

Characterization of Recycled Coarse Aggregate (RCA) via a Surface Coating Method

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Abstract: Recycled coarse aggregate (RCA) made from waste concrete is not a suitable structural material as it has high absorption of cement mortar, which adheres on the aggregate surface and on the tiny cracks thereon. Therefore, when using RCA made from waste concrete, much water must be added with the concrete, and slump loss occurs when transporting. Hence, its workability is significantly worse than that of other materials. In this study, surface of RCA was coated with water-soluble polycarboxylate (PC) dispersant so that its characteristics improved. Each possibility was evaluated: whether its slump loss can be controlled, by measuring its workability based on the elapsed time; and whether it can be used as a structural material, by measuring its strength. Moreover, the carbonation due to cement mortar adhesion was measured through a carbonation test. As a result, RCA coated with PC dispersant was found to be better than crushed coarse aggregate and RCA when the physical properties of the fresh concrete and the mechanical, durability of the hardened concrete were tested.

Keywords: recycled coarse aggregate (RCA), polycarboxylate (PC) dispersant, coated RCA (CRCA), water reduction ratio, workability.

1. Introduction

When deteriorated structures are demolished and rebuilt, construction waste is produced, and some of which is illegally used as landfill materials that cause serious environmental pollution, thus becoming a social problem (Oikonomou 2004; Hendriks et al. 2000). On the other hand, crushed coarse aggregate (CCA) is generally used as a replacement for natural aggregate for environmental reasons and due to the limited or erratic supply of natural aggregate. According to infrastructure's demand, however, the use of recycled coarse aggregate (RCA) as a replacement for natural aggregate and CCA is beneficial to the environment as it decreases the environmental pollution and recycles construction waste (Symonds 1999; Akash et al. 2007). Recently, RCA was recommended for use in pavement construction (sub-base, anti-freeze layer, and sub-grade) and regular construction (as concrete, precast, and backfill) as well as for raising the ground level and for covering with soil. It is rarely used for concrete, however, because its physical characteristics and strength are worse than those of natural aggregate and CCA (Rahal 2007; Park and Sim 2006; FongWinston et al. 2002). In particular it has a higher absorption rate than normal aggregate, needs much more

water for mixing, and has a high slump loss rate depending on the elapsed time. These characteristics of RCA account for its low workability, strength, and durability (Tabsh and Abdelfatah 2009; Katz 2003; Levy Salomon et al. 2004; Eguchi et al. 2007). In this study, to improve the performance of RCA and to reduce its absorption, its surface was coated with polycarboxylate (PC) dispersant. To verify the efficacy of such technique, the slump and air content losses of fresh concrete in this study were evaluated based on the elapsed time. In addition, the water reduction ratios of the mixtures' water contents were analyzed, and the compressive strength, tensile strength, and carbonation of the hardened concrete were evaluated to determine if it can be used as a structural material.

2. The Mechanism of Coated RCA (CRCA)

For the PC-dispersant-coated RCA, early absorption was prevented at mixing, and the water contents needed for mixing was reduced because the PC dispersant dispersed the cement particles (Yamada et al. 2001; Khalil and Word 1980). Moreover, after mixing, the water-soluble dispersant slowly may be controlled the slump loss over time. The mechanism of the PC-dispersant-coated RCA is shown in Fig. 1.

Figure 1 shows the reaction mechanism of CRCA, where (a) is the RCA prior to coating. After coating, a film was formed on RCA's surface, as shown in (b). To make concrete, CRCA was mixed with other materials (cement, water, etc.), as in (c), and RCA's water absorption was restrained by

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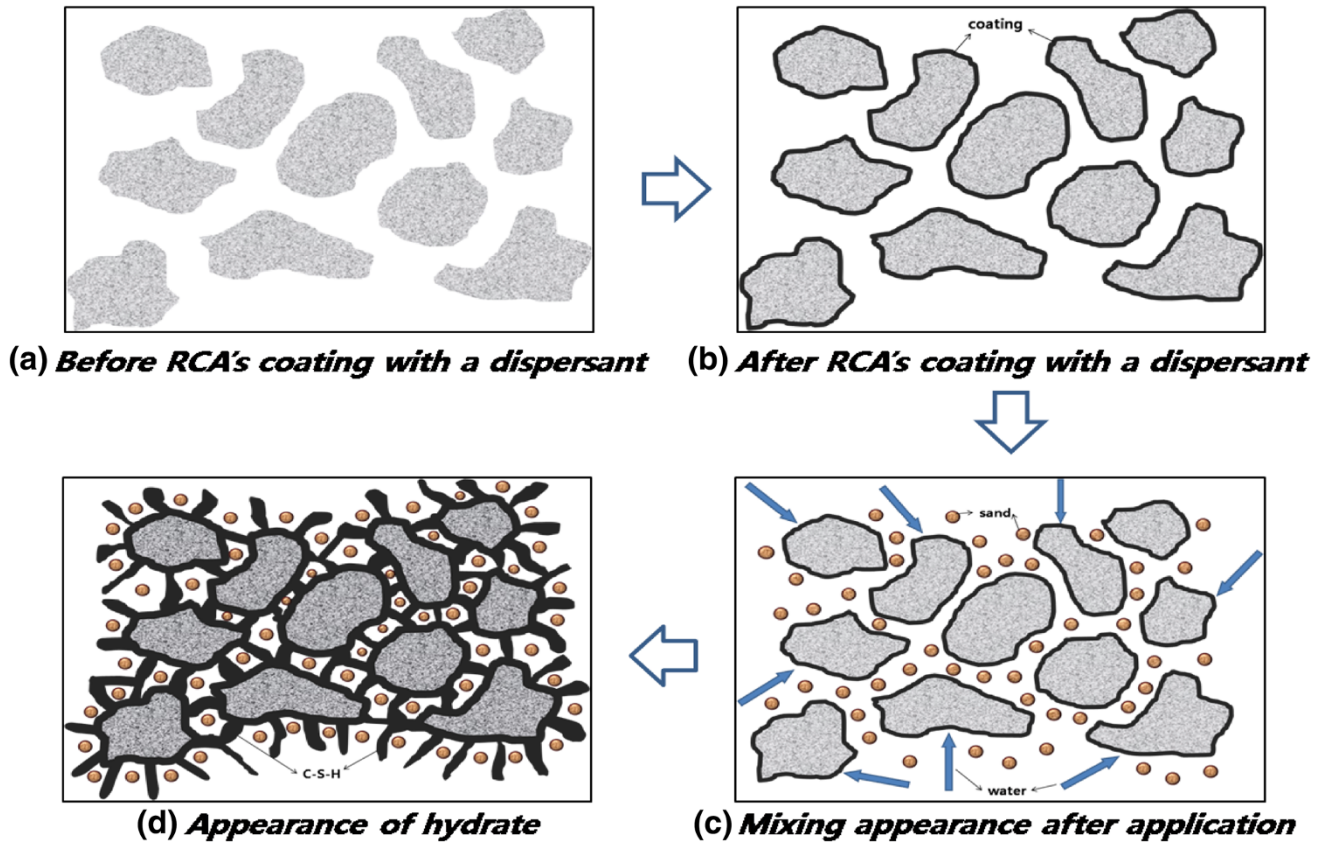


Fig. 1 Reaction mechanism of the coated RCA.

the film that had been formed on the surface of the RCA. Finally, when the dispersant on surface of RCA slowly reacted, C-S-H hydrate was formed around the aggregate, as in (d). Therefore, CRCA may be prevented over-absorption water during mixing so that performance of concrete improved.

3. Experimental

CCA and RCA were used in this study, and their test results are shown in Table 1. It shows in the test results that the density of RCA was lower than that of CCA, and that the absorption rate of RCA was almost triple that of CCA (Mindess 2003).

PC dispersant, which is used to make concrete, was applied to the surface of RCA to form a film. It was placed

inside a rotary drum and was sprayed onto the aggregate at a ratio of 1 % of RCA's wt % so that 0.1–0.3 mm film is formed commonly (Kim et al. 2005; Jiusu et al. 2009). The images of RCA before and after coating with the PC dispersant are shown in Fig. 2 (The right images in the figure are close-up images.). Each image shows that cement mortar was attached on surface of RCA and film was formed.

In the pilot test, the concrete mixtures were found to have the following properties: W/C = 49.9 %; S/a = 48.2 %; target slump = 150 mm; and target strength = 24 MPa. RCA was then replaced with CRCA in five steps (0, 25, 50, 75, and 100 %) and was used in the experimental. The properties of the fresh and hardened RCA and CRCA were investigated according to ASTM tests, and the properties of CRCA were compared with those of CCA. The type and replacement ratio of each mixture and the mix proportion to form CRCA's film are shown in Table 2.

Table 1 CCA's and RCA's properties.

	CCA		RCA
G_{max} (mm)	25	G_{max} (mm)	25
Density (g/cm^3)	2.62	Density (g/cm^3)	2.55
Absorption rate (%)	0.72	Absorption rate (%)	2.35
FM	6.91	FM	6.49
Abrasion rate (%)	25.1	Abrasion rate (%)	36.6
Unit weight (kg/L)	1.564	Ratio of absolute volume	60.1

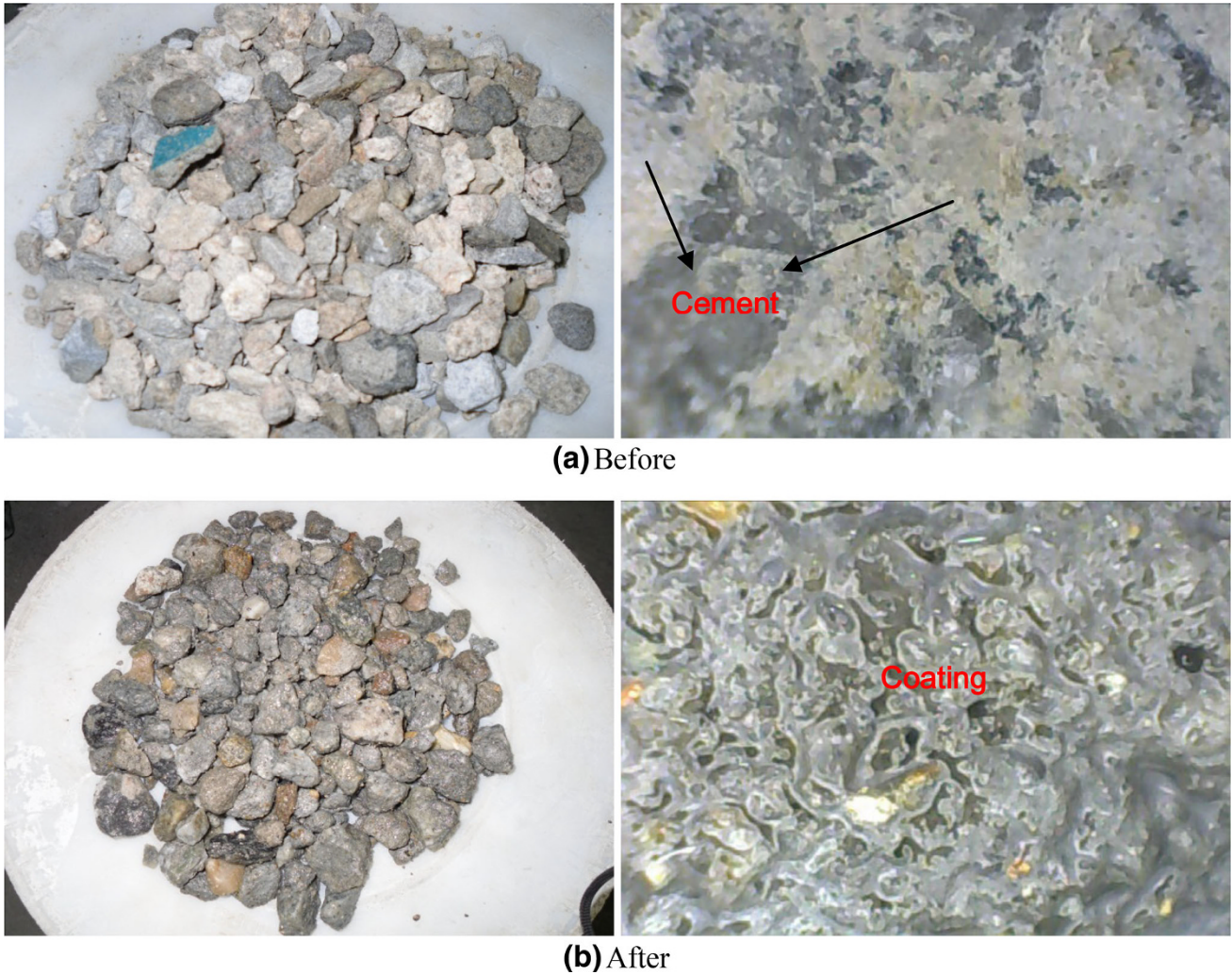


Fig. 2 Before and after RCA coating with PC dispersant.

Table 2 Mix proportion by replacement and CRCA fabrication.

Type	Remarks
W/C = 49.9 %; S/a = 48.2 % (binder: 347 kg/m ³) Superplasticizers = 0.5 % of cement wt%	Control (CCA 100 %) RCA 100 % CRCA (25, 50, 75, and 100 %)
CRCA's film	PC dispersant = ratio of 1 % of RCA's wt%

The slump and air content were measured at half an hour and 1 h to determine if the workability was improved by RCA's surface coating and was within the margin of error (150 ± 25 mm, 4.5 ± 1.5 %). The unit water content was also measured to determine if it satisfied the 150 mm target slump and if the partial of PC dispersant of CRCA was reacted at the initial mixing stage. The unit water content was gained by comparison with the control within target slump $150(\pm 25)$ mm at initial stage.

To evaluate the compressive and tensile-strength properties, three specimens each of RCA, CCA, and CRCA were prepared according to ASTM C 192. $\varnothing 100 \times 200$ -mm specimens were used when the compressive and tensile strengths were measured according to ASTM C 39 and ASTM C 496, respectively, at days 7 and 28, after 20 ± 2 °C water curing. Moreover, the carbonation was

investigated through accelerated carbonation test because concrete has highly alkaline via hydration reaction since mortars were attached to the RCA's surface (Sim and Park 2011). The carbonation velocity coefficients were represented using the following equation:

$$X_c = K \cdot \sqrt{t},$$

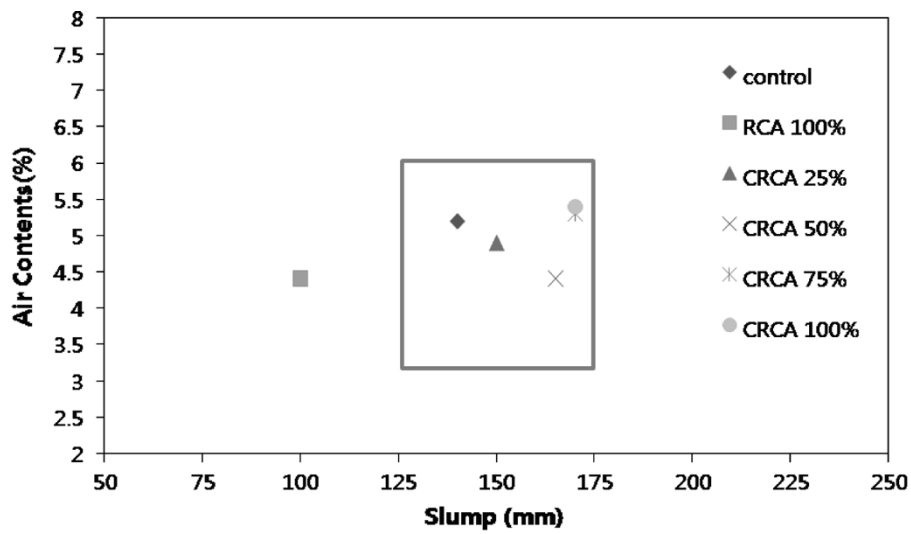
where X_c is the carbonation depth (mm), K is the carbonation velocity coefficient (mm/ $\sqrt{\text{week}}$), and t is the carbonation period (week).

4. Results and Discussion

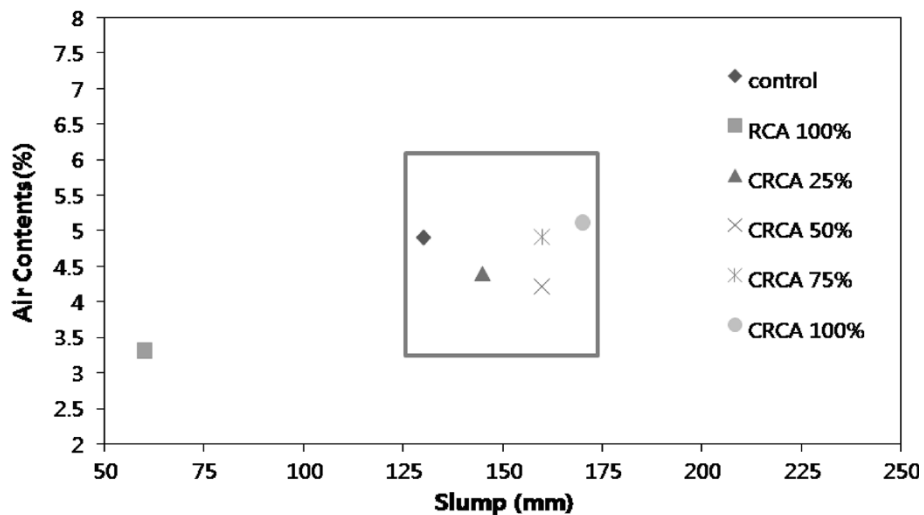
The slump and air content loss depending on the elapsed time are listed in Table 3.

Table 3 Slump and air content losses depending on the elapsed time.

Types	Slump (mm)			Slump loss (mm)		Air content (%)			Air content loss (%)	
	0 min	30 min	60 min	30 min	60 min	0 min	30 min	60 min	30 min	60 min
Control	165	140	130	25	35	5.8	5.2	4.9	0.6	0.9
RCA 100 %	170	100	60	70	110	5.4	4.4	3.3	1.0	2.1
CRCA 25 %	175	150	145	25	30	5.6	4.9	4.4	0.7	1.2
CRCA 50 %	175	165	160	10	15	4.9	4.4	4.2	0.5	0.7
CRCA 75 %	170	170	160	0	10	5.3	5.3	4.9	0	0.4
CRCA 100 %	175	170	170	5	5	5.5	5.4	5.1	0.1	0.4



(a) 30 min elapsed time



(b) 60 min elapsed time

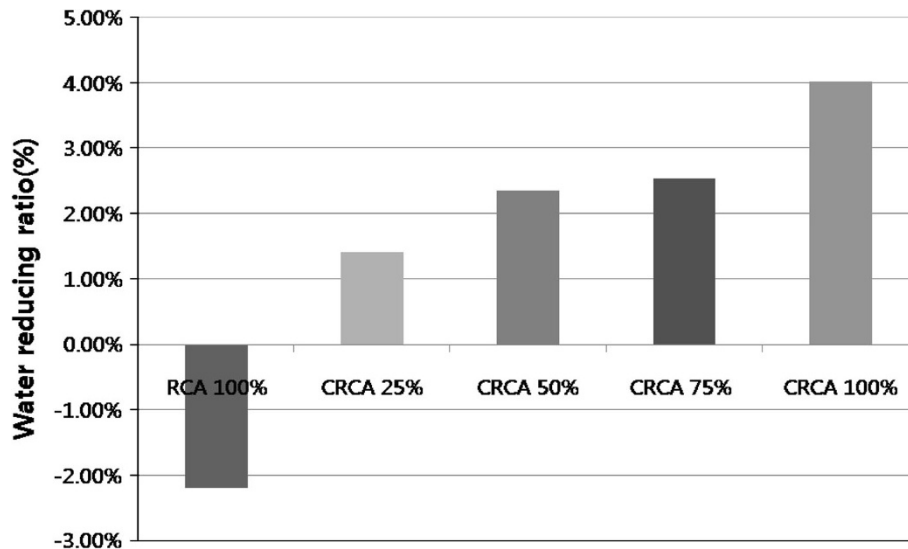
Fig. 3 Relation between slump and air content.

In Table 3, the slump and slump loss of all the mixtures, except those of RCA 100 %, changed within the margin of error (150 ± 25 mm), depending on the elapsed time, and

the greater the percentage of CRCA replacement was, the lesser change in the amount of slump loss. These results think that water absorption of RCA, which has high

Table 4 Difference of unit water content and the water reduction ratio.

Type	Difference of unit water content (kg/m ³)	Water reduction ratio (%)
Control	0	0
RCA 100 %	3.8	-2.20
CRCA 25 %	-2.5	1.41
CRCA 50 %	-4.0	2.35
CRCA 75 %	-4.3	2.54
CRCA 100 %	-6.8	4.03

**Fig. 4** Water reduction ratio compared to that of the control.

absorption, was mitigated by the PC dispersant film, which acted slowly.

In the case of RCA 100 %, however, it showed the largest change in the slump due to the high absorption of RCA. At more than 75 % CRCA replacement, because the dispersant excessively reacted, slight bleeding appeared. All the mixtures' air content loss did not change considerably within the margin of error (4.5 ± 1.5 %), except that of RCA 100 %, because CRCA reduced the absorption of entrained air (Ryu 2002). Also, due to the CRCA replacement, the air content did not change considerably. The relation between slump

and air content is shown in Fig. 3, and all the mixtures were within the allowable range at the 30 and 60 min elapsed times, except for RCA 100 %. The box in Fig. 3 indicates margin of error on slump and air contents, and mixture of RCA 100 % was not included in box.

By comparison with the control, each mixing water contents was gained within target slump 150 mm(± 25 mm) at initial stage. The water reduction ratios, which were converted to unit water contents, are shown in Table 4 and Fig. 4. The difference of unit water content and water reduction ratio showed -6.8 – 3.8 kg/m³, -2.20 – 4.03 %,

Table 5 Compressive and tensile strength values.

Type	Compressive strength (MPa)		Comparison with the control (day 28)	Tensile strength (MPa)		Comparison with the control (day 28)
	Day 7	Day 28		Day 7	Day 28	
Control	19.0	27.1	1.00	1.5	2.3	1.00
RCA 100 %	17.5	25.5	0.94	1.3	1.9	0.83
CRCA 25 %	26.5	32.4	1.20	1.7	2.4	1.04
CRCA 50 %	23.4	30.8	1.14	1.6	2.3	1.00
CRCA 75 %	27.5	31.9	1.18	1.8	2.5	1.09
CRCA 100 %	26.1	31.0	1.14	1.8	2.5	1.09

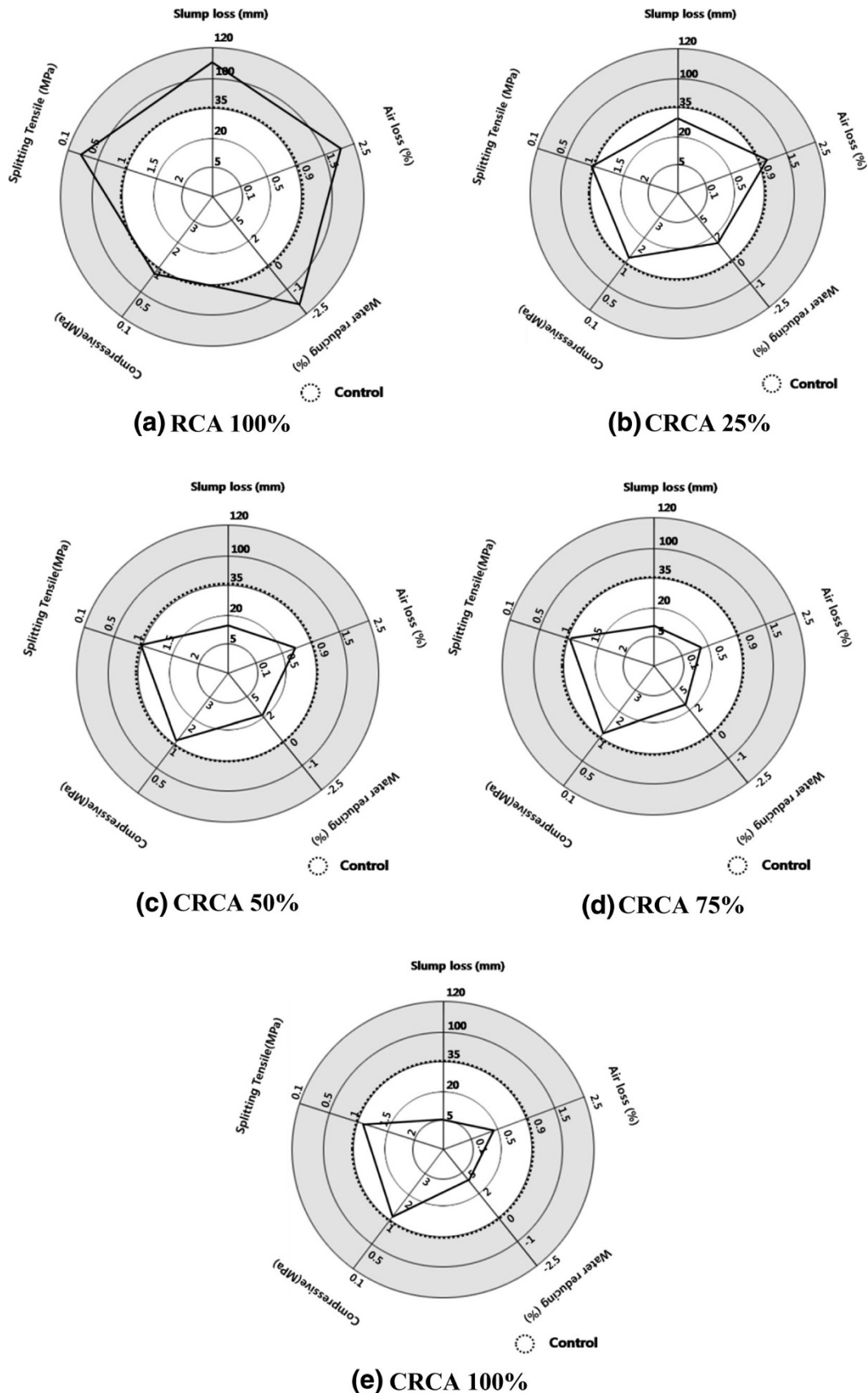


Fig. 5 Analysis of the physical characteristics and compressive and tensile strengths of the mixtures through comparison with those of the control.

respectively. Especially, with increasing of CRCA replacement, the unit water content decreased and the water reduction ratio increased. RCA 100 %'s unit water content

increased, however, due to the high absorption. In the case of CRCA, because the coating that was formed by the water-soluble PC dispersant on RCA's surface was partially

Table 6 Carbonation depths and carbonation velocity coefficients.

Types	Carbonation depth (mm)					Carbonation velocity coefficient (mm/ $\sqrt{\text{week}}$)
	1 week	4 week	8 week	13 week	26 week	
Control	1.02	2.61	4.24	6.24	9.12	1.843
RCA 100 %	1.89	4.02	6.22	10.23	14.48	2.687
CRCA 25 %	1.38	3.03	5.21	7.45	11.14	2.162
CRCA 50 %	1.55	3.18	5.42	4.65	11.55	2.228
CRCA 75 %	1.40	3.01	5.11	7.74	11.41	2.222
CRCA 100 %	1.62	3.41	5.46	9.01	13.06	2.165

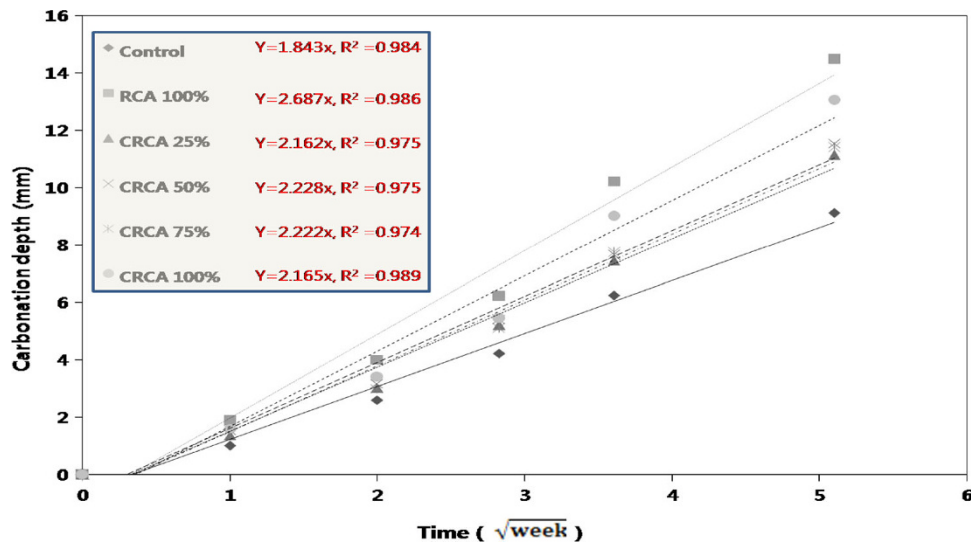


Fig. 6 Carbonation depth with time (week).

dissolved, the water reduction ratio improved at the initial stage (Ramachandran 1995; Yang et al. 2006).

The compressive and tensile strengths of all the mixtures are shown in Table 5. The ratio of compressive and tensile strength by comparison to the control showed 0.94–1.20, 0.83–1.09, respectively. Especially, the mixtures (including CRCA) were stronger than the control on day 7 and had similar compressive strength values on day 28, and tensile strength is similar to control. In the case of RCA 100 %, however, the compressive and tensile strengths were lower than those of the control, as in the previous studies Tabsh and Abdelfatah (2009). As the concrete with CRCA had low water content due to the PC dispersant that was mixed with it, the concrete that was blended with CRCA was stronger than the control.

The physical characteristics and compressive and tensile strengths of all the mixtures were compared with those of the control, as shown in Fig. 5. The control circle indicates values of test results of control mixture on slump and air contents loss, compressive and tensile strength, water reduction. The shapes of mixture with CRCA show within control circle so that it was indicated the degree of satisfaction. On the other hand, that of mixtures with RCA was deviated control circle significantly. Therefore, the values of

all the mixtures, except for RCA 100 %, were found to be similar to or even better than those of the control.

The carbonation depths and carbonation velocity coefficients are shown in Table 6. Based on test results, data were fitted using the above equation, and then the regression analysis results are presented in Fig. 6. The carbonation depth at 26 week and the carbonation velocity coefficient showed 9.12–14.48 mm, 1.843–2.687 mm/ $\sqrt{\text{week}}$. Also, because correlation coefficient of the carbonation velocity coefficient by regression analysis indicates 0.95 over, it shows high reliability. The results show that the control had the highest penetration resistance and that RCA 100 % had the lowest. It was also shown that RCA had lower penetration resistance than normal aggregate, and that the mixtures with CRCA had similar carbonation depths regardless of the replacement.

5. Summary

In this study, the surface of RCA was coated with water-soluble PC dispersant, and whether the concrete performance improved was determined through a test. The conclusions are listed below.

- (1) The slumps of all the mixtures, except that of RCA 100 %, did not significantly change within the margin of error with the elapsed time, and the greater the increase in the CRCA replacement was, the lesser the changes.
- (2) With increasing the CRCA replacement, it showed the lower the unit water content and the higher the water reduction ratio due to the PC dispersant coating of CRCA.
- (3) All the mixtures, except for RCA 100 %, had similar or higher compressive and tensile strengths compared to the control. The carbonation penetration resistance values were also similar.

Therefore, all the test results of the concrete with CRCA were satisfactory compared to the control. That with more than 75 % CRCA replacement, however, showed slight bleeding. Thus, the use of CRCA needs attention, and its supplementary points will be examined in future studies. Also, for large-scale engineering application, further study may be conducted by a spray process during RCA manufacture.

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