stand for 15 min in a bucket covered with a lid to prevent evaporation. After that, half of the concrete was poured onto a 5 mm sieve of 350 mm diameter, which sat on a sieve pan on a weighing scale. After 2 min, the mass of mortar which passed through the sieve was measured and expressed as a percentage of the weight of the original sample on the sieve.

The L-box test was performed in accordance with EFNARC standards [16]. This test has been used to assess the flowability and passing ability of concrete. During the test, SCC was allowed to flow upon the release of a trap door from the vertical section to the horizontal section via a few reinforcement bars of a L-shape box. The height of the concrete at the end of the horizontal section was compared to the height of concrete remaining in the vertical section.

The compressive and splitting tensile strengths of concrete were measured using a Denison compression machine with a loading capacity of 3000 kN according to BS 1881 Part 116 and 117, respectively. The compressive strength test was carried out on the concrete specimens at the ages of 1, 4, 7, 28 and 90 days while the splitting tensile strength test was carried out on the concrete specimens at the age of 28 days.

A modified British Method (BS1881, part 5) [17] was used and 70 × 70 × 285 mm concrete specimens were prepared for the drying shrinkage test. After removing the specimens from the curing tank after 28 day of curing, the initial length of each specimen was measured. After the initial reading, the specimens were conveyed to a drying chamber with a temperature of 55 °C and a relative humidity of 95% until further measurements at 1, 4, 7, 28, 56, 90 and 112 days after the initial measurement. Before each measurement was taken on the scheduled day, the specimens were first removed from the drying chamber and conveyed to a cooling chamber for about 4 h in order to cool the specimens to a constant temperature of 25 °C and a relative humidity of 75%. The length of each specimen was then measured within 15 min before delivering the specimens back to the drying chamber for the subsequent drying process. The procedure of drying, cooling and measuring continued until the final length measurement was recorded at 112 days.

The chloride penetrability of concrete was determined at the ages of 28 and 90 days in accordance with ASTM C1202-94 [18] using a 100 mm diameter × 50 mm thick concrete disc obtained from the 100 mm diameter by 200 mm concrete cylinders. The resistance of concrete against chloride ion penetration is represented by the total charge passed in coulombs during a test period of 6 h.

3. Analysis of test results and discussion

3.1. Fresh properties

The test results of slump flow, blocking ratio and wet density of recycled aggregate SCC (RA-SCC) in Series I, II and III are shown in Table 8 and the slump values are plotted in Fig. 1.

It is evident from Table 8 and Fig. 1 that the slump flow diameter increased with an increase in the fine recycled aggregate con-

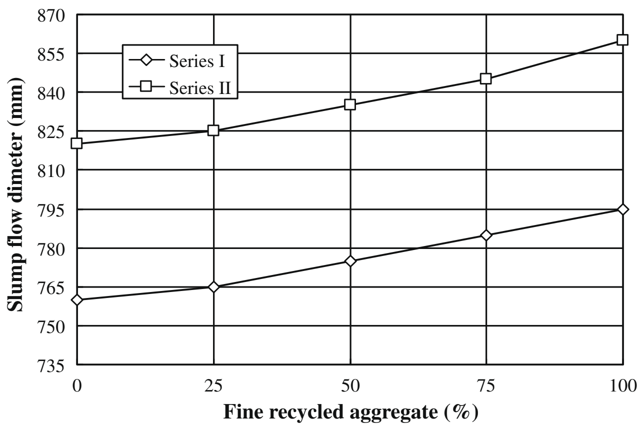

Fig. 1. Effect of fine recycled aggregates on slump flow diameter of RA-SCC mixtures in Series I and II.

tent. This was attributed to the high water absorption capacity of the fine recycled aggregates compared to river sand. As the fine recycled aggregate content increased, more water was added into the concrete mixes initially to compensate for the higher water absorption of the fine recycled aggregate (as the recycled aggregate was used in the air-dried condition) (see Table 7), thus increasing the initial slump flow diameter. In addition, from Table 3, it can be seen that after 10 min of immersion, the water absorption of the fine recycled aggregate only reached 51% of that at 24 h. It was highly probable that part of the additional water could not be taken up by the aggregate particles during the first minutes and hence the excess of water contributed to the increases in the slump flow. On the other hand, the slump loss of the RA-SCC mixtures increased with increasing fine recycled aggregate content due also to the higher water absorption capacity of the fine recycled aggregates which took up the free water quickly.

From Table 8 it can be seen that the blocking ratio varied from 0.85 to 0.93 for the RA-SCC mixtures in Series I. The blocking ratio was between 0.87 and 0.94 for the RA-SCC mixtures in Series II. Furthermore, the blocking ratio of the RA-SCC mixtures in Series III was between 0.87 and 0.94 as the W/B ratio decreased from 0.44 to 0.35. The results indicated that the RA-SCC mixtures prepared in this study achieved adequate passing ability and maintained sufficient resistance to segregation.

From Table 8, it can also be seen that the segregation ratio of the concrete mixtures in both Series I and II increased with an increase in the fine recycled aggregates content. This was attributed to the higher water absorption capacity of the fine recycled aggregate. According to the European specification [16], the segregation ratios of all RA-SCC mixtures in this study ranging from 5 to 15%, were considered satisfactory.

Table 8 shows that the wet density of the RA-SCC mixtures decreased with an increase in the percentage of fine recycled aggregate content. This was mainly attributed to the difference in the densities between the fine recycled aggregates and sand. Furthermore, the wet density slightly increased as the W/B ratio decreased from 0.44 to 0.35 which corresponded to a reduction in the water content from 180 to 145 kg/m^3.

3.2. Hardened properties

The test results of compressive strength of the RA-SCC mixtures in Series I, II and III are summarized in Table 9. Each presented value is the average of three measurements. It is evident in Table 9 that incorporation of 25% and 50% of fine recycled aggregates as a sand replacement did not significantly affect the 28-day compressive strength of the SCC mixtures in Series I. However, at the early ages (1, 4 and 7-day) compressive strength was slightly decreased as the % replacement of sand by the fine recycled aggregates increased from 50 to 100%. This is consistent with Khatib's results on non-SCC concrete prepared with fine recycled aggregate [13]. At the late curing ages (28 and 90-day), the compressive strength of the RA-SCC mixtures in Series I prepared with 75% and 100% fine recycled aggregates was approximately 10% lower than that of the control-1.

The compressive strength of the Series II SCC mixes was different from those in Series I. The compressive strength of Series II SCC mixes was higher than that of Series I SCC mixtures due to reduced W/B ratios of Series II SCC mixtures. Table 9 indicates that the early age (1, 4 and 7-day) compressive strengths of the RA-SCC mixtures were higher than that of the control-2. The increase was more obvious for the 25 and 50% sand replacement mixes. Furthermore, at the later ages (28 and 90 days), Table 9 indicates that the compressive strengths of the RA-SCC mixtures prepared with 25% and 50% fine recycled aggregates were higher than those of the control-2. For those SCC mixtures prepared with 75% and 100% fine recycled aggregates, the 28 and 90-day compressive strengths were close to those of the control-2 except for the 90-day compressive strength of the concrete mixture with 100% fine recycled aggregate. This may be due to the presence of f-FA, and the pozzolanic reaction between $Ca(OH)_2$ in the fine recycled aggregate and the

Table 8
Fresh properties of RA-SCC mixtures in Series I, II and III.

Mix code	Initial slump flow	Slump flow (after 1 h)	Slump loss (%)	Segregation ratio (%)	L-box test		Wet density (kg/m^3)
	Diameter (mm)	Diameter (mm)			Ratio (%)	Time (s)	
Series I							
Control-1	760	740	2.6	8.9	0.85	36.3	2220
RF25	765	735	3.9	9.1	0.87	29.5	2210
RF50	775	730	5.8	9.5	0.90	20.5	2200
RF75	785	725	7.6	10.3	0.91	25.1	2180
RF100	795	715	10.1	11.1	0.93	23.8	2170
Series II							
Control-2	820	800	2.4	10.3	0.87	23	2200
RF25	825	795	3.6	10.4	0.89	20.4	2160
RF50	835	785	6.0	10.6	0.91	20.7	2140
RF75	845	775	8.3	10.3	0.92	14.7	2120
RF100	860	770	10.4	9.9	0.94	13.4	2140
Series III							
RF100A	860	770	10.4	9.9	0.94	13.4	2140
RF100B	810	750	7.4	10.8	0.94	27.0	2180
RF100C	795	735	7.5	10.2	0.87	18.7	2150

Table 9
Compressive strength of RA-SCC mixtures in Series I, II and III.

Mix code	Recycled agg. fine (%)	W/B	Compressive strength (MPa)				
			1-day	4-day	7-day	28-day	90-day
Series I							
Control-1	0		10.3	26.8	32.9	44.3	56.5
RF25	25		11.2	29.0	34.0	44.5	54.7
RF50	50	0.53	8.8	25.3	31.1	43.4	55.7
RF75	75		9.4	26.0	29.7	41.3	50.8
RF100	100		9.8	23.6	29.2	38.7	50.1
Series II							
Control-2	0		11.1	30.3	36.8	53.7	78.9
RF25	25		13.8	38.3	43.9	64.3	82.6
RF50	50	0.44	17.5	38.4	42.1	62.3	81.4
RF75	75		13.8	32.3	40.9	56.3	75.3
RF100	100		15.1	29.2	38.3	53.2	71.7
Series III							
RF100A	100	0.44	15.1	29.2	38.3	53.2	71.7
RF100B	100	0.40	15.6	33.1	44.0	59.1	77.0
RF100C	100	0.35	16.6	39.8	43.8	64.2	81.8

fly ash forming additional C–S–H and enhancing strength. This is consistent with the authors' previous findings that fine recycled aggregates possessed certain self-cementing ability [19]. For the RF100 mix, the lower strength recorded was probably due to the excessive amount of water added to compensate for the water absorption of the recycled fine aggregates.

Table 9 shows the compressive strength of RA-SCC mixtures in Series III prepared by using 100% fine recycled aggregate as the fine aggregate. As expected, the compressive strength increased as the W/B ratio decreased at all the test ages.

The results of the tensile splitting strength of the SCC mixtures in Series I, II and III at 28 days are shown Fig. 2. Each presented value is the average of three measurements. It can be seen that the 28-day tensile splitting strengths of the RA-SCC mixtures in Series I were slightly lower than that of the control-1 mixture. But the tensile splitting strengths of the Series II mixes were higher than that of the control-2, as was seen for compressive strengths.

The test results of the resistance to chloride ion penetration of the RA-SCC mixtures in Series I, II and III are shown in Fig. 3. The presented value is the average of two measurements. It can be seen that the chloride-ion penetrability of the RA-SCC mixtures in Series I can be classified as moderate or low [18]. Contrary to compressive strength, the resistance to chloride ion penetration increased with fine recycled aggregate content. This can likely be attributed the filler effect of the fine recycled aggregate as it was comprised of a higher percentage of small particles (<0.30 mm) than the river sand (see Table 4).

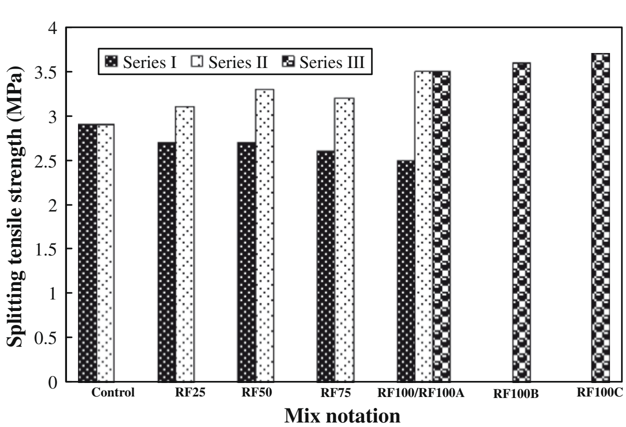

Fig. 2. Splitting tensile strength of RA-SCC in Series I, II, and III at 28 days.

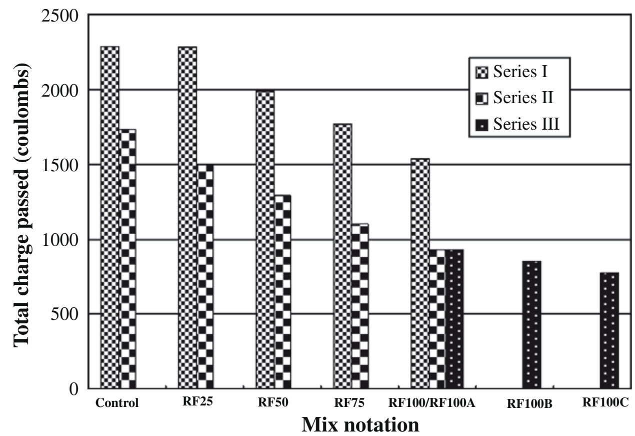

Fig. 3. Total charge passed (coulombs) of RA-SCC mixtures in Series I, II, and III at 28 days.

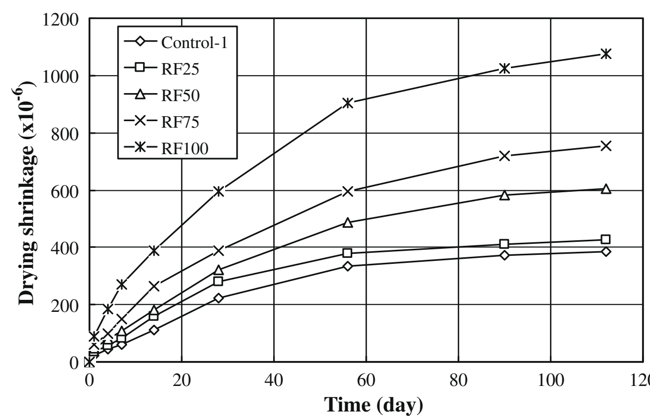

Fig. 4. Drying shrinkage development of RA-SCC mixtures in Series I.

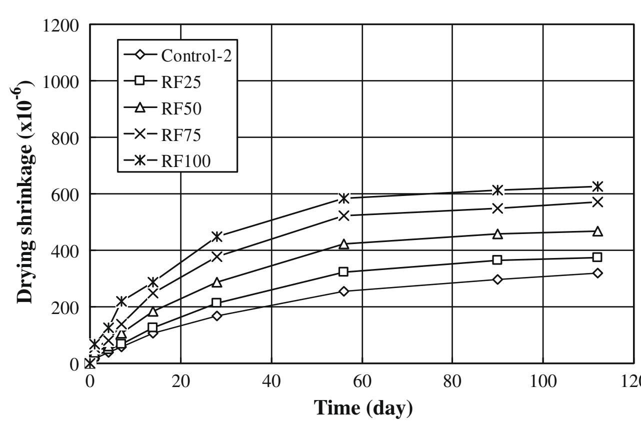

Fig. 5. Drying shrinkage development of RA-SCC mixtures in Series II.

Similarly, it was found that the resistance to chloride ion penetration of the Series II mixes increased as the fine recycled aggregate content increased. As expected, the resistance to chloride ion penetration increased as the W/B ratio decreased from 0.44 to 0.35 (Series III).

The drying shrinkage development curves are shown in Figs. 4–6. Each presented value is the average of three measurements. It can be seen that at all the test ages, the drying shrinkage values

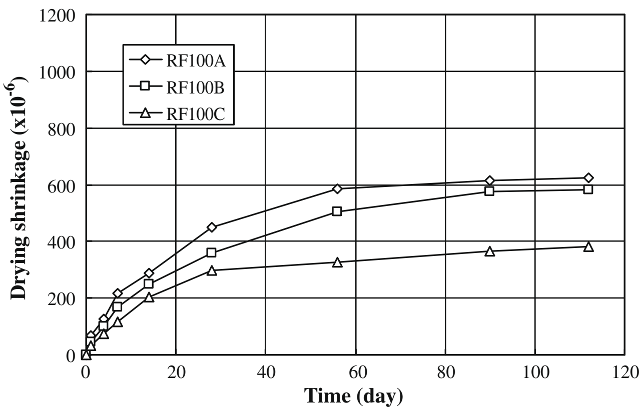

Fig. 6. Drying shrinkage development of RA-SCC mixtures in Series III.

increased with an increase in fine recycled aggregate content. This can be explained by the mortar adhering to the fine recycled aggregates which contributed to an increase in the volume of paste (old + new) as the fine recycled aggregate content increased, thus increasing the drying shrinkage [20]. But the results of Series III mixes show that the drying shrinkage can be controlled by decreasing the W/B ratio [21], although at lower W/B ratios autogenous shrinkage may become significant and should be evaluated for such mixtures.

4. Conclusions

The following conclusions can be drawn from this research:

1. The results of the present investigation show that both coarse and fine recycled aggregates can be used for SCC production.
2. The slump flow and blocking ratio of the RA-SCC mixtures increased with increasing fine recycled aggregate content. The initial slump flows of all the RA-SCC mixtures prepared were at least 760 mm and the blocking ratios varied from 0.85 to 0.94. The addition of f-FA resulted in an increase in slump flow and blocking ratio.
3. The compressive and tensile splitting strengths of the RA-SCC mixtures prepared without the addition of fly ash decreased with increasing fine recycled aggregate content. The maximum compressive and tensile splitting strength were achieved by using 25–50% fine recycled aggregates as a replacement of river sand.
4. The resistance to chloride ion penetration of the RA-SCC mixtures increased with an increase in the fine recycled aggregate content.
5. The drying shrinkage of the RA-SCC mixtures increased with an increase in the fine recycled aggregate content but it can be controlled by the use of a lower W/B ratio.

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