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Technical Paper

Strength, shrinkage and creep of concrete including CO_2 treated recycled coarse aggregate

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Abstract: Strength development and long-term behaviour of recycled aggregate concrete (RAC) were investigated. Recycled coarse aggregate (RA) replaced natural coarse aggregate (NA) by 30%, 50%, and 100% by vol. in this study while natural fine aggregate was always used. For the investigation of strength development, 3, 7, 28, 56, 90, and 180 day compressive strengths and 28 day split tensile strength and flexural strength have been determined. Shrinkage and creep behaviours of RAC with 0%, 50%, and 100% RA replacing NA have been studied up to 6 months. The compressive strength of RAC was not affected by 30% replacement, but it was reduced by 50% and 100% replacement. Split tensile strength was not affected significantly while flexural strength was reduced with increasing amount of replacement. Shrinkage strain of RAC with 50% RA was similar to that of natural aggregate concrete, but shrinkage increased with 100% replacement. Specific creep of RAC with 100% RA increased by 38% over that of natural aggregate concrete. The strength of concrete with CO_2 treated RA was lower than that of concrete with RA without CO_2 treatment. Shrinkage of RAC with and without CO_2 treatment was similar, while the creep of RAC with CO_2 treated RA was smaller than that of RAC including RA without CO_2 treatment.

Keywords: recycled coarse aggregate, recycled aggregate concrete, strength, creep, shrinkage, carbonation.

1. Introduction

In South Korea, an economic boom has started in late 1960s about 50 years ago and many building and civil engineering infrastructures have been built starting from the late 1960s. The amount of construction and demolition waste (C&DW) generation is huge and takes about 50% of national waste generation, primarily due to demolition of old structures constructed during the economic boom period. Annual C&DW generation was 68 million tonnes in 2011, where the waste concrete took about 65% followed by waste asphalt concrete (19%), mixed waste (10%), and others [1].

The effective reutilization of waste concrete typically includes use as road subbase material, secondary product such as bricks and blocks as well as recycled aggregates. Although the environmental impact for the reutilization varies depending on the end product, the most effective way to reutilize waste concrete is in the form of recycled aggregate especially from the view point of resource conservation. It should be noted that the use of structural quality recycled aggregate is not wide spread practice yet: Only 1-2% of waste concrete is used as structural grade recycled aggregate in South Korea for example.

There are many different standards that regulate the quality of recycled aggregate in different countries. For example, in Europe, only recycled coarse aggregate is accepted [2]. In South Korea and Japan, both recycled fine aggregate and recycled coarse aggregate are used [3-6]. Despite complicated modern day production technology of recycled aggregate including multiple-stage crushing, it is not possible to completely remove old mortar adhered to original natural aggregates. The adhered mortar makes the mechanical properties of the recycled aggregate inferior to those of natural aggregate, especially density and water absorption [7].

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Two different approaches can be employed to improve the mechanical properties of recycled aggregate: i.e. strengthen the adhered mortar or remove the adhered mortar. One of the strengthening approach of the adhered mortar is accelerated carbonation [8-12].

There have been many studies on the long-term behaviour of recycled aggregate concrete, but very few on the shrinkage and creep behaviour of recycled aggregate concrete using carbonated recycled aggregate [13-20].

This study aims to investigate the following:

(1) Improvement of mechanical properties of recycled coarse aggregate (RA) by accelerated carbonation to lower absorption and to increase density;
(2) Monitor strength development of recycled aggregate concrete (RAC) with RA replacing NA by 30%, 50%, and 100% by vol. compared to that of natural aggregate concrete (NAC); and
(3) Investigate the long-term properties such as shrinkage and creep of RAC with RA replacing NA by 50% and 100% by vol. compared to those of NAC.

2. Materials properties and preparation for long-term test

2.1 Aggregates and accelerated carbonation of recycled coarse aggregate

Crushed natural coarse aggregate (NA) and recycled coarse aggregate (RA) of 25-mm nominal size were used. Crushed natural fine aggregate (FA) was always used. RA was supplied by a local commercial waste concrete treatment company. Figure 1 shows sieve analysis results of NA, RA, and FA [21]. RA did not satisfy the density and absorption requirements by KS F 2573, which is density of 2,500 kg/m^3 or greater (O.D.) and water absorption of 3% or smaller. Since RA did not satisfy the requirements in terms of density and water absorption, it was attempted to improve the quality of RA by accelerated carbonation following KS F 2584 [22] as the carbonation of concrete would result in increased strength and reduced permeability [23]. The carbonation of adhered mortar can be expressed by Eq. (1).

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O \quad (1)$$

RA was carbonated in a carbonation chamber for three days (72 hours). The rate of carbonation depends on the moisture content of the adhered mortar and the relative humidity of the ambient medium [23,24]. To achieve the moisture content ideal for carbonation, the following procedure was adopted in this study.

RA was soaked in water for 10 minutes. Dry cloth was then used to clean up surface moisture of the aggregates. In the next step, RA was exposed to room environmental condition for five hours where the temperature was 21°C typ. and R.H. was 40%-45% typ. Moisture content of RA was measured every one hour during the five-hour period. As a result, the moisture content at entry to the carbonation chamber ranged between 63% and 67%.

During the three-day-long accelerated carbonation, the temperature inside the chamber was maintained at 20 ± 2 °C, R.H. was 60 ± 5%, and carbon dioxide (CO_2) concentration was 5 ± 0.2%, respectively, while the pressure inside the chamber was the same as the atmospheric pressure. The carbonated recycled coarse aggregates thus produced are called CRA in this study.

2.2 Adhered mortar amount of RA

RA mechanical properties are dependent on amount of adhered mortar. Pre-soaking in acid was the method adopted in this study to determine adhered mortar amount [27]. After RA was oven dried for 24 hours, RA was soaked in 20% hydrochloric acid (HCL) at 20°C for 24 hours and then soaked in distilled water. Difference in weights before and after soaking was used to determine adhered mortar amount as shown in Eq. (2):

$$\text{Adhered mortar amount} = (W_1 - W_2)/W_1 \times 100, \% \quad (2)$$

where W_1 is bulk weight of aggregate before soaking (O.D.) and W_2 = bulk weight of aggregate after soaking (O.D.).

Table 1 summarizes the mechanical properties of all aggregates determined in this study in terms of water absorption, density, adhered mortar amount, crushing value, and fineness modulus (F.M.). Figure 2 shows RA with adhered mortar (before soaking) and RA without adhered mortar (after soaking).

2.3 Mix design

Volumetric concrete mix design of 100% natural aggregate concrete (NAC) was for a target strength of 30 MPa. Table 2 shows the mix design and properties of fresh concrete. All aggregates were prepared and mixed in SSD condition. Recycled aggregate concrete (RAC) was produced by substituting 30%, 50%, and 100% of NA with RA by volume. Multiple test cylinders (Φ100 x 200 mm) were made for compressive strength test and split tensile strength test, while prismatic specimens (100 x 100 x 400 mm) were used for flexural strength test.

All cylindrical and prismatic specimens were demolded one day after casting and then cured under water until the test age. Compressive strength was tested at 3, 7, 28, 56, 90, and 180 days. Elastic modulus of concrete and Poisson's Ratio were also determined at 28 days during compressive strength test while three replicate specimens were tested. Split tensile strength and flexural strength were determined only at 28 days while two replicate specimens were tested.

2.4 Preparation for shrinkage measurement

Shrinkage tests were conducted using a prismatic specimen (100 x 100 x 400 mm) for five different concretes: NAC, RAC-50, RAC-100, CRAC-50, and CRAC-100. One day after casting, beam mold was removed and the specimens were brought to inside an environmental chamber where temperature was set at 20°C and R.H. was set at 60%. A thermocouple was used to measure temperature inside the chamber while a portable hygrometer was used to measure R.H. As the specimens were exposed to air, shrinkage measurement started immediately using an embedded strain gauge (60-mm length) and additional two strain gauges (60-mm length) mounted on two side faces of the beam. Teflon sheet was used at bottom surface of the beam to eliminate friction between the steel base plate and the concrete beam. Shrinkage data were taken using a data logger connected to a computer at every 1 hour. The shrinkage measurement continued for 180 days.

2.5 Preparation for creep test

Creep test started 35 days after casting using a 150 x 300 mm cylinder for five different concretes: NAC, RAC-50, RAC-100, CRAC-50, and CRAC-100. The creep test specimens were cured under water for 35 days after which they were placed in the same environmental chamber for the shrinkage measurement until the end of the creep test which continued for 150 days. Two cylinder specimens were placed in a loading frame typ. on a 50,000-lb-(220-kN) capacity load cell, while the applied sustained load was about 30% of 28-day compressive strength. From a companion cylinder stored right next to the creep test specimen, shrinkage data were also retrieved. The creep measurement was made by means of three strain gauges per cylinder: one embedded strain gauge and two strain gauges mounted on two side faces symmetrically (same as shrinkage measurement). The second data logger connected to a computer was used while the data acquisition rate was one data set at every ten minutes.

Table 1 Mechanical properties of aggregates

Aggregate type		Water absorption (%)	Density, SSD (kg/m^3)	Crushing value (%)	Adhered mortar amount (%)	F.M.
Coarse aggregate	NA	0.48	2,690	17.4	--	7.3
	RA	3.84	2,430	21.2	24.2	7.4
	CRA	3.14	2,490	--	--	--
Fine aggregate (FA)		0.78	2,590	--	--	2.56

Table 2 Mix design for 1 m^3 concrete and slump and air content of fresh mix

Index	W/C	S/A	C (kg)	W (kg)	Sand (kg)	NA (kg)	RA (kg)	CRA (kg)	Ad. (kg)	Slump (mm)	Air content (%)
NAC	0.5	0.48	364	182	806	909	--	--	2.73	155	5.0
RAC-30						640	248	--		--	4.4
RAC-50						457	413	--		160	4.9
RAC-100						--	821	--		165	5.1
CRAC-30						640	--	254		150	4.3
CRAC-50						457	--	423		155	5.7
CRAC-100						--	--	847		150	5.6

NOTE: W/C was 0.5 by wt.; S/A was 0.48 by vol.; super plasticizer was used at 2.73 kg; RAC-30 recycled aggregate concrete with 30% replacement of NA by RA; CRAC-50 carbonated recycled aggregate concrete with 50% replacement of NA by RA; natural fine aggregate was used for all mixes.

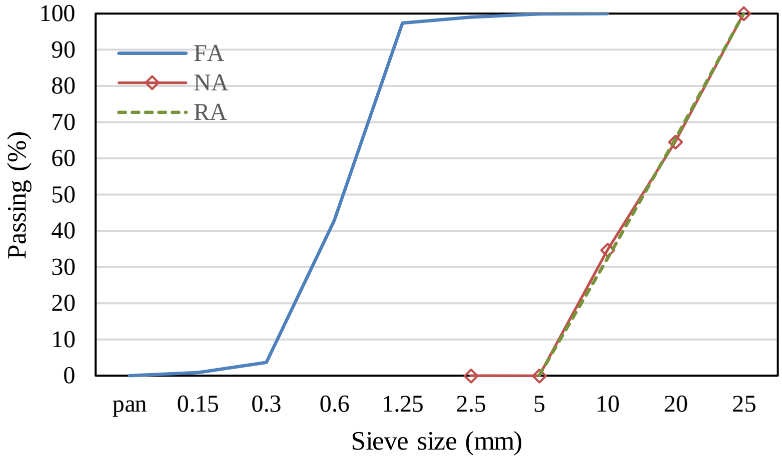

Fig. 1 – Gradation of NA, RA and FA

(a) RA before soaking (b) RA soaked in 20% HCL (c) RA after soaking

Fig. 2 – Method used to determine adhered mortar amount

(a) Shrinkage (b) Creep

Fig. 3 – Shrinkage measurement and creep test in progress

3. Test Results

3.1 Mechanical properties of NA, RA and CRA

In Table 1, the mechanical properties of NA, RA, and CRA are summarized as well of those of fine aggregates. It is seen that the water absorption of RA (3.84%) is significantly larger than that of NA (0.48%), SSD density of RA (2,430 kg/m^3) is 90% of NA (2,690 kg/m^3) while the crushing value of RA (21.2%) is larger than that of NA (17.4%). The adhered mortar amount which plays a major role for the high absorption and low density is 24.2% for RA in

Table 1. It is also shown in Table 1 that, after carbonation treatment, the density of RA increases from 2,430 kg/m^3 (SSD) to 2,490 kg/m^3 (SSD) and the water absorption decreases from 3.84% to 3.14%. Therefore the three-day accelerated carbonation scheme adopted in this study was effective and it can be safely assumed that all or part of the adhered mortar got carbonated which resulted in decreased absorption and increased density.

3.2 Strength, elastic modulus and Poisson's Ratio of hardened concrete

Table 3 and Figures 4 and 5 show the compressive strength development. Compressive strengths of NAC can be compared with those of RAC-30, RAC-50, and RAC-100 in Table 3 and Figs. 4 and 5. Figure 5(a) shows that the compressive strength is similar for NAC and RAC-30, which indicates that the compressive strength is not affected by 30% replacement of NA with RA. Compressive strengths of RAC-50 and RAC-100 are lower than that of NAC. The results indicate that the strength is not influenced with 30% replacement of NA with RA but it is influenced with increasing replacement ratio of RA by 50% and higher. The strength reduction is not large even with 50% and 100% replacement. For example, at 28 days, the compressive strength of NAC is 34.4 MPa while it is 33.1 MPa (96% of NA) and 34.4 MPa (100%), respectively, for RAC-50 and RAC-100. After 180 days, the compressive strength is 39.4 MPa for NAC while it is 37.5 MPa for RAC-50 (95%), and 36.6 MPa for RAC-100 (93%).

Table 3 and Figure 5(a) also show that the strength development after 28 days is similar between NAC and RAC: i.e. the strength increases slowly and steadily even after 28 days up to 180 days as shown. KS F 2573 currently allows maximum 30% RA replacement [3]. Test results confirm that current 30% limit is valid. It is noted that the strengths of RAC-50 and RAC-100 are not much lower than that of NAC. There is a possibility that the current maximum replacement limit of 30% can be raised in case of good quality RA that meets the requirements of KS F 2573.

Figure 5(b) compares the strength development of NAC and CRAC-30, CRAC-50, and CRAC-100. Again the compressive strength of CRAC-30 with 30% replacement of NA with CRA is similar to that of NAC. However, the compressive strengths of CRAC-50 and CRAC-100 are significantly lower than that of NAC at all test ages. Test results suggest that, although the compressive strength is not affected by 30% replacement of CRA, it is reduced by replacement of CRA by 50% or higher. It must be noted in Table 3 that the compressive strengths of CRAC-50 and CRAC-100 are lower than those of RAC-50 and RAC-100, respectively, at all test ages. This unexpected results need explanation because, after accelerated carbonation, the mechanical properties of CRA such as density and absorption improved over that of RA. At present authors do not have a clear explanation to this phenomenon. A hypothesis is suggested that, with three-day accelerated carbonation scheme adopted in this study, only the part of adhered mortar gets carbonated, which may result in poor bond with new cement paste at surface of carbonated adhered mortar.

Current test results agree well with that in the existing literature [8-20]. Andal et al. [18] tested strength and shrinkage of concrete using 20-mm recycled coarse aggregates of preserved quality and commercial quality (density = 2,310-2,320 kg/m^3, absorption = 4.88-5.32%, w/c = 0.45). They have suggested that the use of 100% RA resulted in some reduction in the strength, but the use of 30% RA as partial replacement of coarse aggregate produced compressive strength similar to that of concrete with 100% virgin coarse aggregate. Doming et al. [16] used 20-mm nominal size RA which replaced NA at 20%, 50%, and 100% (density = 2,460 kg/m^3, absorption = 5.19-6.08%, w/c = 0.5). They have observed that when the effective w/c was maintained constant, the compressive strength was the same so the substitution of NA by RA did not have a significant effect. Geng et al. [14] used 25-mm nominal size RA which replaced NA by 100% (density = 2,713 kg/m^3, absorption = 5.07%, w/c = 0.45). They have observed some reduction of compressive strength from 100% RA concrete than NA concrete, but the reduction was less than 10%.

Figure 6 shows the tensile strength test results in terms of both split tensile strength (black bar) and flexural strength (white bar) at 28 days. The split tensile strength (f_{sp}) test data show that the split tensile strength is not much affected by replacement of NA by RA (or CRA) with exception of RAC-100. On the other hand, the flexural strength (f_r) tends to decrease with increasing replacement ratio of NA with RA (or CRA). However, the flexural strengths are above the flexural strength predicted by the KCI Structural Concrete Design Code [28]. It can be concluded that the split tensile strength is not significantly affected by replacing NA with RA up to 100%. The flexural strength is negatively affected with increasing replacement ratio of NA with RA, but it still satisfies the code required flexural strength.

Table 3 and Figure 7 show elastic modulus measured at 28 days. The 30% replacement of NA by RA (or CRA) does not influence the elastic modulus. For 50% and 100% RA replacement, the elastic modulus reduces a little but are at least 90% that of NAC and are within 10% margin from the predicted value by KCI Structural Concrete Design Code [28]. It needs to be noted that due to relatively soft adhered mortar, the elastic modulus of RA is typically lower than that of NA which in turn negatively affect the elastic modulus of RAC. Such negative effect is not clearly shown in Table 3 and Fig. 7. Table 3 also shows Poisson's Ratio for NAC, RAC, and CRAC. Despite some scatter in test data, the Poisson's Ratios range between 0.18 and 0.22 and there is no clear indication that the Poisson's Ratio is influenced by replacement of NA by RA even up to 100% replacement.

3.3 Shrinkage of recycled aggregate concrete

Figure 8 shows temperature and R.H. in the environmental chamber during the test period. It can be seen that the temperature is relatively constant at 19.5°C and varies between 19°C and 21°C. R.H. ranges between 48% and 85% in the chamber reflecting seasonal variation of outside weather with a mean of 59.7%.

Figure 9 shows measured shrinkage strain versus time. Shrinkage strains show steady and fast increase during the first two weeks followed by steady increase during the next three months. After about 3-1/2 months, the shrinkage strain development somewhat levels out (or it still keeps increasing but at a much lower rate). Therefore, in Table 4, the shrinkage strain values are summarized at each time mark, i.e. after 2 weeks, 3-12/ months, and 6 months (180 days).

Table 3 – Summary of strength, elastic modulus and Poisson's Ratio

Index	Compressive strength, f_{cu} (MPa)						Tensile strength (MPa)		Elastic Modulus (GPa)	Poisson's Ratio
	f_3	f_7	f_{28}	f_{56}	f_{90}	f_{180}	f_{sp}	f_r		
NAC										
mean	22.4	25.6	34.4	35.6	37.9	39.4	2.56	6.10	26.1	0.19
min.	21.9	25.6	33.2	35.2	37.6	39.1	2.55	5.81	25.9	0.18
max.	22.8	25.7	36.9	36.3	38.8	39.5	2.57	6.39	26.2	0.20
RAC-30										
mean	25.2	28.8	37.2	37.9	37.5	39.6	2.62	6.00	28.1	0.20
min.	25.2	27.5	36.3	36.9	34.7	38.0	2.49	5.82	26.2	0.18
max.	25.3	29.8	37.8	38.8	39.9	42.6	2.75	6.18	29.9	0.22
RAC-50										
mean	21.0	25.1	33.1	34.2	35.0	37.5	2.67	5.67	23.6	0.21
min.	20.9	23.4	31.9	33.9	33.0	37.1	2.66	5.42	21.5	0.18
max.	21.2	26.2	34.3	34.4	36.0	37.8	2.68	5.92	25.9	0.24
RAC-100										
mean	22.1	24.5	34.4	33.2	35.0	36.6	2.24	5.25	25.2	0.20
min.	21.7	22.8	33.8	32.5	34.0	33.1	1.85	5.12	24.5	0.17
max.	22.7	26.0	34.7	34.1	37.2	40.3	2.63	5.38	26.2	0.22
CRAC-30										
mean	23.1	27.5	33.6	36.1	37.8	41.0	2.71	5.59	25.7	0.22
min.	22.6	26.0	32.6	35.2	36.1	40.7	2.20	5.50	24.6	0.18
max.	23.7	28.5	34.3	36.9	39.9	41.3	3.22	5.69	27.1	0.27
CRAC-50										
mean	15.5	19.5	27.0	28.0	28.5	32.2	2.48	5.38	25.4	0.20
min.	15.2	18.3	24.6	26.8	26.42	31.0	2.43	5.18	23.7	0.19
max.	15.7	21.3	29.5	29.6	30.34	33.3	2.54	5.57	26.5	0.23
CRAC-100										
mean	17.6	19.0	27.5	30.3	27.4	30.3	2.73	5.16	23.8	0.18
min.	16.2	18.0	24.4	29.6	24.4	29.2	2.64	5.14	23.4	0.17
max.	19.5	20.7	30.6	31.0	32.8	32.8	2.82	5.18	24.0	0.20

NOTE: Compressive strength is average of three test; tensile strength is average of two tests; elastic modulus and Poisson's Ratio are taken at 28 days.

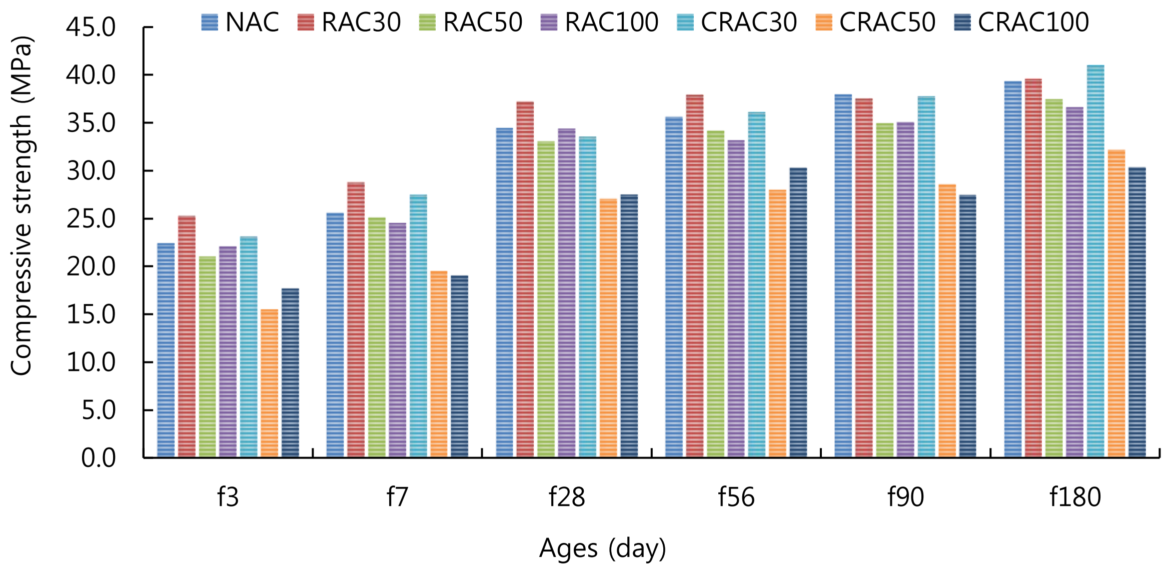

Fig. 4 – Compressive strength test results by age

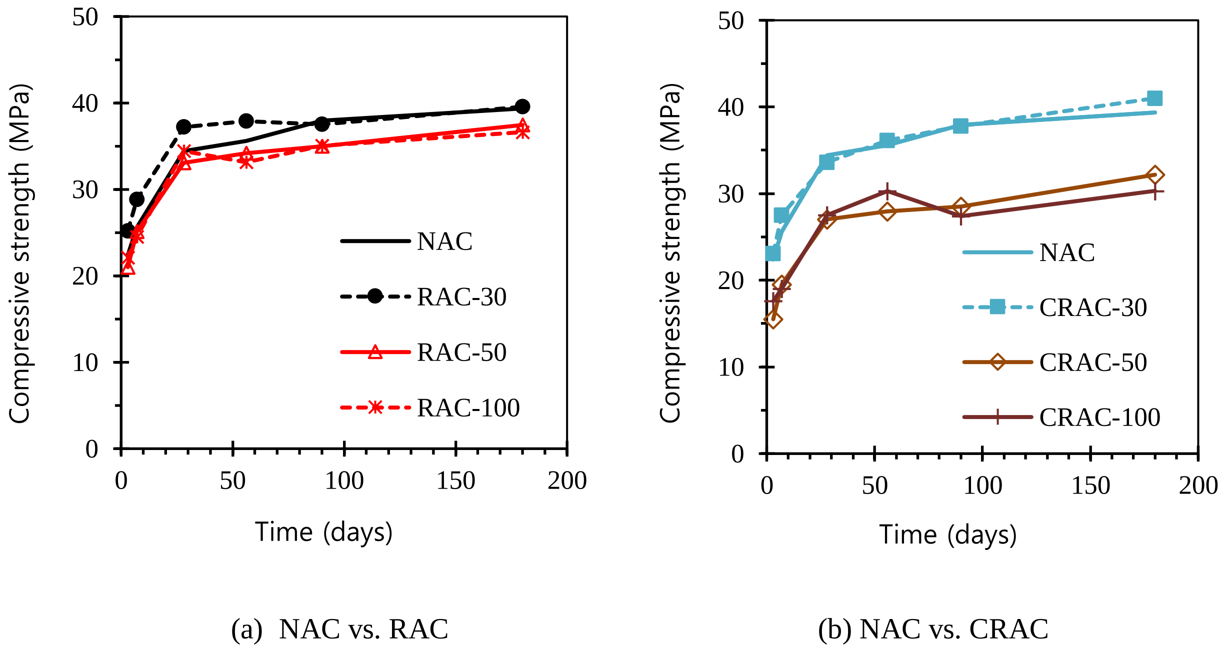

Fig. 5 – Compressive strength development of NAC, RAC and CRAC

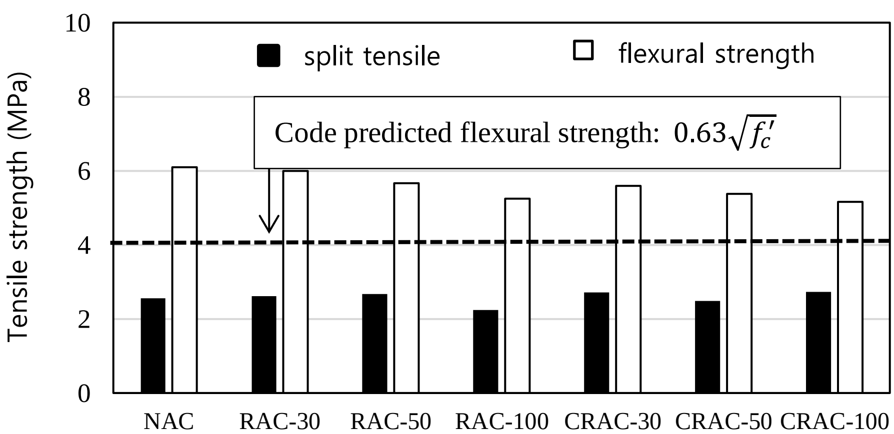

Fig. 6 – Tensile strength at 28 days

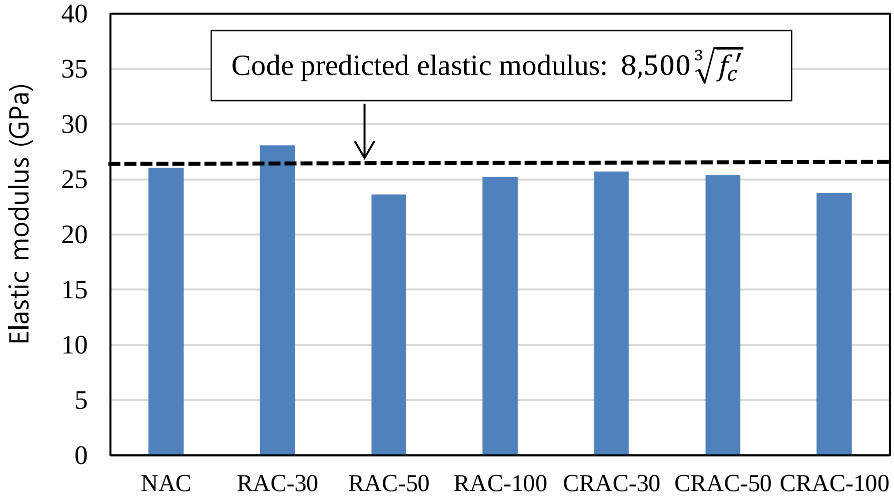

Fig. 7 – Elastic modulus at 28 days

In Table 4, in case of NAC, the shrinkage strain is 206 μm/m after 2 weeks, 690 μm/m after 3-1/2 months, and 712 μm/m after 6 months. It is seen that about 29% of the maximum shrinkage developed during the first two weeks and about 97% of the maximum shrinkage (recorded in 6-months period) developed during the first 3-1/2 months.

Table 4 also shows the shrinkage strains of RAC and CRAC normalized by that of NAC. In Table 4 and Figure 9, the shrinkage of NAC, RAC-50, and CRAC-50 is almost the same (84%-103% of NAC). The shrinkage of RAC-100 and CRAC-100 is larger than that of NAC at all ages (103%-114% of NAC). It can be suggested that the shrinkage of 50% recycled coarse aggregate concrete is the same as that of NAC and the shrinkage of 100% recycled coarse aggregate concrete is larger than that of natural aggregate concrete. In addition, there are no differences in the shrinkage behavior between RAC and CRAC for all replacement ratios tested.

Manzi et al. [19] reported shrinkage strain of about 860 μm/m at 180 days from RAC with 63.5% RA (density 2,250-2,430 kg/m^3, w/c = 0.48, absorption = not disclosed) and 650-680 μm/m at 180 days from RAC with 36.5% RA. The shrinkage strains reported by Manzi et al. are comparable to those measured in this study. Other researchers reported larger shrinkage strains. Andal et al. [18] reported 50% more shrinkage from 100% replacement of RA (density = 2,310-2,320 kg/m^3, absorption = 4.88-5.32%, w/c = 0.45) after 180 days. Domingo et al. [16] reported about 20% increased shrinkage from RAC with 50% RA replacement and about 70% more shrinkage with 100% RA replacement after 180 days (density = 2,460 kg/m^3, absorption = 5.19-6.08%, w/c = 0.5). The reason for the relatively small amount of shrinkage strains compared to that of NAC determined from this study can be relatively good quality RA with low amount of water absorption (absorption = 3.84%, 4.88-5.32%, and 5.19-6.08% for RA used in this study, by Andal et al., by Domingo et al., respectively). Although the effective w/c can be maintained during batching, concrete using RA with higher absorption capacity will lead to more porous concrete, which can be more susceptible for moisture loss inducing increased drying shrinkage.

Figure 10 shows the shrinkage strains for NAC, RAC-50, and RAC-100 predicted by ACI 209 Technical Committee report [29]. Shrinkage strain-time curves of NAC and RAC-50 predicted by ACI 209 are in good agreement with the current test data especially after 180 days. Measured shrinkage of RAC-100 in this study is higher than the ACI 209 predicted value, while the difference is about 15%.

3.4 Creep of recycled aggregate concrete

Creep test began 35 days after casting and continued for 150 days. Creep test specimens were cured under water right after demolding until the test day (t = 35 days). Sustained load that corresponds to about 30% of the 28-day compressive strength (See Table 3) was applied at 35 days and the same sustained load was maintained for the duration of the creep test. A total of five different concretes was tested: NAC, RAC-50, RAC-100, CRAC-50, and CRAC-100. Since two creep specimens were tested using one loading frame, RAC-50 and RAC-100 were tested using the same loading frame and hence were subjected to the same sustained load. CRAC-50 and CRAC-100 were also tested using the same loading frame. NAC was tested while the overall test procedure followed ASTM C512 recommendations [30].

Table 4 – Shrinkage strain vs. time (unit: μm/m)

Index	Time after shrinkage measurement			Shrinkage normalized by NAC at time of		
	2 weeks	3-1/2 months	6 months	2 weeks	3-1/2 months	6 months
NAC	206	690	712	1.0	1.0	1.0
RAC-50	175	697	725	0.85	1.01	1.02
RAC-100	220	747	803	1.07	1.08	1.13
CRAC-50	173	706	731	0.84	1.02	1.03
CRAC-100	213	746	809	1.03	1.08	1.14

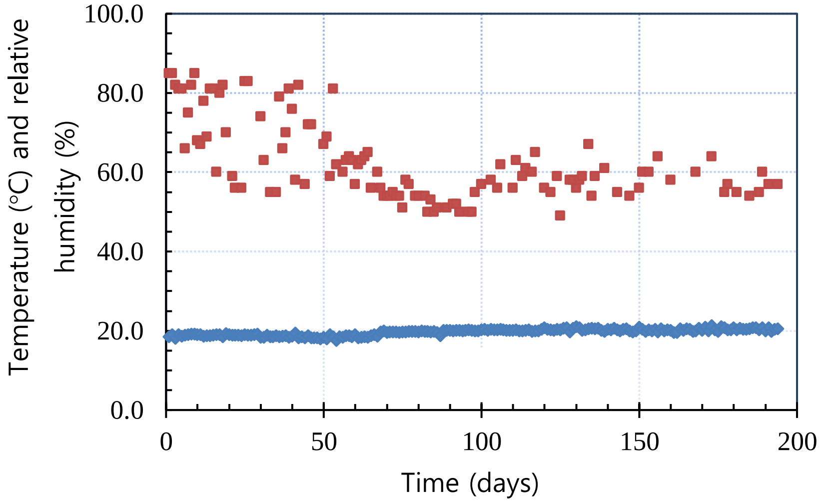

Fig. 8 – Temperature and R.H. in environmental chamber

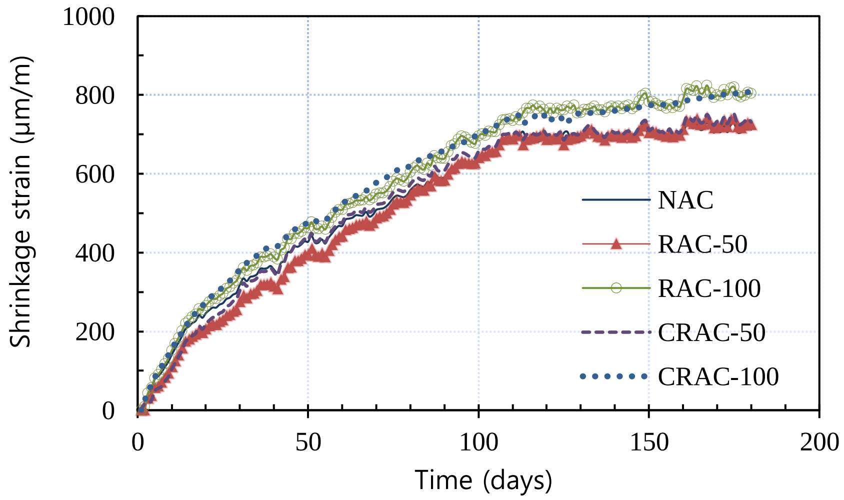

Fig. 9 – Shrinkage vs. time

Table 5 summarizes the creep test results. Figure 11 shows the total strain developed in all creep test specimens that include short-term strain (elastic strain) at t = 35 days and long-term strain that consists of shrinkge strain and creep strain. Both elastic strain and srinkage strain were deducted from the total strain to determine the net creep strains, and the results are shown in Fig. 12. It needs to be noted that the sustained load level each creep test specimen is subjected to is different, and therefore the creep strains shown in Fig. 12 need to be normalized in terms of unit sustained stress (i.e. 1 MPa). The results are shown as specific creep in Fig. 13. In Table 5 and Figure 13, it is seen that NAC experiences the smallest specific creep of 81 μm/m/MPa after 150 days. The largest specific creep is determined from RAC-100 that is 112 μm/m/MPa (138% of NAC) followed by RAC-50 with 101 μm/m/MPa (125% of NAC). The creep test results show that the creep of RAC is significantly larger than that of NAC.

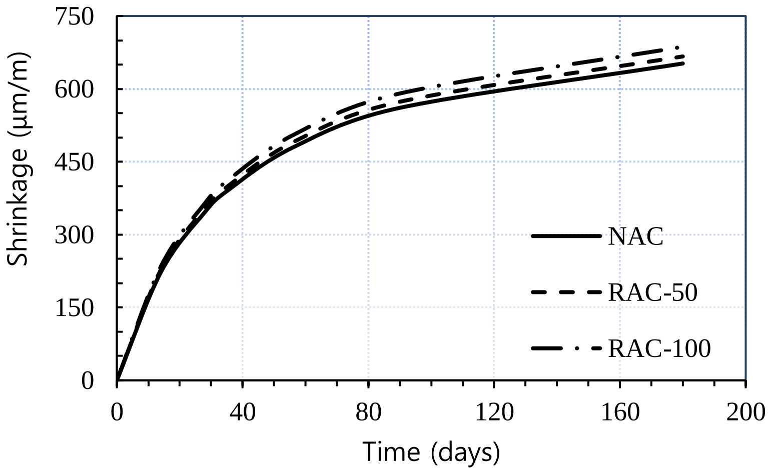

Fig. 10 – Shrinkage prediction model by ACI 209 [29]

Current test data match well with those available in the literature. Manzi et al. [19] showed that specific creep of RAC with 63.5% RA (density 2,250-2,430 kg/m^3, w/c = 0.48) substitution was 90 μm/m and 90-95 μm/m for RAC with 36.5% RA substitution after 150 days. Domingo et al. [16] reported that the specific creep of RAC with 50% RA (density = 2,460 kg/m^3, absorption = 5.19-6.08%, w/c = 0.5, sustained loading about 30% of compressive strength started at 28 days) substitution increased over that of NAC by 29% and increased for RAC with 100% RA substitution by 32% over that of NAC. In addition, Rye et al. [15] after systematic analysis of existing data matrix available in literature has concluded that the creep of concrete increases with a decreasing rate with increasing RA, giving an average increase of 32% at 100% RA content. The specific creep of CRAC is smaller than that of RAC: i.e. it is 96 μm/m/MPa for CRAC-50 (119% of NAC). Also specific creep of 91 μm/m/MPa is determined from CRAC-100 that is 112% of NAC. It may needs to be noted that the specific creep of CRAC-100 is smaller than CRAC-50 after 150 days, which is an unexpected test result. In this study the duration of creep test is only 150 days. In the longer term, the difference between the two creep test data may become smaller in Fig. 13.

Creep coefficient (Φ) is shown in Table 5 and Fig. 14 for all creep test specimens which ranges between 1.97 for NAC and 2.76 for RAC-100. Therefore the creep coefficient of RAC-100 is as large as 140% of NAC. In case of RAC-50, the creep coefficient is 136% of NAC. The creep coefficient of CRAC-50 and CRAC-100 is 115% and 120% that of NAC, respectively. The Φ value is smallest for NAC as expected followed by CRAC-50, CRAC-100, RAC-50, and RAC-100. Again the current test data match well with those published. Geng et al. [14] reported that the creep coefficient ratio (Φ/Φ_{NAC}) is about 1.3 for RAC with w/c = 0.5 including 100% RA (RA density = 2,713 kg/m^3, absorption = 5.07%). Figure 15 shows the creep coefficient predicted by ACI 209 Technical Committee report for NAC, RAC-50, and RAC-100 [29]. Creep coefficient-vs.-time curves predicted by ACI 209 are lower than the current test data shown in Fig. 14. The difference is about 30% for NAC and it is much larger for RAC-50 and RAC-100. The prediction of creep strains depends on many influencing factors such as time of loading, temperature, R.H., strength as well as some fresh concrete properties. Especially the large differences between the ACI predicted values and the current test data means that the ACI 209 formula developed exclusively for NAC is not applicable for RAC.

Table 5 – Creep test results 150 days after sustained load application

Index	NAC	RAC-50	RAC-100	CRAC-50	CRAC-100
Total strain (μm/m)	1,575	1,601	1,754	1,358	1,347
Shrinkage (μm/m)	321	262	292	303	351
Elastic strain (μm/m)	423	364	389	322	297
Creep strain (μm/m)	831	976	1,074	733	699
Specific creep (μm/m/MPa)	81	101	112	96	91
Creep coefficient	1.97	2.68	2.76	2.27	2.36
Creep coefficient Φ/Φ_{NAC}	1.0	1.36	1.40	1.15	1.20

NOTE: Applied stress is 10.3 MPa for NAC; 9.63 MPa for RAC-50 and RAC-100; and 7.66 MPa for CRAC-50 and CRAC-100.

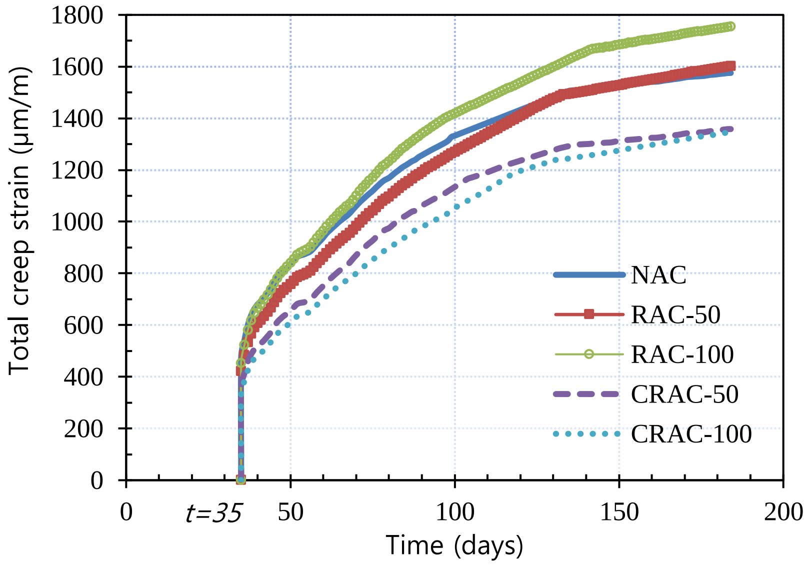

Fig. 11 – Total strain vs. time

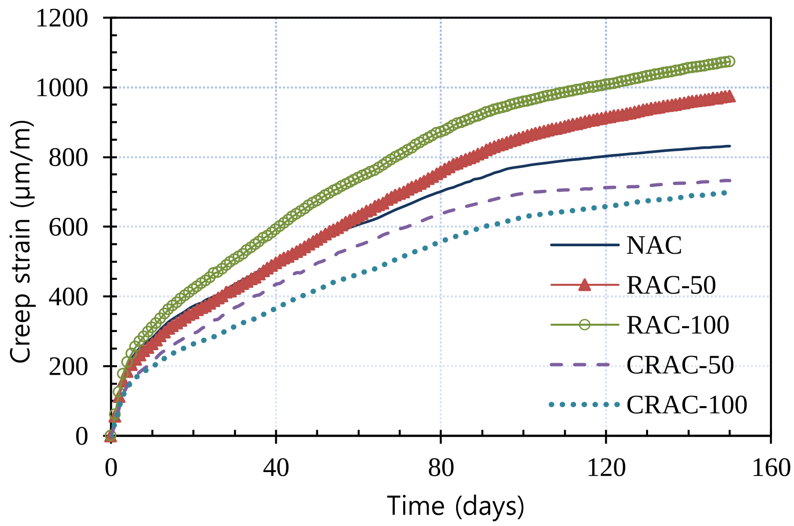

Fig. 12 – Creep vs. time after loading

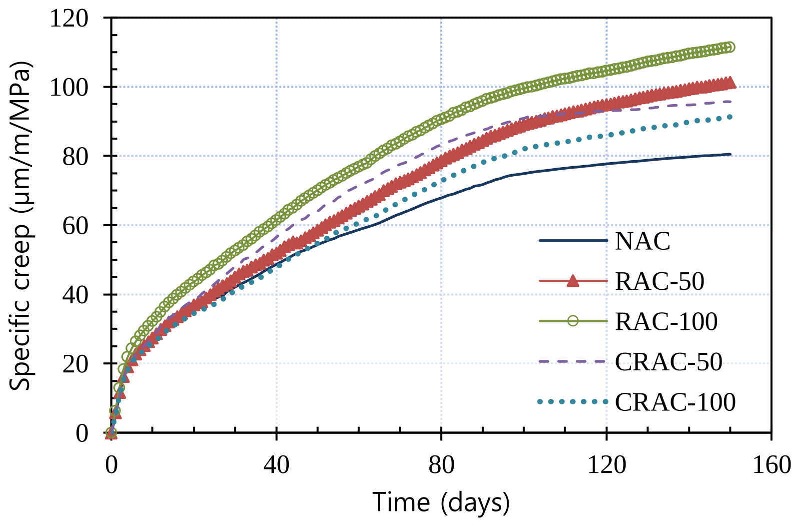

Fig. 13 – Specific creep vs. time after loading

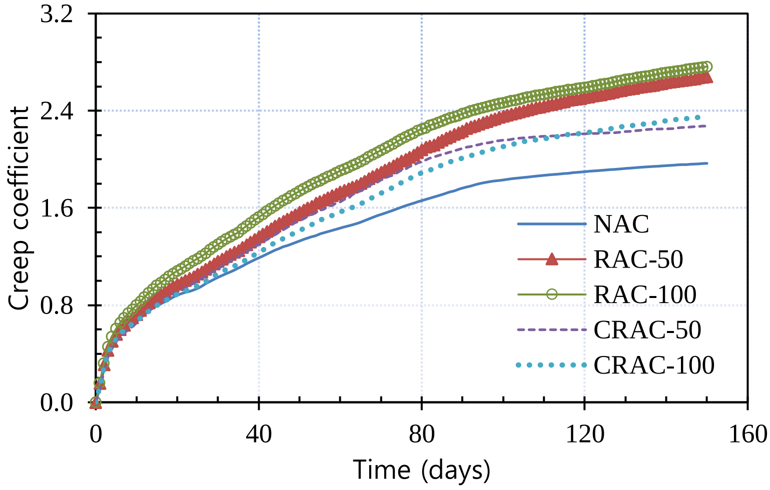

Fig. 14 – Creep coefficients vs. time after loading

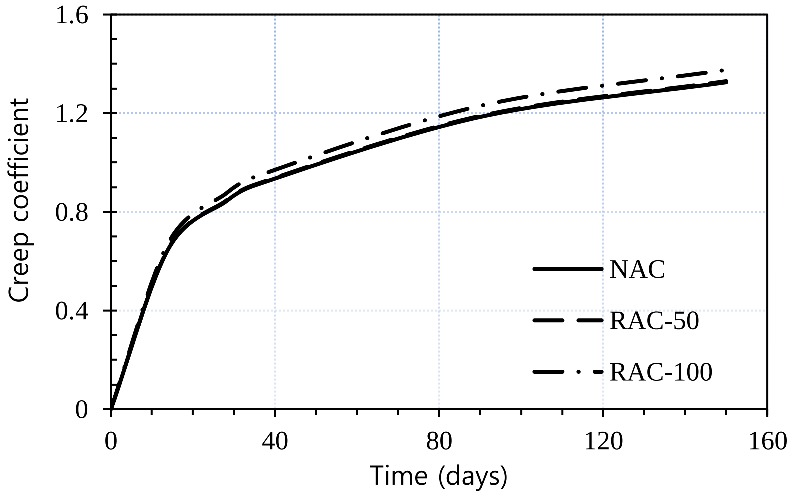

Fig. 15 – Creep coefficient prediction model by ACI 209 [29]

4. Conclusions

Strength development, shrinkage, and creep of RAC was investigated. RA replaced NA by 30%, 50%, and 100% by vol. For the investigation of strength development, 3, 7, 28, 56, 90, and 180 day compressive strength and 28 day split tensile strength and flexural strength have been determined. Shrinkage and creep behavior of RAC with 0%, 50%, and 100% RA replacing NA has been studied up to 180 days and 150 days, respectively. RAC including RA treated with 3-day accelerate carbonation (CRA) was also used. The following conclusions are drawn from this study.

(1) The physical properties of RAC, such as density and water absorption, improve by accelerated carbonation, but the improvement of mechanical properties is not directly related to the strength improvement of RAC incorporating the CO_2 treated RA.

(2) Compressive strength of RAC with 30% RA or CRA is similar to that of NAC and the compressive strength of RAC with 50% or 100% replacement is reduced from that of NAC, while the strength reduction is smaller than 10%.

(3) Split tensile strength is not significantly affected by RA replacement up to 100%. Flexural strength decreases with increasing amount of replacement, but the flexural strengths are above the value required by structural concrete design code.

(4) Elastic modulus of RAC tends to decrease with increasing RA replacement, but it is not significantly reduced (less than 10%).

(5) Shrinkage of RAC with 50% RA is similar to that of NAC. Shrinkage of RAC with 100% RA increases over that of NAC up to 13% after 180 days.

(6) Specific creep of RAC with 50% and 100% RA increases over that of NAC by 25% and 38%,

respectively, after 150 days of sustained loading.

(7) RAC with CO_2 treated RA has similar shrinkage behavior to RAC with RA not treated by CO_2 while creep of RAC with CO_2 treated RA is smaller than that of RAC with RA not treated with CO_2.

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This work was supported by the Korea Technology and Information Promotion Agency for SMEs (TIPA) grant funded by the Korea government (Proj. No.: C0531527). Authors also gratefully acknowledge the support from Dongbu-ENT Corp. in the form of recycled coarse aggregate supply throughout this study.

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