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Freeze–Thaw Resistance and Drying Shrinkage of Recycled Aggregate Concrete Proportioned by the Modified Equivalent Mortar Volume Method

Sungchul Yang[1)],*, and Hwalwoong Lee[2)]

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Abstract: To evaluate the effect of the mix proportioning method on drying shrinkage and freeze-and-thaw resistance of recycled concrete aggregate (RCA) concrete, two series of concrete mixes were made using the modified equivalent mortar volume (EMV) method and the conventional ACI method. In this study, different sources of RCAs were manufactured from on-site plants on air bases and at a commercial recycling plant. Keeping the total mortar at the same level, concrete mixes were proportioned by the modified EMV method, using different scale factors: $S = 1$ (with RCA substitution of 23%), $S = 2$ (with RCA substitution of 47%), and $S = 3$ (with RCA substitution of 73%). It was assumed that the residual mortar volume in the RCA concrete was represented in the sum of the volume of mortar and the volume of aggregate, in variance to the scale factors. Test results showed that the modified EMV method for all the mixes yielded the drying shrinkage property of the RCA concrete comparable to that of the companion concrete with natural coarse aggregate. On the other hand, it was observed in the freeze-and-thaw test that the modified EMV method could be marginally applied to the limited condition with $S = 2$.

Keywords: recycled concrete aggregate, drying shrinkage, freeze-and-thaw, mix design.

1. Introduction

Due to environmental regulations, difficulty in quality control, and decrease in strength properties, the use of recycled concrete aggregate (RCA) has been mostly limited to nonstructural applications, especially in pavement layers despite its economical and eco-friendly benefits (Ministry of Land, Transportation and Maritime Affairs 2009; Ministry of Environment 2014; Kang et al. 2014; Yang et al. 2014; Fathifazl 2008; Fathifazl et al. 2009). In particular, if RCA concrete is proportioned according to the conventional American Concrete Institute (ACI) method, it would be difficult to enhance its properties such as the modulus of elasticity, drying shrinkage, and freeze-and-thaw resistance (Fathifazl 2008; Fathifazl et al. 2009; Abbas et al. 2009).

In the case of a military airfield on a base in Seoul, South Korea, its runway was paved with good quality concrete materials that has lasted around 30–40 years. Engineers predict (Yang et al. 2014) that a half of all the airport runaways in South Korea will undergo surface reconstruction within 5–10 years. A few air bases have already been under reconstruction, and the RCAs produced on-site on air bases have been used only for the sub-base materials, regardless of the potentially good RCA quality that the air bases can produce. It is noticeable that the RCA recycled on the air base normally contains fewer impurities than other structures and at most contains some asphalt and rubber from the patching and joint sealing areas.

In addition to the factors already mentioned that limit RCA concrete use, there is also a security regulation and financial conflict between the air base and recycling plant owners. Regarding the regulation, it would be unavoidable to take out the old paving concrete waste to an external recycling plant and bring the standard grade RCA back to the air base reconstruction site after recycling due to the strict RCA quality requirement. The Korean standard (KS) specifications require a specific gravity of 2.5 and water absorption of less than 3% of the RCA for structural and paving concrete use (Ministry of Land, Infrastructure and Transportation 2009; Korea Expressway Corporation 2011; Incheon International Airport Corporation 2012). In actuality, 4–6 steps of additional crushing processes are being carried out at the recycling plant in order to satisfy the KS specifications (see Fig. 4), resulting in a loss of time and money (Kang et al. 2014).

An innovative method to solve this problem has been introduced by Fathifazl (2008), Fathifazl et al. (2009) and Abbas et al. (2009). They undertook an extensive literature review and summarized the mechanical and durability

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[1)] School of Architectural Engineering, Hongik University, 2639 Sejong-ro, Jochiwon, Sejong 30016, South Korea.
*Corresponding Author; E-mail: scyang@hongik.ac.kr
[2)] Construction Safety Division, Korea Infrastructure Safety Corporation, 315 Goyangdae-ro Ilsanseo-gu, Goyang 10223, South Korea.

properties of RCA concrete (Fathifazl 2008). The concrete properties using the conventional RCA method are mainly affected by the volume of the residual mortar (RM) attached to the RCA. It was pointed out in 17 studies (Fathifazl 2008) that the elastic modulus of RCA concrete decreased by 0–45%, compared to that of the companion natural aggregate concrete. Other researchers also confirmed that RCA concretes had lower elastic modulus than normal aggregate one (Tavakoli and Soroushian 1996; Eguchi et al. 2007; Padmini et al. 2009; Limbachiya et al. 2012; McNeil and Kang 2013; Wardeh et al. 2015). This means that the elastic modulus of RCA concrete is a function of that of the mortar and also has a proportional relationship with the volume of the mortar (Fathifazl 2008). It was also mentioned in 11 studies (Fathifazl 2008) that the drying shrinkage of the RCA concrete exhibited a 6–111% increase, compared to that of the conventional mix concrete. Other studies also showed that RCA concrete had higher drying shrinkages than normal aggregate one (Eguchi et al. 2007; Limbachiya et al. 2012; Sagoe-Crentsil et al. 2001). This is due to the fact that the drying shrinkage is proportional to the volume of the mortar. Consequently, Fathifazl, et al. came up with the equivalent mortar volume (EMV) method, treating the residual mortar as part of the total mortar content of the RCA concrete, (i.e. residual plus fresh mortar) and demonstrating that the elastic modulus does not decrease and that the drying shrinkage does not increase.

In essence, airport pavements require very delicate riding smoothness, and this is greatly related to the low slump of the paving surface. The low slump, often under 50 mm (Korea Expressway Corporation 2011; Incheon International Airport Corporation 2012), can be achieved for paving due to the compaction of the concrete mix. A paving concrete mix is therefore typically proportioned with a marginal amount (usually less than 700 kg/m^3) of fine aggregates. It was pointed out in the previous study (Yang and Lee 2017b; Kim et al. 2016) that the nature of the EMV mix proportions leads to a far smaller amount of fine aggregates, in some case less than 600 kg/m^3, creating a harsh mix. It may have a smooth finish if the slip form paver forcibly vibrates more than 10,000 times per minute, but normally there will be a range of shortage in the amount of sand or fresh mortar. Therefore, the modified EMV mix proportioning method has been proposed (Yang and Lee 2017a, b; Kim et al. 2016), assuming that a certain volume fraction of the residual mortar may be mathematically treated as original virgin aggregate, while the other fraction as a part of the total mortar.

This study aims to assess the effect of different mix proportioning methods (the conventional ACI method versus the modified EMV method) on the drying shrinkage and freeze-and-thaw resistance of concrete. The modified EMV method and the conventional method were used for comparison. Several RCAs were produced from the on-site plants on air bases and at a commercial recycling plant in South Korea. To verify the applicability of the modified EMV method, especially for the drying shrinkage and freeze-and-thaw of RCA concrete, two series of mixes were made using the modified EMV mix design, along with the original EMV and the conventional mix design, with various types and sources of coarse RCA.

2. Modified Equivalent Mortar Volume Method

The EMV mix design was originally proposed by Fathifazl (2008). It was ensured in the EMV concept that the total volume of natural aggregate in recycled concrete aggregate (RCA) concrete is equal to the volume of natural aggregate in the conventional concrete with the same specified properties (Fathifazl 2008; Fathifazl et al. 2009; Abbas et al. 2009). Thus, the new fresh mortar volume in the RCA concrete (RAC) mix is required to be reduced as much as the residual mortar content (RMC). The RMC was obtained using the following equation:

$$\mathrm{RMC} = (W_{\mathrm{RCA}} - W_{\mathrm{OVA}})/W_{\mathrm{RCA}} \times 100 \qquad (1)$$

where W_{RCA} is the initial oven-dry weight of the RCA samples before the test and W_{OVA} is the final oven-dry weight of the original virgin aggregate (OVA) after complete removal of the residual mortar (RM). However, it was noted earlier that in the typical paving concrete mix the EMV concept leads to too little mortar content. It was also previously mentioned that the lack of fillers causes slump loss and a detrimental shape due to too much reduction in the amount of cement, water, and sand (Yang and Lee 2017b).

Therefore, it was assumed in the modified EMV model (Yang and Lee 2017b) that the RM attached to RCA works as aggregate in fresh concrete, and works as mortar after it is hardened. Considering this treatment, the RM volume in RAC was represented as the sum of the volume fraction of mortar V_{RMa}^{RAC} and the other volume faction of aggregate V_{RMb}^{RAC}, as follows:

$$V_{RM}^{RAC} = V_{RMa}^{RAC} + V_{RMb}^{RAC} \qquad (2)$$

where

$$V_{RMa}^{RAC} = V_{RCA}^{RAC} \times \left[1 - \left(1 - \frac{1}{S} \times RMC\right) \times \frac{SG_b^{RCA}}{SG_b^{OVA}}\right] \qquad (3)$$

where V_{RCA}^{RAC} is the RCA volume in the RAC; SG_b^{RCA} and SG_b^{OVA} are the bulk specific gravities of RCA and the original virgin aggregate (OVA), respectively; and, S is a scale factor that determines the volume fraction.

Now, the parameter R, which was defined as the ratio of the fresh natural aggregate content of RAC to the fresh natural aggregate content of the companion conventional mix, was modified (Yang and Lee 2017b) as follows:

$$R = 1 - \frac{V_{RCA}^{RAC}}{V_{NA}^{NAC}} \times \left(1 - \frac{1}{S} \times RMC\right) \times \frac{SG_b^{RCA}}{SG_b^{OVA}} \qquad (4)$$

where the volume of fresh NA in the natural aggregate concrete (NAC) is represented by V_{NA}^{NAC} and the volume of

RCA in the RCA concrete by V_{RCA}^{RAC}; SG_b^{RCA}, SG_b^{OVA} as the bulk specific gravities of RCA and the OVA, respectively. Note that the original definition of the parameter R was proposed by Fathifazl (2008).

Then, the volume of new mortar in RAC mix V_{NM}^{RAC} is calculated from the volume of mortar in NAC mix V_M^{NAC}, and the volume of natural aggregate (NA) in NAC mix V_{NA}^{NAC} as follows:

$$V_{NM}^{RAC} = V_M^{NAC} - V_{RMa}^{RAC} \tag{5}$$

$$V_M^{NAC} = 1 - V_{NA}^{NAC} \tag{6}$$

$$V_{NA}^{NAC} = \frac{W_{OD\cdot NA}^{NAC}}{SG_b^{NA} \times 1,000} \tag{7}$$

where the oven-dry weight of NA in NAC mix is represented as $W_{OD.NA}^{NAC}$.

The oven-dry weight of RCA in RAC mix $W_{OD.RCA}^{RAC}$ and oven-dry weight of NA in RAC mix $W_{OD.NA}^{RAC}$ can be determined as follows:

$$W_{OD\cdot RCA}^{RAC} = V_{RCA}^{RAC} \times SG_b^{RCA} \times 1000 \tag{8}$$

$$W_{OD\cdot NA}^{RAC} = V_{NA}^{RAC} \times SG_b^{NA} \times 1000 \tag{9}$$

where the volume of RCA in RAC mix V_{RCA}^{RAC} is represented by rearranging Eq. (4),

$$V_{RCA}^{RAC} = \frac{V_{NA}^{NAC} \times (1 - R)}{\left(1 - RMC \times \frac{1}{S}\right) \times \frac{SG_b^{RCA}}{SG_b^{OVA}}} \tag{10}$$

By multiplying the quantities of the ingredients of the mortar in the companion NAC by the $\frac{V_{NM}^{RAC}}{V_M^{NAC}}$ ratio, the corresponding quantities of water, cement, and fine aggregate in RCA concrete can be calculated as follows:

$$W_w^{RAC} = W_w^{NAC} \times \frac{V_{NM}^{RAC}}{V_M^{NAC}} \tag{11}$$

$$W_c^{RAC} = W_c^{NAC} \times \frac{V_{NM}^{RAC}}{V_M^{NAC}} \tag{12}$$

$$W_{OD\cdot FA}^{RAC} = W_{FA}^{NAC} \times \frac{V_{NM}^{RAC}}{V_M^{NAC}} \tag{13}$$

where the weights of water and cement are represented as W_w^{RAC} and W_c^{RAC}, respectively, and the oven-dry weight of fine aggregate as $W_{OD\cdot FA}^{RAC}$. A sample mix proportioning can be found in Ref. (Yang and Lee 2017b).

3. Experimental Details

3.1 Materials

3.1.1 Cement

A type I Portland cement was used in this study. The specific gravity of cement used in the mixture design was 3.15 and the specific surface area was 3200 cm^2/g. Chemical admixture used for this study were a solution of air entraining and water reducing agent.

3.1.2 Recycled Concrete Aggregate

This experimental study used recycled aggregates produced from three different sources in South Korea (see Fig. 1). The Sa-Cheon (*SC*) aggregate that is represented as '*C*' in Table 1 (and from there on) is a maximum size of 25 mm RCA. It was crushed further again in the Dae-Gil (*DG*) recycling plant after initially demolishing and crushing the old runway concrete pavement at the *SC* air base reconstruction site. Secondly, the *DG* aggregate that is represented as '*D*' is a maximum size of 25 mm RCA, and produced from unidentified sources of construction and demolition waste (CDW) at the *DG* recycling plant. The CDW consists of recycled aggregates with various impurities such as brick, glass, and asphalt. Lastly, the *SN* aggregate, which is represented as '*A*' aggregate, is a maximum size of 40 mm RCA, and manufactured from the old runway concrete pavement at the *SN* air base reconstruction site.

Figure 2a shows a picture of the RCA production facilities installed on the *SN* air base. For reasons of cost, dry process crushing facilities are typically adopted. Figure 3a represents a schematic diagram of production processes at the on-site recycling plant. Note that only two to three stages of crushing processes are undertaken. Figure 2b is a picture of the RCA manufacturing facilities at the *DG* recycling plant. Figure 3b represents a schematic diagram of production processes at the recycling plant. It should be noted that a wet type of process facilities with multiple crushing stages is often operated in order to satisfy the high quality requirement of the RCA standards. Weimann and Müller (2004) reported that the mechanical impact of the material from the

Fig. 1 Images of recycled aggregate alongside their sources (Lee 2014).

Table 1 RCA properties.

Aggregates	RCA source	Specific gravity	Water absorption (%)	RMC	Soundness[a]	Abrasion resistance[b] (%)
RCA 1	'C' (SC air base)	2.42	5.37	n.a[c]	7.7	22.7
RCA 2	'D' (DG plant)	2.37	5.39	n.a[c]	14.8	30.3
RCA 3	'A' (SN air base)	2.35	4.45	35.5	6.1	30.0

[a] Determined by KS F 2507 (2007a) equivalent to ASTM C 88.

[b] Determined by KS F 2508 (2007b) equivalent to ASTM C 131.

[c] Not available.


(a) (b)

Fig. 2 RCA production facilities (Lee 2014). **a** Air base, **b** plant.

wet treatment increased finer grains in the total mass of the treated material. This increase was mainly due to abrasion of the adherent residual mortar (Weimann and Müller 2004).

Material properties and production sources of the RCAs are recorded in Table 1. From a polarization microscope test for the three test samples, the minerals that constitute the original virgin aggregates were found to be tuff, hornfels, and shale for the '*C*' RCA, with andesite, hornfels, and quartz porphyry for the '*D*' RCA, and quartzite, orthoquartzite, and mica-gneiss for the '*A*' RCA (Lee 2014).

According to the quality control requirements (Ministry of Land, Infrastructure and Transportation 2009), the RCA contained less than 0.5% wood and less than 1% foreign materials by weight. The properties of the RCAs were tested according to the KS methods (KS F 2007a, b), and are given in Table 1. All three RCAs have failed to meet the required KS standards on structural concrete in terms of the specific gravity of 2.5 and the water absorption of 3.0%.

The RMC value of '*A*' RCA only was determined by the same method suggested by Abbas et al. (2008) Two samples were used to determine the RMC values in individual size fractions. After drying the samples for 24 h at 105 °C, the oven dried samples were immersed for 24 h in a 26% by weight sodium sulfate solution. While still immersed in the sodium sulfate solution, the RCA samples were subjected to five cycles of freezing and thawing, i.e., 16 h at −17 °C and 8 h at 80 °C. After the last freeze-and-thaw cycle, the solution was drained from the sample, and the aggregate was washed with water over a No. 4 sieve. The washed aggregate was then placed in an oven for 24 h at 105 °C and its oven-dried weight was measured.

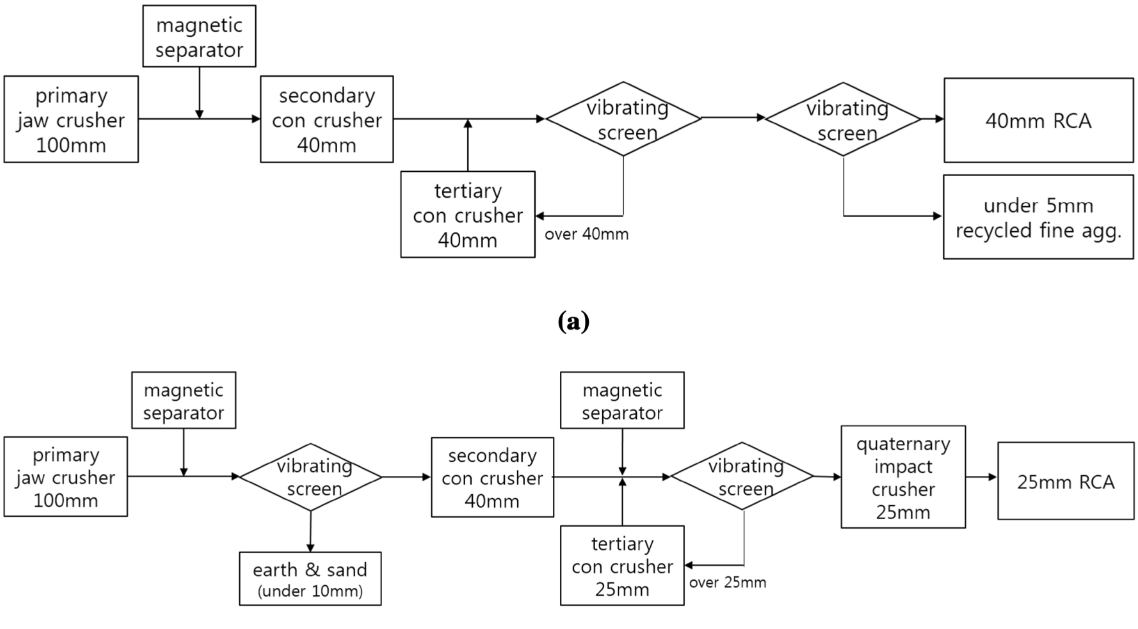
3.1.3 Fine Aggregates and Natural Aggregates

Two similar fine aggregates were used in this experiment (See Table 2). Fine aggregate 1 is natural sand with the specific gravity of 2.62 and the water absorption of 0.58% and was used in mix series 1. Fine aggregate 2 has the specific gravity of 2.55 and the water absorption of 0.95% and was used in mix series 2. For coarse aggregate, natural crushed granite aggregate was used. The specific gravity was 2.64 and the water absorption was 0.77%.

3.2 Mix Design

Two series of mixes were designed for typical road-paving concretes (see Table 3). A control concrete with 35 MPa of compressive strength was used. The first series of mixes were designed for a highway-paving concrete with a maximum aggregate size of 25 mm, while the second series of mixes were designed for an airport-paving concrete with a maximum aggregate size of 40 mm. The target air content for all mix designs was a minimum of 4.0%. Due to the low slump requirement for the paving concrete, all mixes were determined to have a slump value under 50 mm.

The mix design identification in Table 3 can be explained as follows. There are three different sets of terms. The first, 1 and 2 denote test series number. The second term *C* designates the conventional mix method, while *E* is the EMV mix method. The third indicates the type of coarse aggregates; *N* implies natural coarse aggregate, while *C* and *A* are the RCAs produced at the on-site recycling plant of the *SC* and *SN* air bases, respectively, and *D* is the RCA produced from the *DG* recycling plant. The numbers following the third, 1, 2, and 3 denote the RCA replacement levels and are related to the *S* values applied in Eq. (3). For example, the 2E-A2 denotes



(a)

(b)

Fig. 3 RCA production processes (Lee 2014). **a** At on-site plant, **b** at recycling plant.

Table 2 Aggregate material properties.

Aggregates	Specific gravity	Water absorption (%)
Fine agg. 1	2.62	0.58
Fine agg. 2	2.55	0.95
Natural coarse agg.	2.64	0.77

Table 3 Concrete mixture designs and material quantities.

Test series	Mix-id	w/c (%)	RCA (%)[a]	Water (kg)	Cement (kg)	Sand (kg)	Coarse Aggregate		WRA[d] (ml)	AE[e] (ml)	Air contents (%)
							NA (kg)	RCA (kg)			
1	1C-N	40.0	0	128	320	736	1157	0	0	64.0	5.0
	1C-C	40.0	100	128	320	736	0	1056	0	38.4	5.5
	1C-D	40.0	100	128	320	736	0	1038	0	38.4	5.3
2	2C-N	38.2	0	140	366	675	1220	0	4047	168.4	5.5
	2C-A	38.2	47.1	140	366	675	611	543	4047	168.4	5.5
	2E-A1[b]	38.2	22.8	126	329	606	1025	303	4049	168.4	4.0
	2E-A2[c]	38.2	46.8	121	318	585	708	623	4051	168.5	4.6
	2E-A3[c]	38.2	72.6	117	305	563	366	969	4751	197.6	4.0

[a] A ratio of RCA volumetric proportion to total coarse aggregates.

[b] S = 1 in Eq. (1) which is the same as the original EMV method is applied.

[c] S = 2 and 3 in Eq. (1) is applied, respectively.

[d] Water reducing agent.

[e] Air entraining agent.

the EMV mix design in the second test series substituted with the '*A*' RCA, but proportioned with $S = 2$ in Eq. (3).

The first series of mixes were designed to confirm how the conventional method with the RCA leads to decreased durability properties such as drying shrinkage and the freeze-and-thaw resistance, compared to the corresponding concrete mix containing natural aggregate. The second series of mixes were then designed to apply the modified EMV

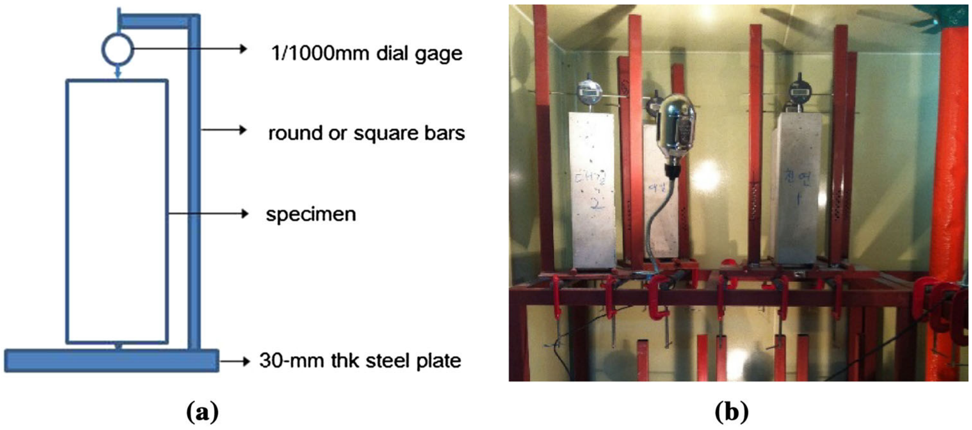


Fig. 4 Experimental specimens with a dial-gauge installed. **a** Schematic diagram, **b** picture.

approach with scale factors, S = 1 (the original EMV mix proportion), S = 2, 3, aiming to have the equivalent durability properties, in comparison with the companion mixes along with the conventional proportioning design.

3.3 Mixing Process for Making the Concrete Specimens

A volume capacity of 60L concrete pan mixer was used in the laboratory. Before the addition of water and the admixture solution, the admixture in the mixing water was thoroughly dispersed. Coarse aggregate and fine aggregate were then added, giving the mixture a few turns. Cement was subsequently added and the mixer was started for about 90 s. Finally water was added while the mixer was running and the concrete was mixed for another 120 s.

3.4 Fresh and Hardened Concrete Properties Testing

The performance of the concrete mixtures was determined by testing the fresh and hardened concrete properties. Immediately after batching, the fresh concrete properties such as air content (summarized in Table 3) and slump were tested. The hardened concrete properties tests performed in this study included compressive strength and modulus of elasticity. Specimens were cast in plastic molds with the specified consolidation method (ASTM 2012), that is, rodding and external vibration, and removed 24 h later. All specimens were moist-cured at around 20 ± 2 °C from the time of molding until the moment of the test. Both compressive strength and modulus of elasticity tests for mix series 1 were performed in the 100 mm × 200 mm cylinder, where the tests for mix series 2 were done in the 150 mm × 300 mm for mix series 2. Two different cylinders were used for mix series 1 and 2 due to their different maximum aggregate sizes of 25 and 32 mm, respectively.

3.5 Test Procedures

For durability properties, there are chloride penetration test (Abbas et al. 2009; Limbachiya et al. 2012; Ying et al. 2016; Lee et al. 2013), carbonation test (Abbas et al. 2009; Limbachiya et al. 2012; Sagoe-Crentsil et al. 2001; Lee et al. 2013), freeze–thaw test (Abbas et al. 2009; Ballim 2000; Lee et al. 2013), and creep (Fathifazl 2008; Smadi et al. 1989) and drying shrinkage tests (Fathifazl 2008; Sagoe-Crentsil et al. 2001; Smadi et al. 1989; Lee et al. 2013). Under the assumption that chloride penetration and carbonation properties may be better observed from the freeze–thaw test, while drying shrinkage may demonstrate a similar trend to creep behavior, freeze–thaw and drying shrinkage tests were conducted in this paper to study durability of RCA concrete.

3.5.1 Drying Shrinkage

Drying shrinkage experiments were performed using a dial gauge as one of the methods suggested by KS F 2424 2015), which is equivalent to ASTM C 157-08. The size of each experimental specimen was 100 × 100 × 400 mm. The drying shrinkage was measured by the dial gauge with an accuracy of up to 1/1000 mm. The specimens were kept inside a temperature-and-humidity controlled chamber (20 °C and 60% of RH). The dial gauge was then installed on top of the specimen to measure the change in the length of the specimen. Figure 4 shows a schematic diagram and experimental specimens with the dial gauges installed. Figure 5a shows the change in the temperature and relative humidity inside the chamber for mix series 1 and Fig. 5b for mix series 2.

3.5.2 Freezing and thawing

The freeze-and-thaw tests were carried out by Procedure A with rapid freezing and thawing in water specified in KS F 2456 (2013), which is equivalent to ASTM C 666-03. The freeze-and-thaw tests were conducted on 100 × 100 × 400 mm prisms by monitoring the relative dynamic moduli at every 50 cycles over a maximum of 300 cycles. The nominal freeze-and-thaw cycle of this test consists of repeated changes in the temperature between 4 ± 2 and −18 ± 2 °C within the range of 2–5 h.

The relative dynamic modulus is determined by measuring the transverse frequency of the specimens as shown in Fig. 6. The specimen under consideration was vibrated in

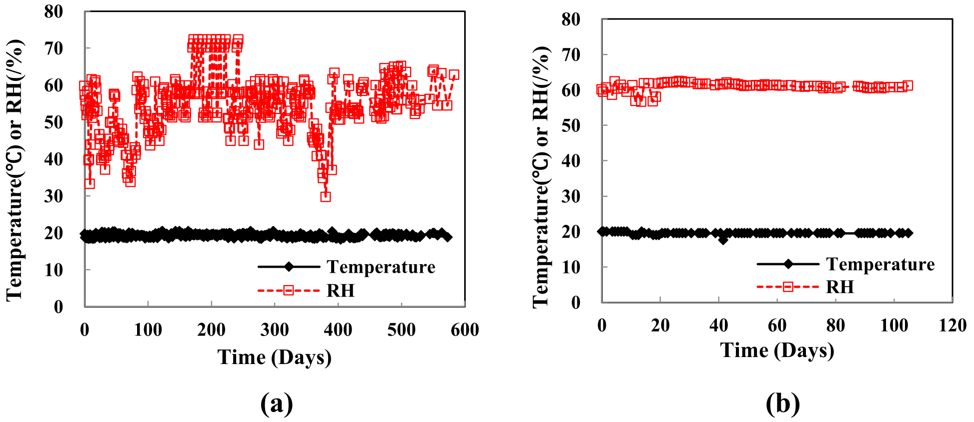


Fig. 5 Change in the temperature and RH inside the chamber. **a** Mix series 1, **b** mix series 2.

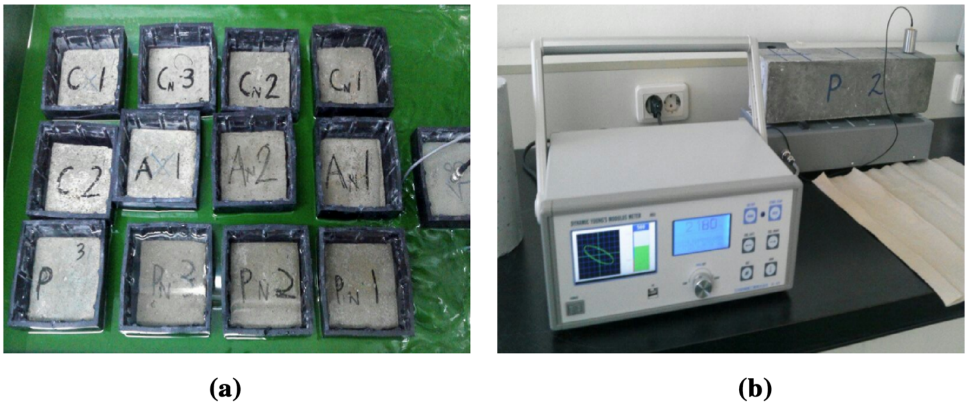


Fig. 6 Apparatus for measuring properties in freeze-and-thaw tests. **a** Specimens, **b** transverse frequency apparatus.

the middle, and the frequency was picked up at the end of the specimen by an accelerometer and was recorded. The relative dynamic modulus, P_c, is calculated based on the following:

$$P_c = \left(\frac{n_1^2}{n^2}\right) \times 100 \tag{14}$$

where P_c (%) is the relative dynamic modulus of elasticity after c cycles of freezing-and-thawing, n_1 is the initial fundamental transverse frequency, and n is the fundamental transverse frequency after c cycles of freezing-and-thawing.

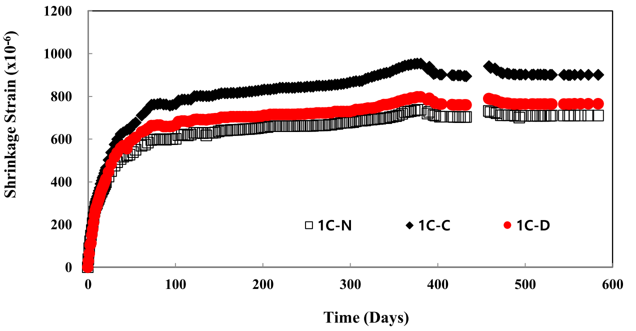


Fig. 7 Effect of aggregate sources on drying shrinkage for mix series 1.

4. Test Results

Previous studies (Yang and Lee 2017a, b; Kim et al. 2016) have shown that the use of the modified EMV mix proportioning method originally would not result in low elastic modulus of RCA concrete mixes. This section reports the test results obtained from the drying shrinkage test and the freeze–thaw test.

4.1 Drying Shrinkage

Figure 7 illustrates the effect of aggregate sources on the drying shrinkage of mix series 1, based on the conventional ACI mix design. The drying shrinkage was measured for 585 days. During days 350–400 of the experiment, the shrinkage strain increased and then decreased repeatedly, showing a ‘hump.’ This was considered to be caused by the dramatic change in the RH, as previously seen in Fig. 5a.

From the age of 20 days, the drying shrinkage difference between different mixes began to appear gradually. A similar difference tendency occurred right after the age of 100 days. At the last measurement at the age of 585 days, the shrinkage strain of the control specimen, 1C-N was 736 μm/m, and that of the plant RCA concrete mix 1C-C was 796 μm/m, indicating about an 8% increase. On the other hand, the shrinkage strain of the airbase RCA concrete mix 1C-D was 954 μm/m, indicating a 30% increase in

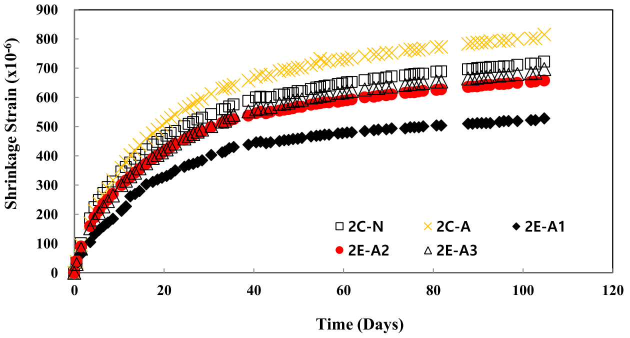


Fig. 8 Effect of mix proportioning method on the drying shrinkage for mix series 2.

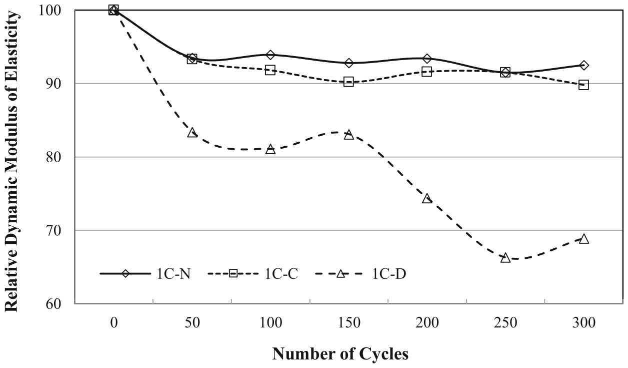


Fig. 9 Effect of aggregate sources on the freeze–thaw resistance for mix series 1.

comparison to the control mix. This is mainly due to the higher unit volume of total mortar in the RCA concrete mixes proportioned by the conventional method, compared to the companion control mix. It was also observed that the air base RCA concrete mix resulted in a worse shrinkage strain, regardless of the similar specific gravity and water absorption when compared to the plant RCA (see Table 2). As mentioned previously, shale particles were found from the air base RCA. This can be explained by the research result of Schuster and McLaughlin (1961), Bentur and Grinberg (1982), Smadi et al. (1989), Ballim (2000), Lee et al. (2013) and Meddah (2015) in that increasing shale content in concrete has a significant effect in increasing both shrinkage and creep strain.

Figure 8 illustrates the effect of the mix proportioning method on the drying shrinkage result of mix series 2 following 105 days. The RCA concrete shrinkage of the conventional method was compared to that of the modified EMV method. A constant difference tendency was observed after the age of about 40 days. At the last measurement at 105 days, the shrinkage strain of the control mix, 2C-N, made with natural aggregate, was 722 μm/m, while that of the 2C-A mix, based on the conventional mix design with the RCA substitution of 47%, increased by 13% to 816 μm/m. On the other hand, the 2E-A1 ($S = 1$), 2E-A2 ($S = 2$), 2E-A3 ($S = 3$) mixes proportioned by the modified EMV mix design, had shrinkage strains of 530, 660, and 700 μm/m, indicating a 27, 9, and 3% decrease, respectively, compared to the control specimen. This decrease is mainly affected by the equivalent total volume in the RCA concrete mixes proportioned by the modified EMV method. All the results of 2E-A1, 2E-A2 and 2E-A3 confirm that the drying shrinkage problem of the RCA concrete can be overcome using the modified EMV mix design, contrary to the conventional mix proportioning method.

4.2 Freeze-and-Thaw

The relative dynamic moduli were calculated using Eq. (14). Figure 9 illustrates the effect of aggregate sources on the freeze-and-thaw resistance of mix series 1 based on the conventional ACI mix design. Test results showed that the control mix 1C-N and the airbase RCA concrete mix 1C-C had a gradual and similar decrease tendency with the freeze-and-thaw cycles, while the plant RCA concrete mix 1C-D rapidly dropped to under 70% at the 300th cycle.

At the 100th cycle, the relative dynamic modules of 1C-N, 1C-C, and 1C-D were 93.9, 91.8, and 81.1%, respectively. However in the case of 1C-D, the relative dynamic modulus was 74.4% after the 200th cycle, not meeting the requirement of 80% by the KS concrete structure specification (Ministry of Land, Infrastructure and Transportation 2009). Generally, the conventional mix design method results in a lower freeze-and-thaw resistance against RCA concrete (Fathifazl 2008; Abbas et al. 2009). Also worth noting is that the plant RCA concrete mix resulted in the worst freeze-and-thaw resistance, regardless of the similar specific gravity and water absorption in comparison to the air base RCA. It may ascribe to be caused by more impurities with unidentified sources contained in the plant RCA. Finally, the relative dynamic modulus of 1C-N, 1C-C, and 1C-D at the 300th cycle were measured as 92.5, 89.8, and 68.9%, respectively. It was shown in Fig. 9 that the 1C-N and the 1C-C resulted in over almost 90% of the relative dynamic modulus even after the 300th cycle.

Figure 10 illustrates the effect of the mix proportioning method on the freeze-and-thaw resistance for mix series 2. Compared to mix series 1, it appears that all the test data in mix series 2 showed a gradual decrease tendency with the freeze-and-thaw cycles but satisfied the KS requirement of 80%, although the 2C-A mix and the 2E-A3 mix appeared to diverge more.

At the 300th cycle, the relative dynamic modulus of 2C-A mix, based on the conventional mix design with the RCA substitution of 47% was 88.5%, indicating an 8% decrease compared to the control mix 2C-N with the relative dynamic modulus of 95.3%. On the contrary, both 2E-A1 ($S = 1$) and 2E-A2 ($S = 2$) mixes proportioned by the modified EMV method with the RCA content of 47 and 73% resulted in the relative dynamic modulus of 95.0 and 93.6%, respectively, being only 0.4 and 2% lower than that of the control mix. Meanwhile if one compares the effect of the mix proportioning method between the conventional mix (2C-A) and the modified EMV mix (2E-A2, $S = 2$) with the same RCA substitution, it will be clearly seen in Fig. 10 that the relative dynamic modulus of the modified EMV mix exhibits a 5.1% stronger resistance than that of the conventional mix. This is

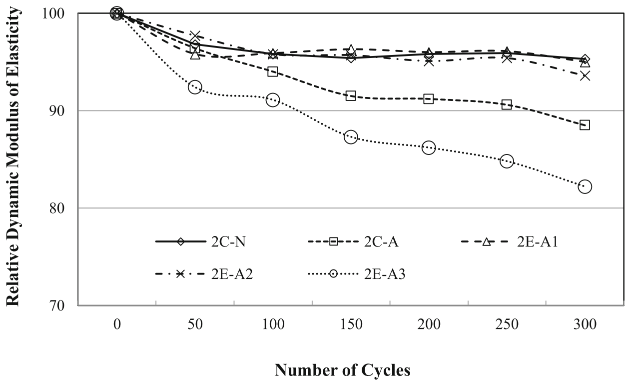


Fig. 10 Effect of mix proportioning method on the freeze–thaw resistance for mix series 2.

ascribed to a lower total mortar volume that was incorporated in the modified EMV method. However, in the case of 2E-A3, using the modified EMV mix design with the RCA substitution of 73% ($S = 3$), while the relative dynamic modulus was 82.2% and a reduction of 6.3% was observed in comparison to 2C-A, based on the conventional mix design with the RCA substitution of 47%, too much of a reduction in water, cement, and sand in 61, 112 kg, and 23 kg per m^3, respectively, from the 2E-A3 mix affects the freeze-and-thaw result in comparison to the 2C-A mix.

5. Conclusions

Drying shrinkage and freeze-and-thaw resistance of RCA concrete have been tested to evaluate the effect of the mix proportioning method, i.e., the modified EMV method and the conventional ACI method. From the results of this study, the following conclusions can be drawn.

(1) Test results showed that the RCA concrete mixes, with the RCA substitution of 23% ($S = 1$), 47% ($S = 2$), and 73% ($S = 3$), proportioned by the modified EMV method, exhibited a 27, 9, and 3% decrease, respectively, in the drying shrinkage at 585 days in comparison to the companion natural aggregate concrete mix. On the other hand, the RCA concrete mix with a substitution of 47%, proportioned by the conventional method, indicated a 13% increase. Thus, the application of the modified EMV method resulted in RCA concrete with lower drying shrinkage, compared to the RCA concrete proportioned with the conventional method.

(2) The RCA concrete mixes, with a substitution of 23% ($S = 1$) and 47% ($S = 2$), proportioned by the EMV method, had strong resistance against the freeze-and-thaw action, being only less than 2% lower than the companion mix, while the RCA concrete mix with a substitution of 47%, proportioned by the conventional method, was 8% higher than the companion mix. Conversely, in the RCA concrete mix with a substitution of 73% ($S = 3$), proportioned by the modified EMV method, a reduction of 6% in freeze-and-thaw resistance was observed in comparison to the RCA mix with a substitution of 47%, proportioned by the conventional method. This was ascribed to too much reduction of the water, cement, and sand in comparison to the conventional mix.

(3) Test results showed that the modified EMV method yielded a drying shrinkage property of the RCA concrete comparable to that of the companion concrete with natural coarse aggregate. On the other hand, it was observed in the freeze-and-thaw test that the modified EMV method could be marginally applied to the limited condition with $S = 2$ (with RCA substitution of 47%).

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