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Mechanical Strength Properties of RCA Concrete Made by a Modified EMV Method

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Abstract: This study used two types of Recycled Concrete Aggregates (RCAs) with the same original virgin aggregate, but with different amounts of residual mortars. To verify that the mechanical properties of the concrete were affected by changing the unit volume of residual mortar, fresh mortar, and total mortar of the concrete, a series of paving concrete mixes were made using a modified equivalent mortar volume (EMV) mix design, along with a conventional American Concrete Institute (ACI) mix design. The test results showed that the RCA concrete with the conventional mix design, which led to a prominent decrease in compressive strength and elastic modulus at each age, had 10% greater total mortar volume than that with the modified EMV mix design. As for the conventional ACI mix, it appears that the replacement ratio of RCA and the volume of the residual mortar in RCA directly affect the modulus of elasticity as well as the compressive strength of concrete. However, for the modified EMV mix, the modulus of elasticity of the concrete may be increased to be equivalent to the companion concrete with natural aggregate by controlling the new mortar volume so that the total mortar volume remains the same regardless of the RCA replacement ratio. It was observed that the smaller new volume requirement makes the RCA paving concrete more environmentally friendly and economically profitable.

Keywords: residual mortar; mortar volume; recycled concrete aggregate; compressive strength; elastic modulus

1. Introduction

Waste concrete can be transformed into high quality Recycled Concrete Aggregate (RCA) after 3–4 steps of a crushing process, which includes the removal of rebar, foreign substances, and residual mortar. The amount of residual mortar attached to the RCA changes during the crushing processes. This change affects the properties of the concrete created afterward. An increase in the amount of residual mortar lowers the physical characteristics of the concrete, such as compressive strength and modulus of elasticity [1–4]. Thus, various studies have been carried out to prevent variation in the characteristics of concrete [5–10].

The equivalent mortar volume (EMV) method proposed by Fathifazl et al. [5] in 2009 has received much academic attention. In the EMV theory, in fresh concrete state before hardening, residual mortar (RM) acts as coarse aggregate, while the RM, however, acts as mortar, after hardening. However, in the case of the American Concrete Institute (ACI) conventional mix design made with RCA concrete, the RM as well as the newly made mortar becomes the total mortar (TM). Total mortar ratio of the RCA concrete in the ACI conventional mix design is greater than that of natural aggregate concrete (NAC) mix. Fathifazl et al. [5] explain that this mortar ratio difference causes a decrease in the modulus of elasticity as well as an increase in the drying shrinkage. Fathifazl [2] proved with 45 research results that the change in the mortar strength and aggregate–mortar bond strength at the interfacial transition zone results in a decrease of the RCA concrete compressive strength by 0%–42%. In 17 articles, he states that the changes in the elastic modulus of natural coarse aggregate, the modulus of elasticity of the mortar, and the volume of the mortar cause the elastic modulus to decrease by 0%–45%. Using these findings, he proposed an equivalent mortar volume (EMV) mix design method on RM and demonstrated that the elastic modulus does not decrease. It should be noted that a decrease in elastic modulus does not always result in an increase of the cracking risk of concrete. Matthew et al. [11] demonstrated that the use of RCA reduces the cracking risk of concrete, by using restrained shrinkage ring tests.

This EMV method considers the residual mortar contained in the RCA as a part of the mortar instead of as an aggregate. Thus, compared to the conventional ACI mix design, the EMV mix design can decrease the amount of newly added mortar. This method not only prevents wasting resources, such as cement, sand, and water, but also eliminates the additional step of removing residual mortar from the RCA production process. The reduced step also contributes in the increase in the RCA value and economic benefits. It has been argued that the EMV method can greatly reduce the amount of cement and sand without changing the material properties before and after hardening of the concrete [5–8]. Mathew et al. [9] reported that the flexural strength and Young's modulus of natural aggregate concrete and recycled aggregate concrete are comparable, with the EMV mix proportioning method. Lee [10] confirmed that the use of the EMV mix proportioning method for structural concrete as well as paving concrete yielded modulus properties that were comparable or superior to the companion mix with conventional ACI mix design. He also proposed the modified EMV mix design. The residual mortar (RM) volume in RCA concrete was represented in the sum of the volume fraction of mortar and the other volume fraction of coarse aggregate using a scale factor to provide a minimum workability on fresh concrete level.

It is essential to determine the accurate amount of RM content in RCA to implement the EMV mix design. Numerous treatment processes have been proposed to come up with the RM content by various researchers [12–17]. These techniques generally use mechanical, chemical, thermal processing, or micro-assisted beneficiation and various combinations of these methods. To date, however, a universal standard method has not been established because different types of original virgin aggregates in RCA are affected by the adopted treatment method. For example, granite is known to be highly resistant to chloric and sulfuric acid, while hydrofluoric acid may dissolve it [14].

Even though many studies state the effectiveness of EMV mix design, there are no studies focusing on the relationship between the properties of concrete and the volumetric characteristics of mortar that is a combination of RM and fresh mortar. This study focuses on the relationship using two types of RCAs with the same original virgin aggregate, but with different amounts of residual mortars. To verify that the mechanical properties of concrete are affected by the changes in the unit volumes of residual mortar, fresh mortar, and total mortar of concrete, a series of concrete mixes were prepared using the modified equivalent mortar volume mix design along with the conventional ACI mix design.

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

To visually determine volume fractions of the mortar and the original virgin aggregate of RCA, concrete was examined by preparing a specimen with only coarse RCA and white cement. Figure 1 shows a polished section of a cylindrical specimen [18]. The white part of the section shown on the left of Figure 1 is white cement mortar, and the rest is RCA. The darker spots of RCA shown on the right of Figure 1 are original virgin aggregates, and the lighter part is residual mortar (RM).

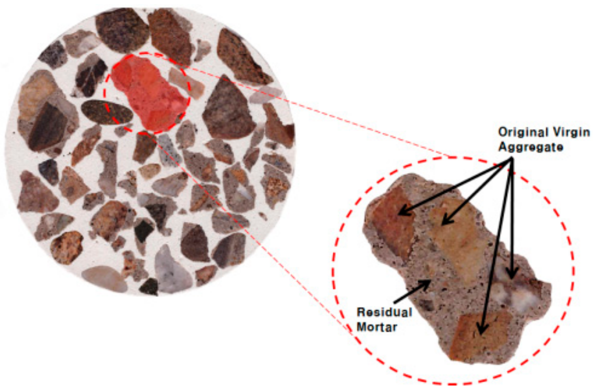

Figure 1. Polished concrete specimen mixed with white cement and coarse RCA only.

Figure 2 below shows the difference between the concepts of the original EMV method and the modified EMV method in which a scale factor, S, is introduced [19]. Symbols used in Figure 2 are explained in Figure 2d Notations. In the EMV mix design, it was ensured that the total volume of natural aggregate (V_{TNA}, partly from RCA as well as partly from new fresh aggregate) in RCA concrete (RAC) is equal to the volume of natural aggregate in conventional concrete with the same specified properties [1]. Thus, the new mortar volume is reduced in proportion to the amount of RM attached to the RCA. However, especially for a paving concrete mix, if RCA is used with more than a certain amount of coarse aggregate or with more residual mortar content (RMC), it was noted that the fine aggregate amount by the EMV concept would lead to be below a certain minimum value [19]. The shape or formability of concrete may then be a concern due to the lack of fillers. The decrease in fresh mortar affects the shape as well as the constructability due to the slump loss.

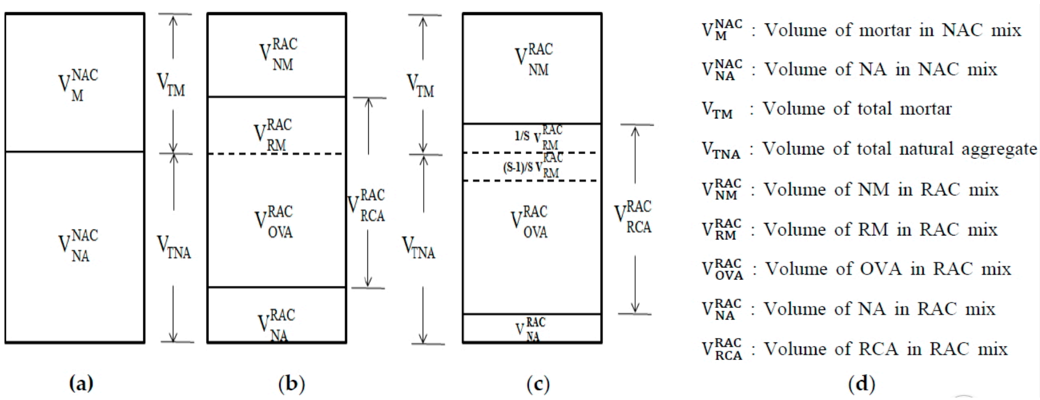

Figure 2. Comparison of various mix design concepts [19]: (**a**) conventional mix; (**b**) original EMV mix; (**c**) modified EMV mix; and (**d**) notations.

It was considered in the modified EMV model [15] that the RM attached to RCA serves as aggregate in fresh concrete, and as mortar after it is hardened. Considering this treatment, the RM volume in RAC was represented in the sum of the volume fraction of the mortar $\frac{1}{S}V_{RM}^{RAC}$ and the other volume faction of the aggregate $\frac{S-1}{S}V_{RM}^{RAC}$, using the scale factor S as follows:

$$V_{RM}^{RAC} = \frac{1}{S}V_{RM}^{RAC} + \frac{S-1}{S}V_{RM}^{RAC} \tag{1}$$

Therefore, the value of R was modified as follows:

$$R = 1 - \frac{V_{RCA}^{RAC}}{V_{NA}^{NAC}} \times (1 - \frac{1}{S} \times RMC) \times \frac{SG_b^{RCA}}{SG_b^{OVA}} \quad (2)$$

where the volume of fresh NA in the natural aggregate concrete (NAC) is represented by V_{NA}^{NAC} and the volume of RCA in RCA concrete by V_{RCA}^{RAC}; and SG_b^{RCA}, and SG_b^{OVA} are the bulk specific gravities of RCA and the original virgin aggregate (OVA), respectively.

The RM volume in RAC is then modified as

$$V_{RM}^{RAC} = V_{RCA}^{RAC} \times [1 - (1 - \frac{1}{S} \times RMC) \times \frac{SG_b^{RCA}}{SG_b^{OVA}}] \quad (3)$$

The volumes of the fresh or new mortar and total mortar are subsequently calculated as

$$V_{NM}^{RAC} = (\frac{W_{OD-FA}^{RAC}}{SG_b^{OD-FA}} + \frac{W_C^{RAC}}{SG_b^C} + W_W^{RAC})/1000 \quad (4)$$

$$V_{TM}^{RAC} = V_{RM}^{RAC} + V_{NM}^{RAC} \quad (5)$$

where the oven-dry weight of fine aggregate in the RAC is represented by W_{OD-FA}^{RAC} and the weights of cement and water are W_C^{RAC} and W_W^{RAC}, respectively. SG_b^{OD-FA} and SG_b^C denote the bulk specific gravities of the fine aggregate and cement, respectively. Additional equations for the modified EMV method can be found in Reference [19].

3. Materials and Mix 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 3380 cm^2/g. The chemical admixture used in this study was a solution of air entraining and water reducing agent.

3.1.2. Aggregates Material Properties

Natural sand was used as a fine aggregate. The specific gravity was 2.62, and the absorption ratio was 0.54%. Table 1 summarizes the material characteristics of the fine aggregate.

Table 1. Physical properties of the fine aggregates.

Specific Gravity			Absorption Capacity (%)
SSD	**Bulk**	**Apparent**	
2.63	2.62	2.65	0.54

This experiment used two types of coarse RCAs (RA1 and RA2), which have the same original virgin aggregate but different amounts of residual mortar. RA2 was additionally created by putting the collected RCA in a VSI (vertical shaft impact) crusher, which removes a significant amount of attached mortar from the abrasion between aggregates [18]. From the polarization microscope test of the three test samples, the mineral name of the original virgin aggregates were found to be shist, biotite shist and diorite [10]. It is known that shist and biotite are related to gneiss. Table 2 summarizes the material characteristics of the coarse aggregates. All of the aggregates size distributions are shown in Figure 3.

It is essential to quantify the residual mortar attached to the RCA to manufacture concrete using the EMV mix design. Although many methods to quantify residual mortar have been proposed, a standard method has not been established. In this study, Abbas's method of removing the residual mortar [12] was considered as a possible chemical treatment method. However, the samples must be put in and taken out of a sodium sulfate solution at specific times, and it takes about 7 days to assess the amount of residual mortar. Thus, a hydrochloric acid solution was used to expedite this process in this study: 36% concentrated hydrochloric acid was mixed with distilled water to make a 1 M concentrated hydrochloric acid solution, and the samples were precipitated. After 24 h, the aggregates were washed with water over a No. 4 sieve. The washed aggregates were placed in an oven at 105 °C for 24 h, and the oven-dried mass was measured. The following equation was used to obtain the RMC value:

$$\text{RMC}\ (\%) = \frac{W_{RCA} - W_{OVA}}{W_{RCA}} \tag{6}$$

where W_{RCA} denotes the initial oven-dried weight (g) of the RCA sample before the test and W_{OVA} is the final oven-dried weight (g) of the OVA after removing the residual mortars.

A natural coarse aggregate (CA) was also tested to prove that only the residual mortar is dissolved by this acid treatment, not the original virgin aggregate. The sampling process of the aggregates from the experiment is conceptually illustrated in Figure 4, in which CA-HCl, RA1-HCl, and RA2-HCl denote the CA, RA1, and RA2 samples after hydraulic acid treatment, respectively. It can be verified from Table 3 that aggregates with residual mortar removed rise in SiO_2, the main component of the whole aggregate, and fall in CaO, the main component of cement. The CA sample meanwhile did not show any significant change in chemical composition.

Table 2. Physical properties of the coarse aggregates.

Test Item	CA	RA1	RA2	KS [a] Requirement [20,21]
Specific gravity (Bulk)	2.60	2.26	2.50	>2.5
Specific gravity (SSD)	2.61	2.40	2.56	-
Specific gravity (Appar.)	2.65	2.62	2.67	-
Absorption capacity (%)	0.77	6.07	2.87	<3.0
Unit weight (kg/m^3)	1510	1370	1500	-
Soundness (%)	7.3	34.9	11.6	<12
Abrasion resistance (%)	23.2	28.8	13.2	<40

[a] The Korean Standard (KS) specifications.

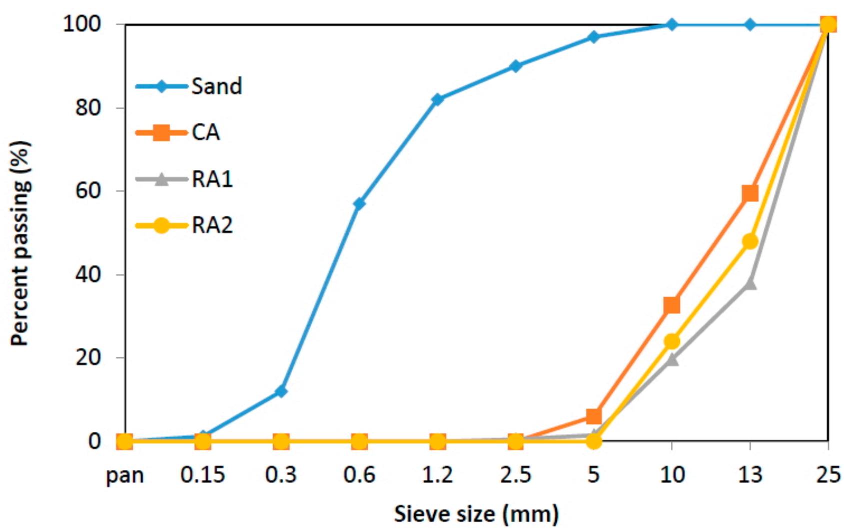

Figure 3. Aggregates grading.

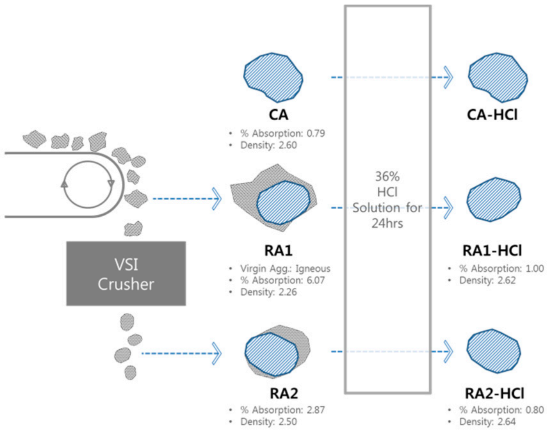

Figure 4. Conceptual illustration of the aggregate treatment process.

Table 3. Chemical composition of the aggregates [22].

Aggregate ID	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	MnO	TiO_2	Rb_2O
CA	63.92	16.44	4.47	1.10	4.15	0.91	8.01	0.06	0.61	0.05
CA-HCl	66.21	16.02	4.37	-	3.40	0.71	8.34	-	0.72	0.06
RA1	40.73	9.41	7.41	1.03	35.48	0.37	3.01	0.17	1.01	-
RA1-HCl	66.54	13.56	7.05	1.23	4.33	0.67	5.11	0.10	1.01	0.03
RA2	54.20	12.40	8.37	1.19	16.36	0.38	8.37	0.13	1.11	0.05
RA2-HCl	68.26	13.91	6.25	1.08	3.20	0.63	5.54	0.07	0.90	0.05

Figures 5 and 6 show samples of the natural aggregates and RCAs, respectively, before and after hydrochloric acid dissolution. Figure 5 shows dismantled virgin aggregates and residual mortars after the hydrochloric acid treatment.

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

Figure 5. Natural aggregate samples before and after HCl immersion [18]: (**a**) before HCl; and (**b**) after HCl.

Even after the hydrochloric acid treatment, some residual mortar may not be completely removed. The unseparated residual mortar was susceptible to small impacts; therefore, residual mortars were quantified after their manual separation.

The specific gravities and the absorption ratios of the three types of aggregates after the hydrochloric acid treatment are presented in Table 4. It was verified that RA1 and RA2 have the same original virgin aggregate based on the similarity of the chemical composition in Table 3 and the similar specific gravities and absorption values after the dissolution process in Table 4.

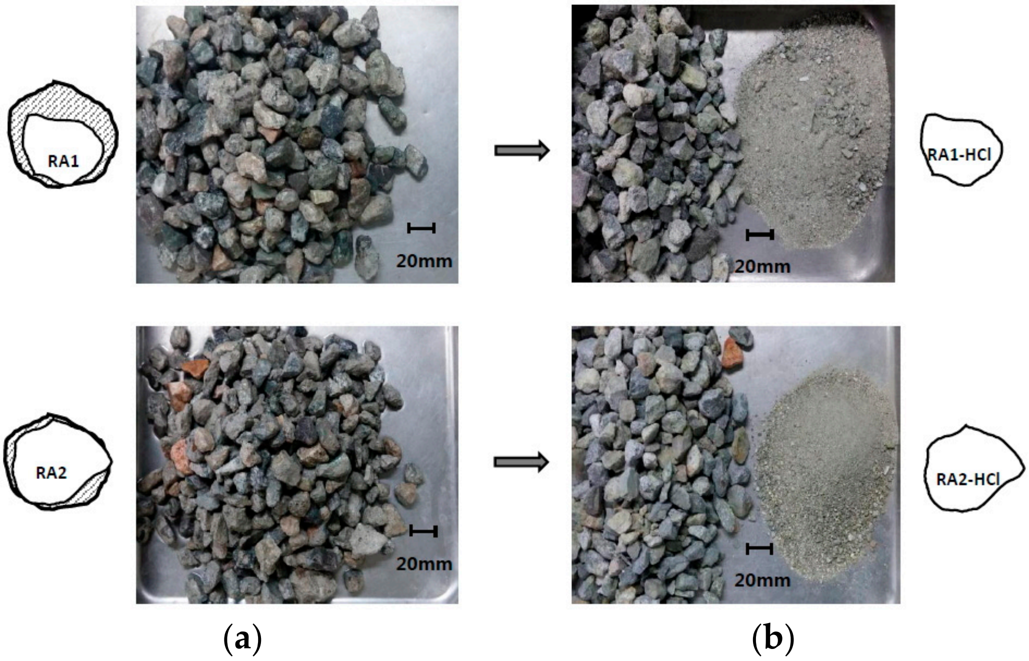

Figure 6. RCA samples before and after HCl immersion [18]: (**a**) before HCl; and (**b**) after HCl.

Table 4. Specific gravity and absorption ratio of the coarse aggregates after HCl immersion treatment.

Test Item	CA-HCl	RA1-HCl	RA2-HCl
Specific gravity (Bulk)	2.60	2.62	2.64
Specific gravity (SSD)	2.62	2.65	2.66
Specific gravity (Appar.)	2.64	2.69	2.69
Absorption capacity (%)	0.76	1.00	0.80

RMC values were finally determined with Equation (5). Test results showed that RA1 and RA2 have 50% and 12% of their aggregate mass from residual mortars, respectively.

Approximate ranges of the RMC values can be confirmed or obtained by the RMC correlation in terms of water absorption and bulk density. Formulas reported by Akbarnezhad et al. [14] estimated that the RMC values of RA1 and RA2 are 55%–60% and 25%–30%, respectively, from the aggregate absorption relation, while the RMC values of RA1 and RA2 are 50%–60% and 10%–20%, respectively, from the bulk density relation.

3.1.3. Mix Design

A series of mixes were designed for a highway paving concrete with a maximum aggregate size of 25 mm, as shown in Table 5. The target air content for all mix designs was a minimum of 4.0% and the slump value was under 50 mm. The water/cement ratio was set to 43% for all the mixes. One can notice that in the modified EMV mixes in Table 5, the amounts of the cement and sand required to blend the RCA paving concrete mix are less than those in the conventional concrete mixes. This is due to the fact that the EMV method uses more coarse aggregates than that of the conventional method, resulting in less fresh mortar content in the former than in the latter. This creates two major benefits: economic and environment-friendly. First, the EMV method is more economically profitable than that of the conventional method because it uses more coarse aggregates, which are low in price, but less fresh mortar, which is high in price. For example, cement and sand are the most expensive components among all the components of a concrete mix. As the amount of the cement and sand used are reduced, the cost the manufacturer has to pay decreases. Secondly, because the EMV method makes more use of

RA than that of the conventional method, the demand for cement and sand is reduced thus saving natural resources and the environment. However, it should be noted that for a general purpose of concrete mix, i.e., structural concrete with slump value of about 150 mm, further study is needed to overcome any possible slump loss which may occur using the modified EMV mix proportioning method, by considering the use of admixtures.

The mix design ID in Table 5 can be explained as follows. There are three different sets of terms. The first, CA, RA1, and RA2, denotes the type of coarse aggregates used. The second, 1–3, denotes the RCA replacement levels and the S values applied in Equations (1) and (2). The third term C designates the conventional mix design, while E is the EMV mix design. For example, RA1-2-E denotes the EMV mix design substituted with RA1 aggregates, but proportioned with S = 2 in Equation (1).

Table 5. Concrete mix designs.

ID	RCA (%) [a]	RMC (%)	S/a [e] (%)	Mix Proportions (kg/m^3)					
				W	C	NA	RA	Sand	Admixture [f]
CA-1-C	-	-	45.0	140	326	1029	0	812	0.65
RA1-1-C	26	50	45.0	140	326	772	236	812	1.63
RA1-2-C	51	50	45.0	140	326	514	473	812	1.63
RA1-3-C	100	50	45.0	140	326	0	946	812	0.65
RA2-1-C	25	12	45.0	140	326	772	252	812	0.65
RA2-2-C	51	12	45.0	140	326	514	505	812	0.65
RA2-3-C	100	12	45.0	140	326	0	1005	812	0.65
RA1-1-E [b]	22	50	39.0	126	293	917	224	730	1.47
RA1-2-E [c]	30	50	40.3	128	299	805	298	745	1.50
RA1-3-E [d]	100	50	32.4	102	237	0	1235	591	0.47
RA2-1-E [b]	24	12	42.8	136	317	811	247	790	0.63
RA2-2-E [c]	45	12	42.7	136	316	594	463	786	0.63
RA2-3-E [d]	100	12	41.6	132	307	0	1072	764	0.61

[a] Ratio of the RCA volumetric proportion to total coarse aggregates. [b] S = 1 in Equation (1) which is the same as the original EMV method is applied; [c,d] S = 2 and 3 in Equation (1) is applied, respectively; [e] Volume ratio of sand (fine aggregate) to total aggregate; [f] A solution of water reducing agent and air entraining admixture.

The unit volumes of mortar in terms of residual mortar, new fresh mortar and total mortar are determined using Equations (2)–(4) and summarized in Table 6. A noticeable rise in the volume fraction of total mortar up to 67% from the conventional mix design can be seen in Table 6, while a volume fraction of total mortar of 55% was maintained for all the EMV mix designs as well as the control mix design (CA-1-C).

Table 6. Mortar volume fractions in concrete.

Mix ID	V_{RM}	V_{NM}	V_{TM}
CA-1-C	0	0.552	0.552
RA1-1-C	0.059	0.552	0.611
RA1-2-C	0.073	0.552	0.625
RA1-3-C	0.115	0.552	0.667
RA2-1-C	0.015	0.552	0.567
RA2-2-C	0.019	0.552	0.571
RA2-3-C	0.031	0.552	0.583
RA1-1-E	0.056	0.497	0.553
RA1-2-E	0.046	0.507	0.553
RA1-3-E	0.151	0.403	0.553
RA2-1-E	0.015	0.538	0.553
RA2-2-E	0.018	0.536	0.554
RA2-3-E	0.033	0.520	0.553

3.2. Mixing Process for Making the Concrete Specimens

A concrete pan mixer with a volume capacity of 60 L 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 mixer a few turns. Cement was subsequently added, and the mixer was run for about 90 s. Finally, water was added while the mixer was running, and the concrete was mixed for another 120 s.

3.3. Specimen Preparation

Two properties of concrete, the compressive strength and modulus of elasticity, were measured. Specimens were casted in a plastic mold with the specified consolidation method [23] and removed 24 h later. All specimens were moist cured at about 20 ± 2 °C from the time of molding until the moment of the tests. The compressive strength and modulus of elasticity of each mixture were the averaged value of three cylinders tested on different days. The cylinders were 100 mm × 200 mm in size.

4. Test Results

4.1. Compressive Strength

Table 7 shows the test results for the compressive strengths of the concrete specimens using the conventional mix and the EMV mix design. Before an analysis is made, it should be noted that the RA1-3-E mix with a volume fraction of fresh (or new) mortar of 0.403 (shown in Table 6) was not workable enough to prepare a specimen. It is regarded that there is a proper range for the new mortar volume that can be applied to the production of recycled aggregate concrete. The RA1-3-E is believed to be outside of the proper range and hence, is excluded from the tendency analysis hereafter. Figure 7 plots the compressive strength of RCA concrete at the age of 7, 28, and 60 days corresponding to the volume fraction of the residual mortar. Figure 8 shows similar data, but with a new mortar volume fraction.

Table 7. Compressive strength results of the concrete specimens.

ID	Compressive Strength (MPa)		
	7 d	28 d	60 d
CA-1-C	24.3	30.9	33.3
RA1-1-C	22.4	27.9	29.9
RA1-2-C	20.6	25.8	28.9
RA1-3-C	19.0	23.6	25.8
RA2-1-C	23.4	30.9	33.6
RA2-2-C	22.9	29.3	33.4
RA2-3-C	23.7	28.1	32.0
RA1-1-E	24.2	30.9	34.5
RA1-2-E	25.0	31.5	31.6
RA2-1-E	23.0	29.5	34.5
RA2-2-E	22.6	29.3	31.6
RA2-3-E	24.2	30.1	33.5

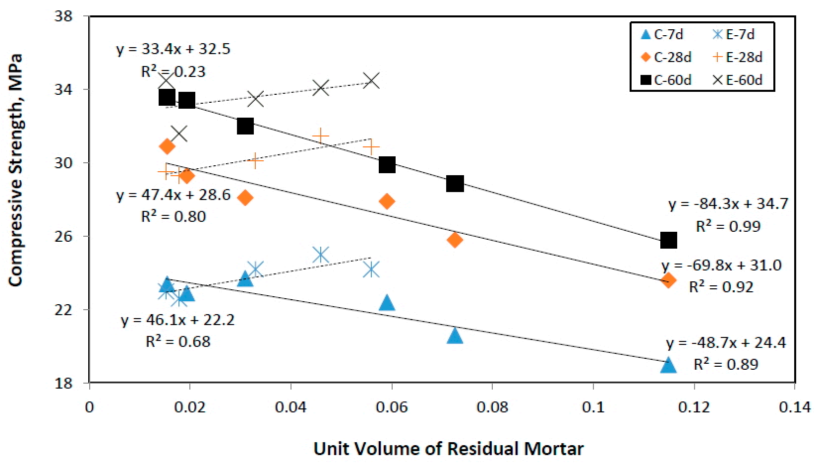

Figure 7. Compressive strength results of the concretes with the residual mortar volume.

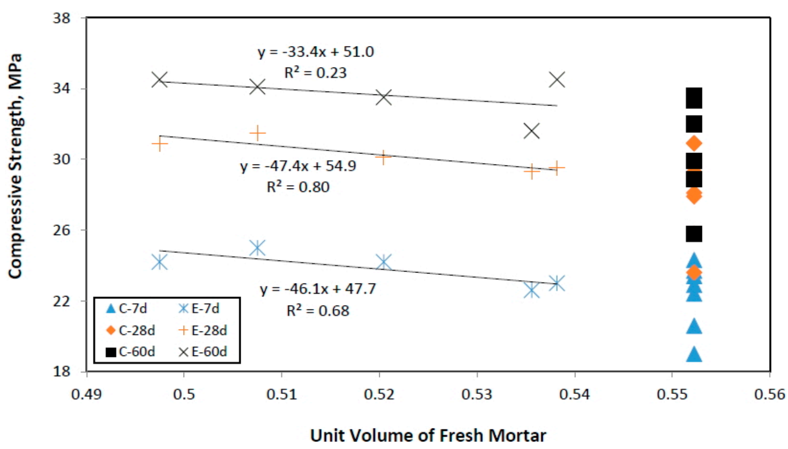

Figure 8. Compressive strength results of the concretes with the new mortar volume.

In Figure 7, the compressive strengths of all the conventional RCA mixes were shown to have a decreasing tendency at each age as the unit volume of their residual mortars (Equation (2)) increased from 2% to 12%, while the EMV mixes showed the opposite trend. In Figure 8, the compressive strengths of the EMV concretes showed a slight decrease with increasing unit volume for their fresh mortar (Equation (3)). It should be noted that the conventional RCA mixes showed a wide range of compressive strength results although the unit volume of new mortar was kept the same.

The compressive strength results are represented as a function of the unit total mortar volume (Equation (4)) in Figure 9. The compressive strengths of the EMV concretes, which remained constant in the total mortar volume, clustered at each age. On the other hand, the compressive strengths of the conventional RCA mixes showed a decreasing tendency at each age as the unit volume of total mortar increased with a variation of about 10%. These results show that the replacement ratio of RCA and the amount (or volume) of residual mortar may act as critical factors to decrease the compressive strengths of the conventional RCA mixes. However, they have a trivial influence on the compressive strengths of the EMV concretes because the total mortar volume is controlled by adjusting the volume (or amount) of new mortar.

Figure 10 compares the relative compressive strengths of the EMV concretes to those of the conventional concretes at the age of 28 days for each series. For the series of RA1 mixes with a RCA absorption rate of 6.1 and a RMC of 50%, the relative compressive strength gain of the EMV concrete was 11%–22%, whereas for the series of RA2 mixes with a RCA absorption rate of 2.87 and a RMC of 12%, the gain was −4.5%–7% (see the percent numbers in Figure 10). It appears that the EMV concrete, although made with RCA that fails to meet the original quality requirement of RCA in terms of specific gravity and absorption rate according to the Korean standards, was still effective achieving compressive strength gain. However, it should be noted that, compared to the results of the control mix (CA-1-C, reference line in Figure 10) in Table 7 the EMV concrete did not produce equivalent strengths consistently at all ages. It was pointed out by Fathifazl et al. [4] that concrete compressive strength is mostly dependent on the strength of mortar and the interfacial transition zone and not a function of the volume fractions.

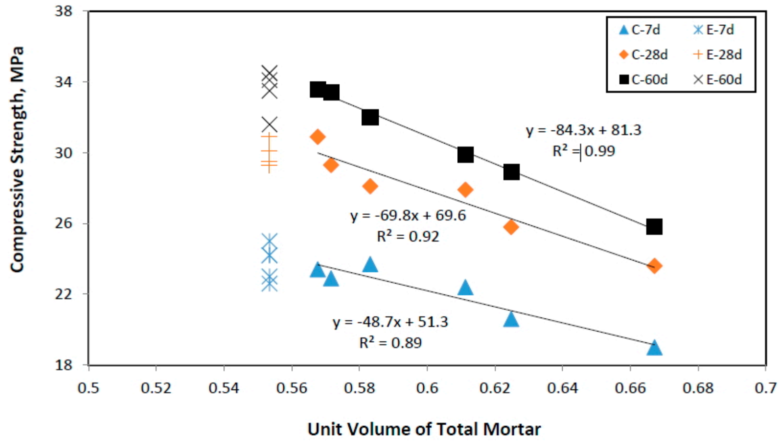

Figure 9. Compressive strength results of the concretes with the total mortar volume.

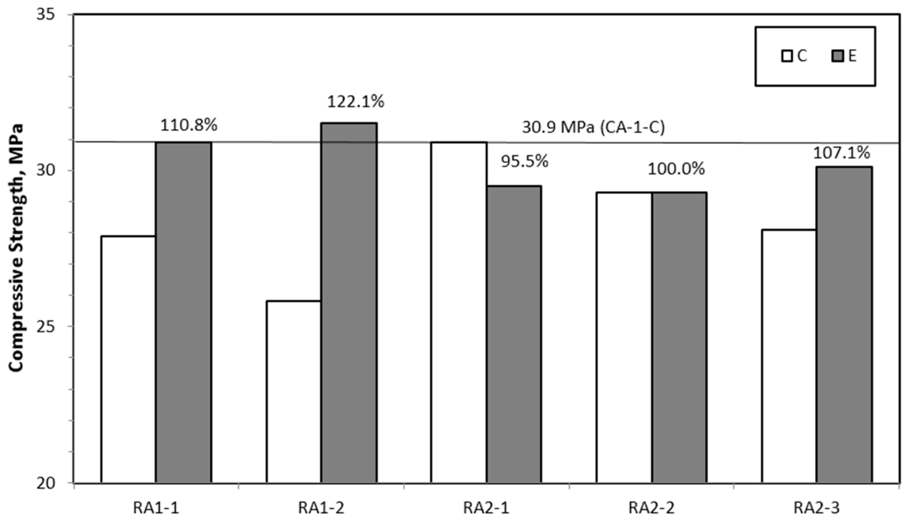

Figure 10. Effect of mix proportioning method on the compressive strength.

4.2. Modulus of Elasticity

The modulus of elasticity measured in this study is summarized in Table 8. Again, the RA1-3-E data were excluded from the analysis for the same reason as before in the previous section. Looking at Table 8 it should be noted that the modulus of elasticity at an age of 28 days from the EMV mix lies between 22.2 and 23.4 GPa, while that from the conventional RCA mix is in a range of 17.4–23.6 GPa, with 21.8 GPa for the control mix (CA-1-C).

Figures 11 and 12 are graphs of the modulus of elasticity of concrete with the unit volume of residual mortar and new mortar, respectively. It could be assumed from Figures 10 and 11 that the unit volume of both the residual mortar and new mortar has little influence on the modulus of elasticity for the EMV mixes. However, the elastic modulus of the conventional RCA mixes resulted in a prominent decrease as the unit volume of their residual mortar increased. This is a similar tendency as seen in the compressive strength results.

Table 8. Modulus of elasticity results for the concretes.

ID	Modulus of Elasticity (GPa)		
	7 d	28 d	60 d
CA-1-C	17.8	21.8	23.9
RA1-1-C	17.2	20.6	22.0
RA1-2-C	15.1	19.3	21.8
RA1-3-C	14.0	17.4	19.7
RA2-1-C	18.0	22.7	24.1
RA2-2-C	18.9	22.4	24.2
RA2-3-C	18.7	23.6	25.3
RA1-1-E	18.5	22.2	23.7
RA1-2-E	19.4	23.4	24.4
RA2-1-E	17.6	22.6	25.0
RA2-2-E	18.3	22.9	24.5
RA2-3-E	19.9	23.2	25.7

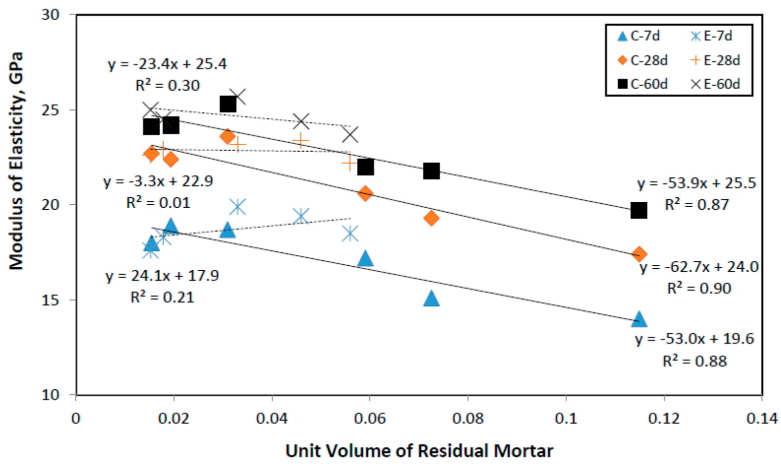

Figure 11. Modulus of elasticity results of the concretes with the residual mortar volume.

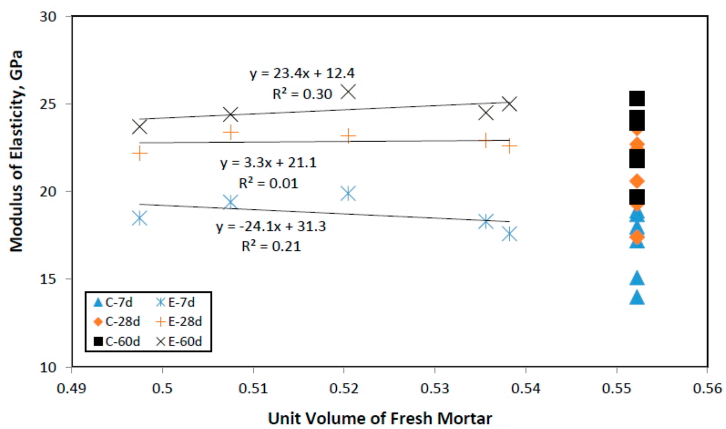

Figure 12. Modulus of elasticity results of the concrete with the new mortar volume.

Figure 13 plots the modulus of elasticity of concrete with the unit volume of total mortar. The modulus of elasticity had results similar to that for the compressive strength; that is, the elastic modulus of the conventional mixes showed a decreasing tendency at each age as the unit volume of total mortar increased with a variation of about 10.0%. Similar to the test results for the compressive strength, it could be concluded that the replacement ratio of RCA and the amount (or volume) of residual mortar may act as critical factors to decrease the elastic modulus of the conventional RCA mixes, too. However, for the modified EMV mix, the modulus of elasticity of the concrete may be improved to be equivalent to the companion concrete with natural aggregate because the total mortar volume is controlled by adjusting the volume (or amount) of new mortar. One cannot emphasize enough the fact that the modified EMV method reduces the cement and sand requirement of the RCA paving concrete mix because it requires less fresh mortar than that required by the conventional method. The smaller new volume requirement makes the RCA paving concrete more environmentally friendly.

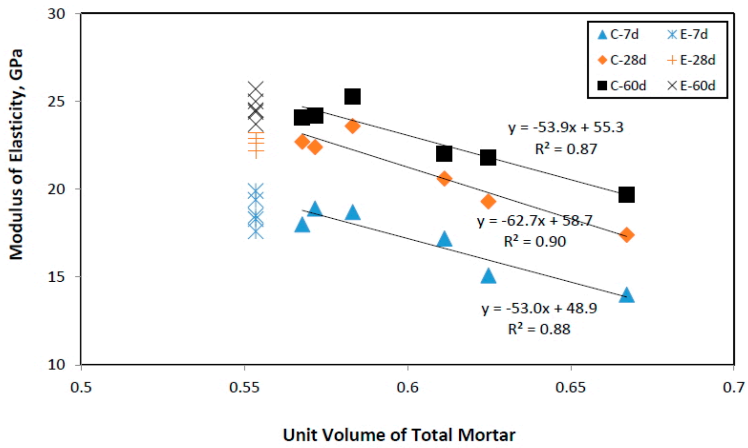

Figure 13. Modulus of elasticity results of the concretes with the total mortar volume.

Figure 14 compares the relative modulus of elasticity of the EMV concretes to those of the conventional concretes at the age of 28 days for each series. For the series of RA1 mixes, the relative elastic modulus gain of the EMV concrete was 8%–21%, whereas for the series of RA1 mixes, the gain was −2%–2% (see the % numbers in Figure 14). It is shown in Figure 14 that the elastic modulus of all the EMV mixes is up to 12% higher than that of the companion CA-1-C mix (reference line in Figure 14). This is mainly attributed to the equality of the total volume. These results clearly show that the use of the modified EMV mixture proportioning method leads to a comparable elastic modulus for the RCA mixes to that of similar mixes made with natural aggregates. 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 mortar [24–26].

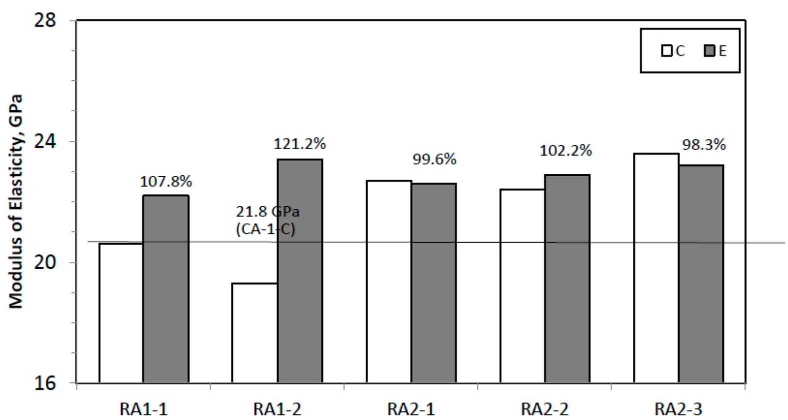

Figure 14. Effect of mix proportioning method on the modulus of elasticity.

5. Conclusions

A series of concrete mixes were made with two different mix design methods, i.e., the modified equivalent mortar volume (EMV) mix design and the conventional ACI mix design, to evaluate the effect of the change in the unit volume of residual mortar, fresh mortar, and total mortar of concrete on the compressive strength and the modulus of elasticity. In order to control the residual mortal content in this experiment, two types of RCAs with different amounts of residual mortars but with the same original virgin aggregate were used. From the results of this study, the following conclusions were obtained.

(1) Test results confirmed that RCA concretes with the conventional ACI mix proportions lead to as much as a 10.0% difference in the unit total mortar volume depending on the RCA substitution level, and they showed a decreasing tendency for the compressive strength and elastic modulus for each age, as the unit volume of total mortar increased.
(2) As for the conventional mix, the replacement ratio of RCA and the volume of the residual mortar in RCA directly influence both the compressive strength and the modulus of elasticity of concrete.
(3) However, for the modified EMV mix, the modulus of elasticity of the concrete may be increased to be equivalent to that of the companion concrete with natural aggregate by controlling the new mortar volume so that the total mortar volume remains the same regardless of the RCA replacement ratio.
(4) The modified EMV method reduces the cement and sand requirement of the RCA paving concrete mix because it requires less fresh mortar than that required by the conventional method. The smaller new volume requirement makes the RCA paving concrete more environmentally friendly and economically profitable.

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