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Structural Performance of Reinforced RCA Concrete Beams Made by a Modified EMV Method

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Abstract: This study aims to show the effect of a modified equivalent mortar volume (EMV) method on the flexural performance of recycled concrete aggregate (RCA). To verify this, an experimental study was carried out firstly by testing fresh and hardened material properties of RCA concrete specimens made by two different mixture design methods, i.e., the modified EMV method and the conventional American Concrete Institute (ACI) method. The flexural performance of five reinforced recycled concrete (RRC) beams mixed with different mixture designs was then investigated. Test results confirmed that the elastic moduli of the RCA concrete specimens made using the modified EMV method are greater than those of the conventional ACI mixture, while the drying shrinkage tended to decrease. The ultimate strengths of RRC beams mixed with the modified EMV method are as much as five percent greater than that achieved with the conventional ACI mixture.

Keywords: recycled concrete aggregate; elastic modulus; equivalent mortar volume; reinforced concrete; flexural strength

1. Introduction

Due to the increased demand for measures to protect the natural environment, since 2008 the Korean government has made it obligatory for public road agencies to use recycled concrete aggregate (RCA). From 2014 onwards, the mandatory use of RCA was increased to maximum replacement levels of 30%, 40% and 50% of the total coarse aggregate for 2014, 2015, and 2016, respectively, for roadside materials [1]. However, regardless of the opportunity to use eco-friendly RCA, the use of RCA is still avoided by many engineers due to quality control issues and the decreased strength of RCA concrete [2].

To overcome the shortcomings of RCA, comprehensive research has been done to determine the basic material properties of RCA and new mixture design methods using this material [2]. In addition, the structural behavior of RCA has been studied by researchers who are interested in the flexural and shear performance capabilities of reinforced recycled aggregate concrete beams [3–11].

Yagashita et al. [3] used three types of RCA with 100% replacement levels. Different types of crushers were used to obtain different levels (i.e., absorption rates) of RCA from the same source of construction and demolition waste. Their results showed that the flexural strength of RCA beams made with high-grade RCA decreased by more than 10% compared to control beam specimens made with natural aggregate. Ajdukiewicz and Kliszczewicz [4] summarized their extensive research findings from comparative tests of flexural beams made of RCA concrete and natural aggregate concrete. They used different strength classes (low, medium, and high) and specimens formulated with different types of coarse RCA (round river gravel, granite, and basalt) with or without the full replacement of recycled fine sand. The differences in the deformability depended on the origin of the aggregate used in the concrete mixtures and a lower modulus of elasticity of concrete was evident with a greater proportion of RCA. In the beams created with RCA concrete, relatively low cracking moment was observed as compared to those created with natural aggregate concrete. The yield moment followed a trend similar to that of the cracking moment capacity. The loading capacity of beams made of RCA concrete was somewhat smaller, on average by 3.5%, in cases of flexural failure. Xiao et al. [5] summarized the results of structural performance tests of RCA beams carried out over during a 15-year periods (1996–2011) in China, in which Zhou et al. [6] proved that the maximum flexural strength of conventional concrete beams decreased by 11%, 12%, 15% and 16% at corresponding RCA replacement ratios of 50%, 60%, 70% and 80%.

In contrast, other researchers [7,8] have acknowledged somewhat lower cracking and yield moments, larger deflection levels, but similar flexural strengths. Maruyama et al. [7] tested 12 beams with different water-cement ratios with RCA and recycled fine aggregate. They reported decreased compressive strength in recycled concrete followed by a lower Young's modulus. Recycled RC (reinforced concrete) beams had larger deflection levels compared to conventional RC beams mainly due to the low Young's modulus. However, they reported no significant difference between the flexural capacities of the RCA beams and those of conventional beams. Sato et al. [8] tested 37 beams with different tensile reinforcement ratios, using 100% RCA in their mixture designs. Their results showed that the RCA beams had larger deflection levels compared to control beams, though identical flexural strengths were noted for all of the beams tested.

The equivalent mortar volume (EMV) method proposed by Fathifazl et al. [2] in 2009 has received much attention. The EMV method considers the residual mortar contained in the RCA as part of the mortar instead of as an aggregate. Thus, compared to the conventional American Concrete Institute (ACI) mixture design, the EMV mixture design allows reduced amounts of newly added mortar. Based on the EMV mix design concept, they demonstrated that the elastic modulus of RCA concrete does not decrease. This was ascribed to the equivalent total mortar ratio of the RCA concrete compared to that of the natural aggregate concrete. They tested 12 flexural beams with different longitudinal reinforcement ratios made of concrete mixed with the EMV mixture proportioning method as well as the conventional ACI mixture method [9], concluding comparable and even superior flexural behavior for RCA beams in both service and ultimate states.

However, it is known that the original EMV mixture proportioning method is appropriate for rich concrete mixtures, which typically contain approximately 800 kg/m^3 of fine aggregate, due to the characteristics of the EMV concept itself. Using this method requires far lower amounts of fine aggregate materials and will therefore greatly reduce mixture amounts and slump loss levels. Thus, a modified EMV mixture proportioning method is proposed by our authors [12,13].

This paper aims to show the effect of the modified EMV method on the flexural performance of RCA concrete. To this end, an experimental study was carried out by testing under flexure a number of reinforced concrete beams mixed with different mixture designs containing RCA with an approximate water absorption ratio of 4.5%.

Before presenting the results of the experiment, a brief description of the modified EMV method is provided in the following section.

2. Modified Equivalent Mortar Volume Method

The primary focus of this study is to show that the modified equivalent mortar volume mixture proportioning method enables RCA concrete (RAC) with properties comparable to those of the conventional mixture or even to the equivalent mortar volume (EMV) mixture of a similar grade. Figure 1 depicts the conceptual difference between (a) the conventional ACI mixture design with the natural aggregate concrete (NAC) mixture; (b) the conventional ACI mixture design with the RAC mixture; (c) the original EMV method proposed by Fathifazl et al. [2] with the RAC mixture; and (d) the modified EMV method with the RAC mixture in which a scale factor, *S*, is introduced [12,13]. In Figure 1, the RCA volume is represented by a dotted background pattern.

The unique characteristic of the EMV method is the treatment of residual mortar (RM) in RCA as part of the total mortar (TM) content of RCA concrete. Meanwhile, TCA in Figure 1 represents the volume of total coarse aggregate. The TM volume in RCA concrete (Figure 1c), which is treated as the sum of the residual and fresh mortar volumes, is equal to the TM volume of natural aggregate (NA) in conventional concrete (Figure 1a) with identical specified properties [2]. Thus, the new mortar volume, which is represented by TM minus RM in Figure 1c, is reduced in proportion to the amount of RM attached to the RCA. However, for a special mixture, if RCA is used with more than a certain amount of coarse aggregate or with more residual mortar content, it was noted that the fine aggregate amount by the original EMV method would lead to be below a certain minimum value. The shape of concrete may be a concern due to the lack of fillers [12,13]. Therefore, in the modified EMV model, the RM volume in RAC was represented in the sum of the volume fraction of the mortar and the other volume faction of the aggregate, using a scale factor in Figure 1d [12,13].

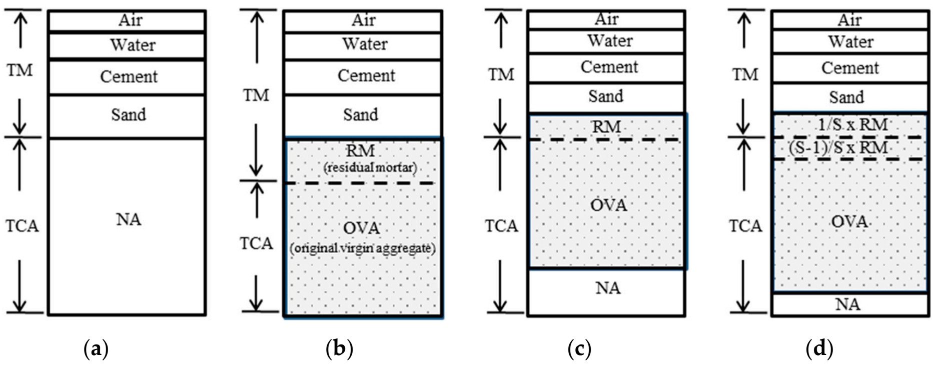


Figure 1. Comparison of various mixture design concepts—(**a**) conventional natural aggregate concrete (NAC) mixture; (**b**) conventional RCA concrete (RAC) mixture (**c**) RAC mixture by equivalent mortar volume (EMV) method; (**d**) RAC mixture by the modified EMV method.

3. Materials and Mixture Design Methods

3.1. Materials

3.1.1. Cement Material and Chemical Admixture

A type I Portland cement was used in this study. The cement specific gravity used in the mixture design was 3.15 and the specific surface area was 3610 cm^2/g. The chemical admixture used for this study was a solution of an air entraining and a water-reducing agent.

3.1.2. Material Properties of the Aggregates

The material properties of the aggregates are tabulated in Table 1. Fine aggregate is washed natural river sand. For the coarse aggregate, natural crushed granite aggregate was used. The RCA was produced by a local recycling plant, and the specific gravity, absorption capacity, and residual mortar content (RMC) are shown in Table 1.

Table 1. Aggregate material properties.

Aggregates	Specific Gravity	Absorption Capacity (%)	Residual Mortar Content (RMC) (%)
Fine Agg.	2.55	0.95	-
Natural coarse Agg.	2.63	0.86	-
RCA	2.49	4.51	32.0

A number of beneficiation techniques in the laboratory have been proposed to determine the RMC value of RCA [14–19]. To date, a universal standard method has not been established due to variations in the RMC values among the different test methods and in the relationship between the bulk density and the water absorption properties. The RMC (residual mortar content) is obtained by means of the equation.

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

where W_{RCA} is the initial oven-dry weight of the RCA (recycled concrete aggregate) samples before the test and W_{OVA} is the final oven-dry weight of the original virgin aggregate (OVA) after the full removal of the residual mortar (RM).

In this study the RMC value of the RCA was determined from Akbarnesnad and Ong's correlation formulas [17]. They reported relationship formulas for the bulk density and water absorption with RMC for two types of RCA produced from Grade 30 concrete (RCA/C30) and Grade 60 concrete (RCA/C60). These are given below.

For RCA produced from Grade 30 concrete,

$$\text{Bulk density } (\mathrm{kg/m^3}) = -6.26 \times \mathrm{RMC} + 2590 \quad (2)$$

$$\text{Water Absorption } (\%) = 0.094 \times \mathrm{RMC} + 0.64 \quad (3)$$

For RCA produced from Grade 60 concrete,

$$\text{Bulk density } (\mathrm{kg/m^3}) = -4.82 \times \mathrm{RMC} + 2{,}590 \quad (4)$$

$$\text{Water Absorption } (\%) = 0.077 \times \mathrm{RMC} + 0.64 \quad (5)$$

Given that the RCA concrete mixtures investigated here are classified as Grade 30 and Grade 60 types of concrete, an RMC value of 32.0% was determined based on the average of the above values (16.0, 41.2, 20.7, and 50.3) from Equations (2)–(5), respectively.

Followed by the concrete mix design experiment, the theoretical RMC value of 32.0% was verified by using a modified method from Akbarnezhad et al. [16]. Into a rotary agitation apparatus that contains about 500 g of RCA samples, 3 M H_2SO_4 solution was slowly added, where its volume was 5 times greater than the volume the RCA sample. Initially, the samples were simply immersed in the H_2SO_4 for 24 h. Then, the samples were continuously rotated in the rotary agitation apparatus at about 10 rpm [16] for two cycles, where each cycle lasted for 24 h. During each cycle, at 8 h and 24 h, the samples were washed on a 4 mm sieve to remove the corroded mortar, and the solution was replaced with a fresh acidic solution. After the completion of the two cycles, the mass of the washed and oven-dried RCA samples was measured to calculate RMC values with Equation (1). The average RMC value for the RCA samples resulted as 30.9%, from 33.0% and 28.7%. Surprisingly, the RMC values acquired from the experiment were very close to the theoretical RMC value derived from Akbarnesnad and Ong's correlation formulas. Figure 2a,b shows RCA samples before and after chemical treatment.

(**a**) (**b**)

Figure 2. RCA samples (**a**) before and (**b**) after chemical treatment.

3.1.3. Mixture Design

A series of mixtures were proportioned based on a typical structural concrete mixture design with a maximum aggregate size of 25 mm, as outlined in Table 2. The target air content for all of the mixture designs was a minimum of 4.0% and the range of the slump value was provisionally 80–120 mm. However, it should be noted that the slump was evenly adjusted due to a mistake by the batch operator, adding more water.

The example in the mixture identification in Table 2 can be explained as follows. There are three different sets of terms. The first is the test series number. Note that the first mixture series were formulated in a laboratory while the second mixture series were done in a PC plant. The second term C designates the conventional mixture design, while E is the EMV mixture design. The third designates the RCA replacement amounts with S applied in the modified EMV mixture design.

Table 2. Concrete mixture designs and material quantities.

Test Series	Mixture (id)	W/C (%)	Water (kg)	Cement (kg)	Sand (kg)	Coarse Aggregate		Admixture [a] (kg)
						RCA, (kg)	NA, (kg)	
1	1-C-0	37.5	180	480	757	0	920	1.87
	1-C-50	37.5	180	480	758	428	460	1.87
	1-C-100	37.5	180	480	759	856	0	1.87
	1-E-50 [b]	37.6	159	424	655	530	564	1.65
	1-E-100 [c]	37.6	155	411	633	1102	0	1.60
2	2-C-0	40.9	196	480	745	0	900	1.87
	2-C-40	40.9 [d]	196 [e]	480	724	340	540	1.87
	2-E-40 [b]	40.9 [f]	179 [g]	439	658	400	635	1.71
	2-E-80 [c]	40.9 [h]	177 [i]	432	645	822	218	1.68

[a] A solution of a water-reducing agent and an air-entraining admixture; [b] S = 1 in the original EMV method is applied; [c] S = 2 in the modified EMV method is applied; [d,e] In the plant, 203 kg of water was used due to the batch operator's mistake, being W/C = 42.3%; [f,g] In the plant, 194 kg of water was used due to the batch operator's mistake, being W/C = 44.2%; [h,i] In the plant, 192 kg of water was used due to the batch operator's mistake, being W/C = 44.4%.

3.2. Mixing Process

A volume capacity of 60 L of a concrete pan mixer was used in the laboratory for the series 1 tests. The admixture was thoroughly dispersed in the mixing water before being added to the mixer. Additionally, coarse aggregate and fine aggregate were added, giving the mixer a few turns. Cement was then added and the mixer was started and allowed to run for about 90 s. Finally, the water was added while the mixer was running and the concrete was mixed for another 120 s. For the series 2 tests, the material properties were established and structural beams were prepared with a volume capacity of approximately 700 L in a large concrete mixer in a PC plant. These were delivered to the Large-Scale Structural Laboratory of Stress at Hanyang University.

3.3. Specimen Preparation

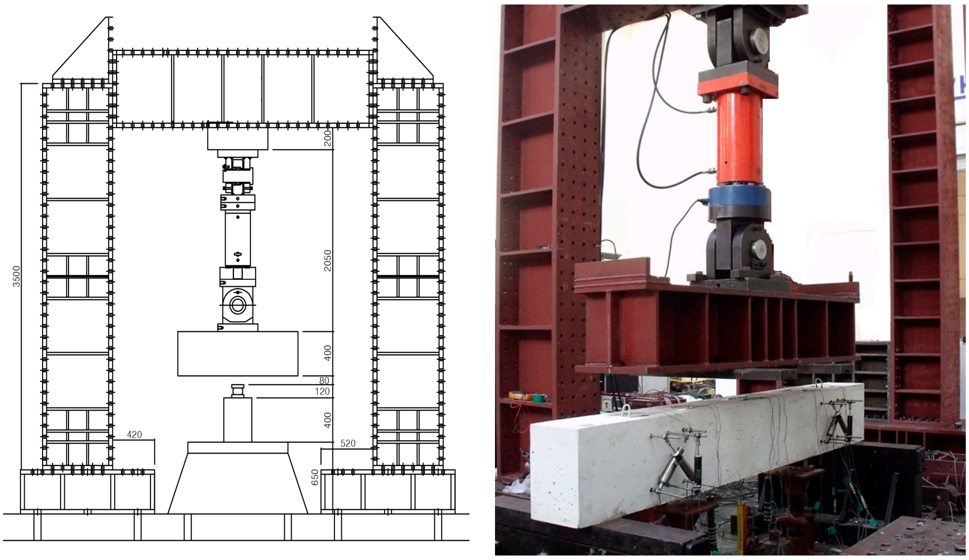
To investigate the properties of the fresh concrete, slump and air content tests were conducted. To assess the material properties of the hardened concrete, specimens were cast in a steel mold with a specified consolidation method [17], and then removed 24 h later. For the series 1 tests, all specimens were cured in a moist condition at approximately 20 ± 2 °C from the time of molding until the moment of the tests. For the series 2 tests, after formwork removal, the cylinders were cured in a water container [20] while the structural beams were cured in air in the PC plant yard. The curing conditions, for which cylinder is stored in water container and beam is cured in air, will alter the actual mechanical properties of all the mixtures. For similar duration of curing, specimens cured in the lab will have higher mechanical properties relative to those cured in the plant yard. However, in this study, relative strength properties between different mixtures were compared thus no correlation applied between different curing methods.

Three cylindrical specimens 100 × 200 mm in size were prepared to assess the compressive strength [21] and modulus of elasticity [22] of each mixture at different ages. For the series 2 tests only, three prisms 100 × 100 × 400 mm in size were prepared to assess the drying shrinkage [23] of the specimens for each mixture: for the drying shrinkage test, the initial curing lasted for seven days.

3.4. Flexural Performance Test Setup and Procedure

3.4.1. Testing Facilities

A load frame was assembled equipped with a maximum load of 2000 kN, with servo-hydraulic load cells intended to apply a two-point load to the test beams, as shown in Figure 3. The load was applied under displacement control at a rate of 0.5 mm/min. The beams were simply supported, 150 mm from each end of the beam, thus making a four-point bending condition.



(a) (b)

Figure 3. (a) Schematic diagram [24]; and (b) Photo of the flexural performance test setup.

3.4.2. Details of the Beams and Instrumentation

In total, five doubly reinforced beams were prepared to assess the flexural performance of reinforced RCA concrete beams for the second mixture series. All of the beams were rectangular (280 mm wide, 400 mm deep, effective length 340 mm) with a span length of 3480 mm, as shown in Figure 4. For each performance test, two beams were prepared as control specimens while one beam was prepared for the remaining mixture IDs [24].

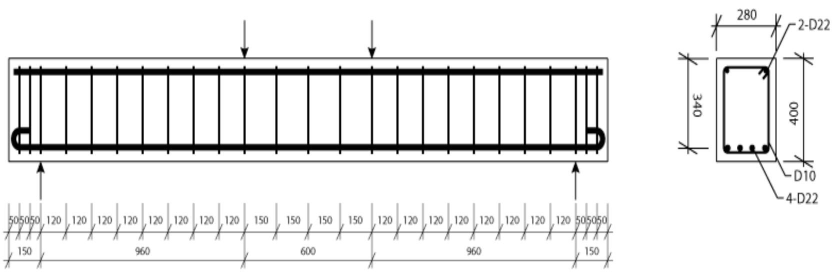


Figure 4. Details of the flexural beam [24].

Linear variable differential transducers (LVDTs) and strain gauges were mounted on the specimens to measure the deflections and strains at various locations. Figure 5 shows only the locations of the LVDTs. During the test, any cracks that formed on the surface of the beam specimen were marked at displacement increments of approximately 1.5, 3, 6, 7.5, 12.5, 25, and 46 mm.

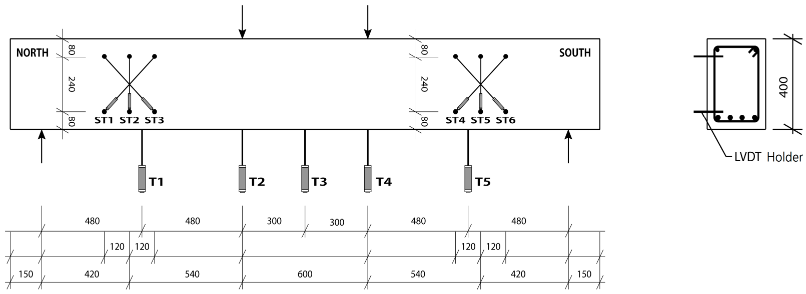


Figure 5. Linear variable differential transducer (LVDT) location on a flexural beam [24].

4. Test Results

4.1. Slump and Air Content

The test results showing the fresh concrete properties of the air content and the slump are shown in Figure 6. For the first mixture series, the slump of the conventional mixture ranged from 120 to 150 mm, but that of the EMV mixture dropped to about 80 mm. It is presumed that the decrease in the fresh mortar stemmed from the characteristics of the EMV mixture method, which is linked to slump loss [12]. The slump loss problem may be controlled by the use of an admixture.

However, for the second mixture series, the slump was evenly adjusted for all mixtures due to a mistake by the batch operator. This resulted in an excess of the unit water required, especially for the EMV mixture design. As explained previously in footnotes of Table 2, 15 kg of more water was used for both EMV mixtures. This led to *W/C* increase of 3.3% for 2-E-40 while *W/C* increase of 3.5% for 2-E-80, coincidentally causing slump increase. The air content reached nearly 4.0% for all of the mixtures.

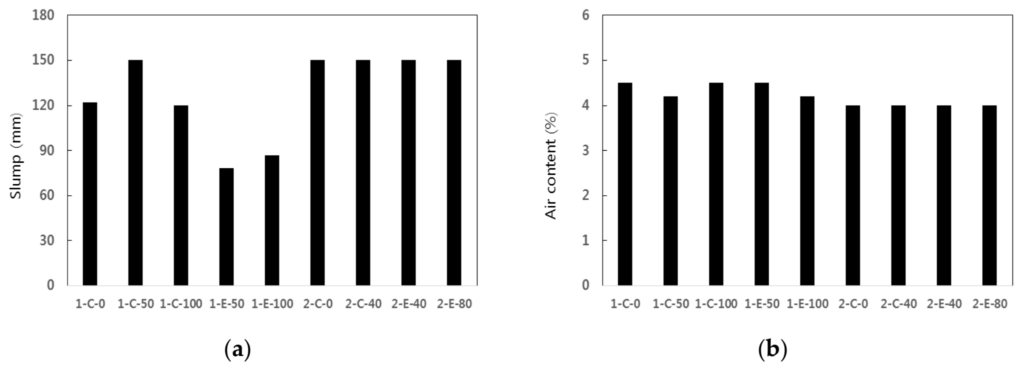


Figure 6. Fresh properties of the concrete mixtures. (**a**) Slump; (**b**) Air content.

4.2. Compressive Strength

The average compressive strengths for all of the mixtures are presented with error bars in Figure 7. For the first mixture series, the average compressive strength of the control mixture (1-C-0) at seven days was 31.4 MPa. The average compressive strengths of the conventional RCA mixtures, 1-C-50 and 1-C-100, were 30.7 MPa and 33.7 MPa, respectively, while those of the EMV RCA mixtures, 1-E-50 and 1-E-100, were respectively 33.2 MPa and 30.7 MPa. Overall, there is two to seven percent variation in the compressive strength, compared to the control mixture.

However, for the second mixture series, the strength variation in different mixtures appeared to be greater. The average compressive strength of the control mixture (2-C-0) at 14 days was 43.0 MPa but that of the conventional RCA mixture, 2-C-40 was 34.9 MPa, indicating a decrease of 20%. Moreover, those of the EMV RCA mixtures, 2-E-40 and 2-E-80, were correspondingly 38.5 MPa and 36.4 MPa, indicating 12% and 17% decreases in the compressive strength. In particular, the strength reduction in the EMV mixtures is attributed to the greater amount of water used in the PC batch plant, as previously explained, causing a sharp increase in the slump. Koo et al. [25] noted that an increase of one percent in the unit water leads to a 1.5 percent drop in the compressive strength. If considering the addition of the unit water in the EMV mixtures, the actual compressive strength levels of those mixtures would be equivalent to that of the control mixture.

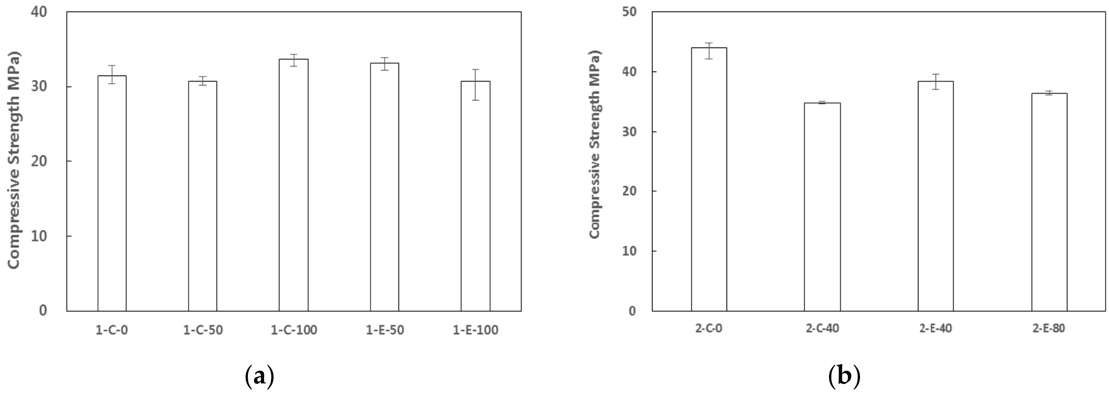


Figure 7. Compressive strength of the concrete mixtures. (**a**) At 7 days (Series 1); (**b**) At 14 days (Series 2).

4.3. Modulus of Elasticity

Figure 8 shows the modulus of elasticity of all of the concrete mixtures with error bars. For the first mixture series, the average elastic modulus of the control mixture (1-C-0) at seven days was 25.1 GPa. The average elastic moduli of the conventional RCA mixtures, 1-C-50 and 1-C-100, were 23.5 GPa and 23.7 GPa, respectively, while those of the EMV RCA mixtures, 1-E-50 and 1-E-100, were correspondingly 25.1 GPa and 24.1 GPa. As expected from the findings of previous research [12,13,24], the moduli of elasticity of RCA concretes with conventional mixture proportions (1-C-50) are less than those from the control mixture (1-C-0) and the EMV mixtures (1-E-50, 1-E-100) here.

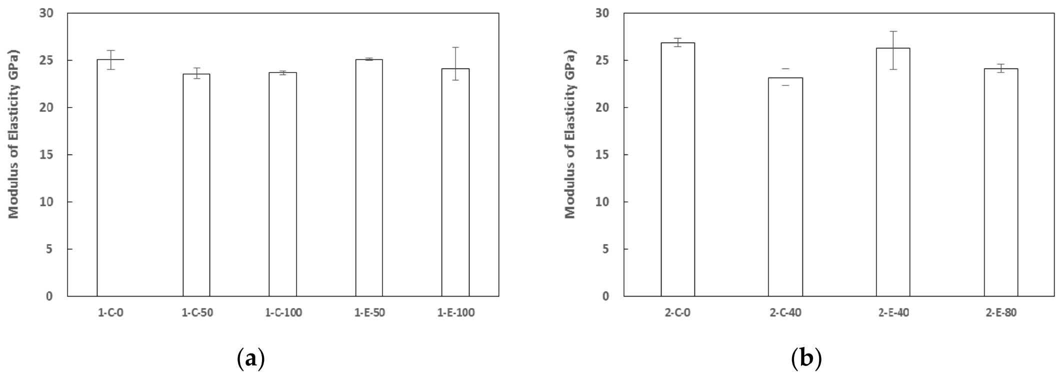


Figure 8. Modulus of elasticity of the concrete mixtures. (**a**) At 7 days (Series 1); (**b**) At 14 days (Series 2).

For the second mixture series, considerable variation in the modulus was noted. The average elastic modulus of the control mixture (2-C-0) at 14 days was 26.8 GPa, whereas that of the conventional RCA mixture, 2-C-40, was 23.2 GPa, indicating a decrease of about 13%. Additionally, those of the EMV RCA mixtures, 2-E-40 and 2-E-80, were respectively 26.3 GPa and 24.2 GPa, indicating 2% and

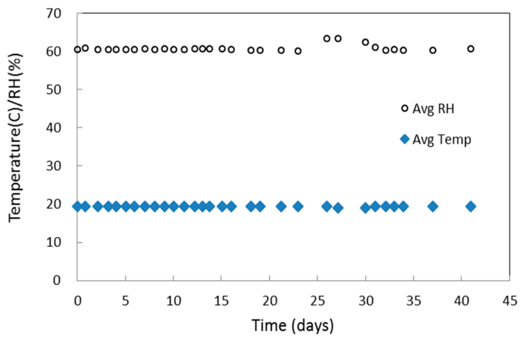
10% decreases in these values. As explained when discussing the compressive strength results, the reduced moduli in the EMV mixtures are mainly cause by the additional water used by the PC batch plant. Again if one considers the addition of the unit water in the EMV mixtures, the actual elastic moduli of those mixtures would be equivalent to that of the control mixture.

Overall, elastic modulus test results show that the RCA concretes created using the modified EMV method are greater than those of specimens created using the conventional ACI mixture design method. This is mainly due to the fact that the elastic modulus is a function of the volume fractions and the elastic moduli of the aggregate and the mortar [2,9,12,13,24].

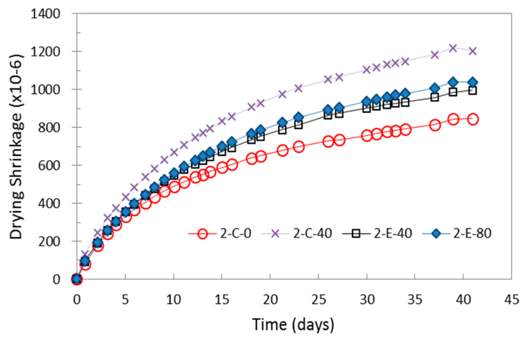
4.4. Drying Shrinkage

Drying shrinkage measurements were conducted for only the second mixture series. The drying shrinkage strain was measured by a digital dial gauge accurate up to 1/1000 mm. The specimens were kept inside a temperature-and humidity-controlled chamber (20 °C and 60% relative humidity (RH)). Figure 9a shows the changes in the temperature and relative humidity inside the chamber.

Figure 9b shows the development of drying shrinkage in the second mixture series over a period of 41 days. Each shrinkage strain curve represents the average value of three specimens. The average shrinkage strain of the control mixture, 2-C-0, at 41 days was 847 μm/m and that of the conventional mixture, 2-C-40, was 1204 μm/m, indicating a 42% increase. Meanwhile, those of the EMV mixtures, 2-E-40 and 2-E-80, were 996 μm/m and 1039 μm/m, indicating changes of 18% and 23%, respectively. It is remarkable that the drying shrinkage strains of 2-E-40 and 2-E-80 are 17% and 14% decreases, respectively, compared to 2-C-40 at 41 days. It is clear that the drying shrinkage strain of the conventional mixture (2-C-40) increases as the unit volume of the total mortar increases. However, it should be noted that more beneficial drying shrinkage may occur if the specified amount of water is used during the modified EMV mixture process in the PC batch plant, as mentioned earlier. For a given cement content, drying shrinkage is known to increase, both with increasing water-cement ratio [26] and slump [27].



(a)



(b)

Figure 9. Drying shrinkage measurement (for the series 2 mixture). (**a**) Temperature and relative humidity (RH) variation; (**b**) Shrinkage strain.

4.5. Flexural Performance

Figure 10 illustrates the cracking patterns of all test beams at failure. In these figures, the inclined lines and dark regions represent cracks and crushed zones, respectively. During loading, flexural cracks after the point of initial cracking propagated to the compression zone. Next, new flexural cracks appeared at both ends of the beams. The longitudinal tension yielded first, followed by concrete crushing in the compression zone. The crack propagation and failure mode of the reinforced control beams (2-C-0 mixture) were similar to those of the EMV40 beam (2-E-40 mixture).

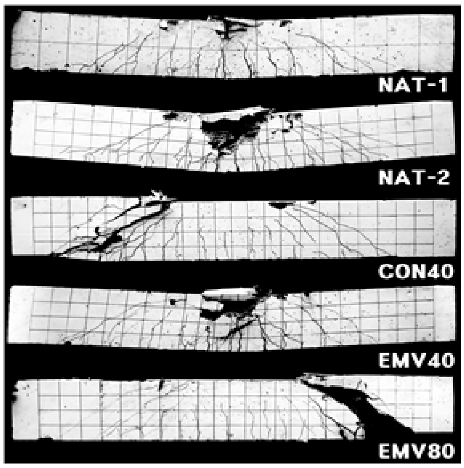
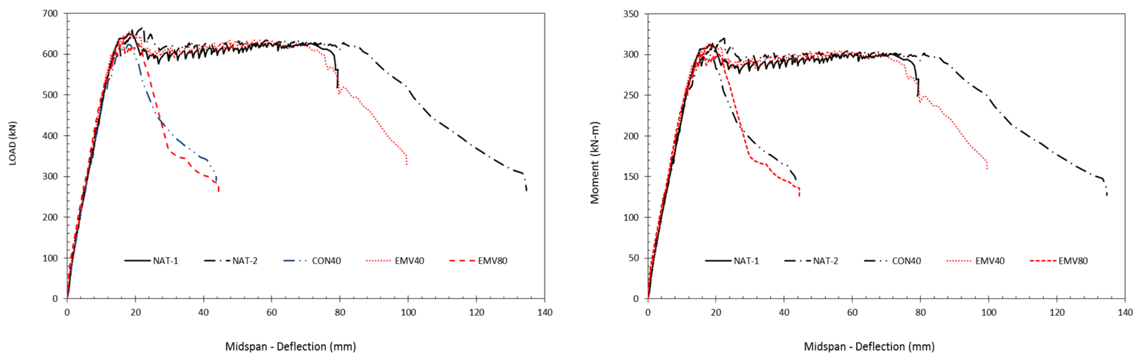


Figure 10. Typical crack patterns of the flexural beams [24].

Figure 11 shows the load-deflection relationship. The NAT-1 and NAT-2 beams (2-C-0 mixture) reached ultimate flexural moment values of 314.2 kN·m and 312.1 kN·m, respectively, representing an average of 313.2 kN·m for the 2-C-0 concrete mixture. The ultimate moment of the CON40 beam (2-C-40 mixture) was 299.2 kN·m, which is five percent less than that of the NAT beams (2-C-0 mixture). For the EMV40 beam (2-E-40 mixture), the ultimate strength was 313.8 kN·m, nearly identical to that of the NAT beams. The test result for EMV80 (2-E-80 mixture) was 302.4 kN·m, i.e., four percent less compared to the NAT beams but marginally more than the flexural capacity of the CON40 beam, created using the conventional mixture design with RCA as a coarse aggregate material.

For the two NAT beams and the EMV40 beam, ductile flexural behavior was noted, whereas the CON40 and EMV80 beams showed non-ductile behavior due to shear failure. The maximum amounts of deflection at the ultimate moment for all of the beams were nearly identical at approximately 18 mm. Unintentionally the difference between the flexural strength capacity and shear strength capacity was marginally designed. In addition, as shown in Table 3, 17 to 23 percent higher than the flexural strength values in the ACI 318-14 specifications were obtained from the RC beam performance tests. Both cases lead to shear failure in the CON40 and EMV 80 beam tests.



(**a**) (**b**)

Figure 11. Flexural strength curves of the flexural reinforced concrete (RC) beams. (**a**) Load-deflection; (**b**) Moment-deflection.

Table 3 presents the experimental ultimate moment values of the test beams at the ultimate load, where $M_{\text{u-exp}}$ denotes the ultimate moment in this experiment. These moments were compared with those of the current ACI 318-11 specifications, $M_{\text{u-ACI}}$, where their ratios are represented by the term exp/ACI. In terms of the ultimate moment, the experimental moments for the control mixture

(2-C-0) and the EMV mixtures (2-E-40 and 2-E-80) are about 22% greater than that in the ACI 318-14 specifications, while that of the conventional mixture (2-C-40) is 17% greater.

Table 3. Flexural performance test results.

Mixture ID	Beam ID	Mu-exp (kN·m)	Mu-ACI (kN·m)	exp/ACI
2-C-0	NAT-1	314.2	256.0	1.23
2-C-0	NAT-2	312.1	256.0	1.22
2-C-40	CON40	299.2	255.3	1.17
2-E-40	EMV40	313.8	253.8	1.24
2-E-80	EMV80	302.4	253.0	1.20

5. Conclusions

This paper aimed to determine the effect of a modified EMV method on the flexural performance of RCA concrete. Hence, an experimental study was carried out initially by testing the material properties of fresh and hardened RCA concrete specimens created using two different mixture design methods, i.e., the modified equivalent mortar volume (EMV) method and the conventional ACI method. The flexural performance capabilities of reinforced recycled concrete beams mixed with different mixture designs were then investigated. However, it should be noted that in the second mixture series, the slump was evenly adjusted for all mixtures due to a mistake by the batch operator, subsequently affecting some of test results. From the results of this study, the following conclusions were obtained.

(1) The slump of the conventional mixture ranged from 120 to 150 mm, but that of the EMV mixture dropped to about 80 mm, due to the characteristics of the EMV mixture method causing a decrease in the fresh mortar. However, an adjustment of the admixture in the EMV mixture may control the slump loss problem.
(2) Overall, there is some variation in the compressive strength of the RCA mixtures compared to that of the control mixture; however, no significant trend could be detected in the compressive strength results.
(3) The moduli of elasticity of the RCA concretes created using the modified EMV method are greater than those of specimens created using the conventional ACI mixture design method. This reconfirms the contention that the elastic modulus is a function of the volume fractions, thus enhancing the effectiveness of the modified EMV method.
(4) The drying shrinkage of RCA concrete specimens created using the modified EMV method tended to decrease, compared to that of specimens made with the conventional ACI mixture design method. It is clear that the drying shrinkage strain of the conventional mixture increases as the total unit volume of the mortar increases.
(5) The ultimate strengths of RC beams mixed using the modified EMV method are as much as five percent greater than those of specimens created using the conventional ACI mixture design method. The experimental moments of all of the beams are about 17%–22% greater than those in the ACI 318-11 specifications.

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