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Effect of Different Types of Recycled Concrete Aggregates on Equivalent Concrete Strength and Drying Shrinkage Properties

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Featured Application: Use of coarse RCA produced from old PC concrete is promising for structural concrete mix, which is proportioned by the modified equivalent mortar volume method, especially for a bottom layer of two-lift paving concrete. This concrete mix exhibits equivalent strength and drying shrinkage properties.

Abstract: Residual mortar attached to recycled concrete aggregate (RCA) always leads to a decrease in Young's modulus and an increase in the drying shrinkage of RCA concrete, mainly due to an increase of total mortar volume. To overcome this inherent problem, the modified and equivalent mortar volume (EMV) methods were proposed by researchers. Despite the comparable test results, both models are still subject to the slump loss problem. Thus, under the same W/C (water to cement ratio) ratio and slump condition, this study assessed the influence of the modified EMV mix method on RCA concrete properties. A total of six mixes were proportioned using the modified EMV method with three different RCAs. Test results show that the concrete mixed with RCA produced from old PC concrete sleepers exhibited compressive strength, Young's modulus, and flexural strength values within 2% variation, equivalent to those values of the companion natural aggregate concrete. In other mixes, compressive strength was found to decrease to 11–20%. It was observed that for 100% replacement of RCA mix, Young's modulus increased to 10% and drying shrinkage increased to 8% only, while for 50% replacement of RCA mix, Young's modulus decreased to 8% and drying shrinkage dropped to 4%.

Keywords: recycled concrete; aggregate; mixture proportioning

1. Introduction

There is a general consensus in the literature that recycled concrete aggregate (RCA) is more porous and heterogeneous than natural aggregate. High-quality RCA can be obtained from waste concrete via a crushing process. This usually entails three to seven steps, including the elimination of foreign substances, rebar, and residual mortar (RM). During the crushing process, the RM quantity adhering to the RCA is altered. The primary properties adversely influenced by the adhered RM are density, absorption, etc. [1]. In particular, adhering RM in RCA results in greater porosity and consequently greater water absorption of RCAs [2], where the porosity is represented by the water absorption [3]. Usually, RCA with lower strength resulted in higher porosity in the aggregate and a newly made interfacial transition zone (ITZ). This, in turn, influences the properties of the concrete that is produced afterward. As a result of the increase in the RM, the physical concrete characteristics are impacted, including the compressive strength, Young's modulus, flexural strength, drying shrinkage, thermal expansion coefficient, freeze-thaw resistance, etc. [4–7]. Thus, many researchers have carried out various experimental studies on the use of RCA, such as using RCA source derived from precast concretes, the two-lift paving method, modification of mixing processes, new mix design approaches, etc. [8–12].

One ideal way of acquiring high-quality RCA is to derive it from precast concrete [13–15] or concrete sleepers. The main advantage of retaining RCA from sleepers is the possibility of producing reliable products and reducing sorting costs. Furthermore, several research groups have investigated the material properties of high performance RCA concrete railway sleepers and found that, in comparison to the use of ordinary concrete, adequate material properties could be obtained [16–18].

According to Federal Highway Administration (FHWA) data [7], the use of RCA on bases of new pavements is currently allowed in 41 state departments of transportation (DOT) in the USA. Among these states, 11 states use RCA for paving concrete mix. Moreover, two-lift concrete pavements have been successfully constructed in the USA with the bottom layer containing low-quality recycled aggregate concrete [19–21]. It was pointed out by Shi et al. [22] that two-lift construction using recycled materials in the bottom lift can have the highest positive impacts from a social and environmental perspective.

Tam and Tam [23] proposed a two-stage mixing approach (TSMA), while Sicakova and Urban [24] suggested a triple- mixing procedure to manufacture strong and durable RCA concrete. TSMA divides the mixing process into two parts: initial mixing of all the aggregates and half of the required water and final concrete mixing with the other half of the required water and cement. It was observed that the strength, shrinkage, creep and permeability properties of RCA concrete were enhanced by adopting TSMA [23,25]. The triple-mixing process divides the mixing process into three parts: coating coarse aggregates mixed by application of additive and a certain amount of the water required for coating, adding cement with fine aggregate, and final concrete mixing with the remaining water and plasticizer. It was observed that the density, compressive and splitting tensile strength, and water absorption capacity properties were improved.

New modified mix proportioning methods for producing RCA concrete have been proposed by a few researchers [4,5,26]. The equivalent coarse aggregate mass (ECAM) method was proposed by Gupta et al. [26]. The main concept is that the attached mortar is treated as part of the sand. Test results show that the compressive strength values of the RAC mixes (up to 50% of RCA replacement ratios) were comparable with the compressive strength of the control natural concrete mixes, while slump decreased with the addition of RCAs. The original equivalent mortar volume (EMV) method proposed by Abbas [4] and Fathifazl [5] is considered effective for structural concrete mixes, typically with about 800 kg/m^3 of fine aggregate. However, the characteristics of the EMV method lead to lower fine aggregate amounts, resulting in a rough mix and slump loss [5,13], but these are acceptable for paving concrete. The low slump problem may be overcome in paving concrete by forcibly vibrating the pavement surface with a slipform paver to finish it [13]. In response to these issues, Kim et al. [27] proposed a revised EMV method. It was assumed that some part of the RM volume fraction may be arithmetically considered as that of the original virgin aggregate (OVA), whereas the other part is considered as total mortar (TM). Figure 1 shows the concepts of different mix designs such as the modified EMV as well as traditional mixture designs. Note that TCA denotes the total coarse aggregate volume. Looking at the conventional mix design in Figure 1b, it can be seen that the TM volume of RCA concrete is greater than the TM volume of natural aggregate (NA) concrete, shown in Figure 1a. It is shown in Figure 1b that RCA is the sum of RM and OVA (equal to TCA). Therefore, the traditional RCA concrete mix design yields TM volume increase, which successively influences material properties. Figure 1c illustrates the unique characteristics of the EMV method. As explained before, the TM volume in the RCA concrete shown in Figure 1c, which is considered as the sum of the new mortar (NM) and RM volumes, is equal to the TM volume of NA in the traditional concrete shown in Figure 1a [8]. The NM volume in Figure 1c decreased in proportion to the RM amount. In the modified EMV model shown in Figure 1d, RM adhering to RCA acts as aggregate in the fresh state concrete, and later hardens as mortar. Now, the volume of RM of RCA concrete is treated by the mortar volume fraction (RM_a) and the other aggregate volume fraction (RM_b). Additional explanation of the revised EMV concept can be found in the reference [13].

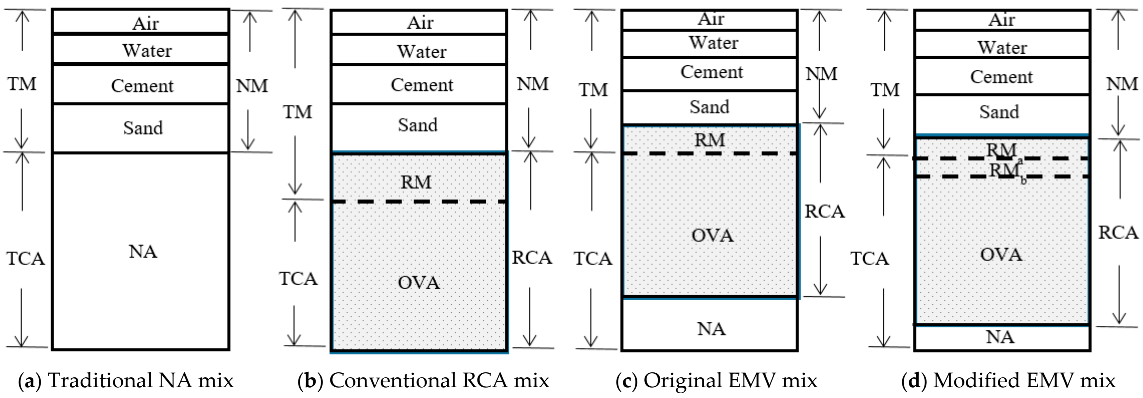


Figure 1. Schematic diagrams of different mix designs; TM: Total Mortar; TCA: Total Coarse Aggregate; NA: Natural Aggregate; NM: New Mortar; RM: Residual Mortar; OVA: Original Virgin Aggregate; RCA: Recycled Concrete Aggregate.

Previous studies have mainly focused on obtaining test results for the elastic modulus [5,8,12,13,27,28] and drying shrinkage [28–30] of RCA concrete mixes with EMV mixes, similar to those of mixes made with NCA or RCA by the traditional mix proportioning method. It should be noted that previous studies on mixes made using the revised EMV method did not consider improvement in compressive strength. Test results illustrated that RCA concretes made with the revised EMV mix method did not always yield compressive strengths that were similar to those of the control mixes [5,8,12,13,27,28].

Despite test results comparable to those for the modified EMV mix designs, the model is still subject to the slump loss problem. It should be noted that previous test results were obtained from EMV mixes, which showed lower slump values with variation of air content, in comparison to the control NA concrete mix proportioned from the ACI mix design. Therefore, this study sought to assess the influence of the revised EMV mix proportion method on the mechanical strength and drying shrinkage properties of RCA concretes, where the same W/C ratio, and slump and air content were applied. This experimental study used three grades of RCAs with different water absorption ratios, where two different RCAs (with water absorption ratio of 3.82% and 6.61%) were crushed from the same source of old concrete. The third RCA was produced from old PC concrete sleepers.

2. Experimental Program

This experimental study used recycled concrete aggregates (RCAs) produced from two different sources in South Korea. The 'RA' aggregate and 'RB' aggregate were crushed with a maximum size of 20 mm RCA from the same source of old concrete at 'I' recycling plant in South Korea. Meanwhile, the 'RR' aggregate was produced with a maximum size of 20 mm RCA from old railway concrete sleepers. The specific gravity [31], absorption ratio [31], LA abrasion coefficient [32], and residual mortar content (RMC) of the RCAs properties were tested [33,34] and are presented in Table 1. Test results showed that the average absorption ratio of 'RA', 'RB', and 'RR' was 3.82%, 6.61%, and 4.53%, respectively. It should be noted that all RCAs did not meet the specified Korean standards (KS) for concrete with respect to 2.5 as the specific gravity and 3.0% as water absorption, except for the 'RA' aggregate, which marginally satisfied the specific gravity standard with a value of 2.52 [35–38].

The RMC values for three RCAs were determined by the thermal treatment suggested by Juan and Gutierrez. [33]. Recycled aggregate samples were prepared and dried in a muffle furnace (DF-5 model made from Daeheung Science in South Korea) at 500 °C for two hours. The sample was then immersed in cold water. Extra mortar that still remained may be removed by the sudden cooling.

Table 1. RCA material properties; RA: Type A recycled aggregate; RB: Type B recycled aggregate; RR: Recycled aggregate derived from Railway concrete sleepers; KS: Korean standards.

Test Items	RA	RB	RR	KS Specification [38]
Specific gravity	2.52	2.34	2.48	>2.5
Absorption ratio (%)	3.82	6.61	4.53	<3.0
LA abrasion coef. (%) [1]	-	-	32.2	<25(paving), 40(others)
RMC [2,3]	25.0 [2]	46.8 [2]	39.9 [2] (40.1 [3])	-

[1] tested by reference [32], [2] RMC test results from thermal treatment of reference [33], [3] RMC test results from chemical treatment of reference [34].

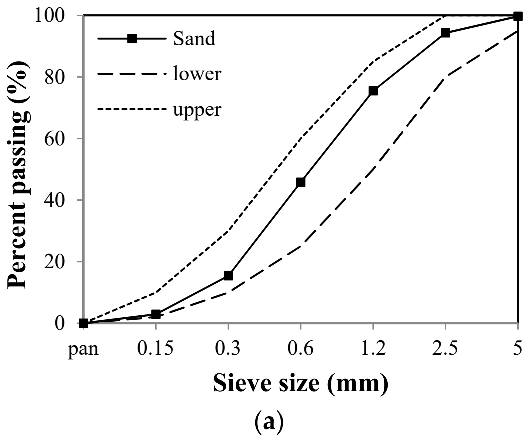
In addition, for the 'RR' aggregate, the RMC value was evaluated by the chemical treatment method recommended by Akbarnezhad et al. [34]. Recycled specimens are prepared in a 2 L beaker and a 3 M H_2SO_4 solution was added, where the volume was five times higher than the RCA sample volume. Finally, the samples were washed with a 4-mm sieve to detach the tangled mortar, and the washed and oven-dried RCA sample weights were weighed to evaluate RMC contents.

The RMC was evaluated by using the following equation [8]:

$$\text{RMC}\ (\%) = (W_{\text{RCA}} - W_{\text{OVA}})/W_{\text{RCA}} \tag{1}$$

where W_{RCA} is the first oven-dried RCA sample weight and W_{OVA} is the final oven-dried OVA weight after removal of the RM. It is surprising from the test results of the 'RR' sample in Table 1 that the average RMC value of 39.9% acquired from the thermal treatment method was very close to the RMC value of 40.1% obtained from the chemical treatment method.

Natural river sand was incorporated as fine aggregate. Aggregate test results showed specific gravity with a value of 2.60 and absorption ratio with a value of 0.95%. Figure 2a shows that the particle size of the river sand is well distributed along the midpoint of the lower and upper limit of the gradation test requirement in Korean standards. Crushed granite was used as natural coarse aggregate (NA) with the specific gravity of 2.71 and the water absorption ratio of 0.37. Table 2 tabulates the material properties of natural aggregates. Figure 2b shows the aggregate gradation results, satisfying Korean standards.



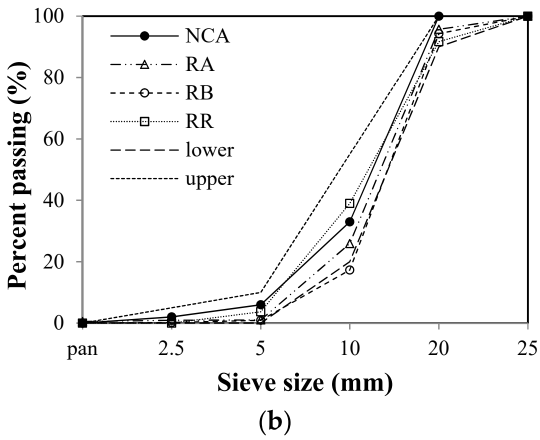


Figure 2. Aggregate gradation: (**a**) fine aggregate and (**b**) coarse aggregates.

Table 2. Material properties of natural aggregate.

Test Items	Specific Gravity	Absorption Ratio (%)
Fine aggregate	2.60	0.95
Natural coarse aggregate	2.71	0.37

3. Experimental Tests

3.1. Mix Design

Six mixtures of 35 MPa grade concrete have been studied. The notations are footnoted in Table 3. Based on the traditional mix design (CNC mix) as the reference mix, five other concrete mixtures were mixed with the modified EMV. Figure 3 shows cement and sand reductions, and coarse aggregate additions in the modified EMV mix designs, compared to those of the reference mix design with NCA. The ERA1 mix proportioned according to the modified EMV method with S = 1 (the original EMV method) results in a 28.3% decrease of cement and 28.2% of sand, but an increase of total coarse aggregate of 25.0%.

Table 3. Mix proportion of concrete per 1 m^3; W/C: Water to cement ratio; FA: Fine aggregate; NCA: Natural coarse aggregate, a: Total aggregate (FA+NCA+RCA).

Number	Mix-ID [1]	W/C	FA/a	RCA, %	*S*	Materials (kg)					
						W	C	FA	NCA	RCA	Admixture [2] (%)
I	CNC	0.39	45.0	0	-	187	480	742	907	0	0.5
II	ERA1	0.39	32.4	100	1	146	374	579	0	1210	0.7
III	ERA2	0.39	38.7	100	2	165	424	656	0	1037	0.5
IV	ERB1	0.39	34.3	50	1	152	390	604	622	537	0.65
V	ERB2	0.39	39.5	50	2	168	431	666	546	472	0.5
VI	ERR3	0.39	38.2	100	3	163	418	646	0	1046	0.5

[1] Firstly, C represent conventional mix and E as EMV mix. Secondly, N denotes natural coarse aggregate and RA, RB, and RR denote RCAs explained in Table 1. Thirdly, 1–3 is calculate from RMa/RM. [2] Superplasticizer was adopted as admixture.

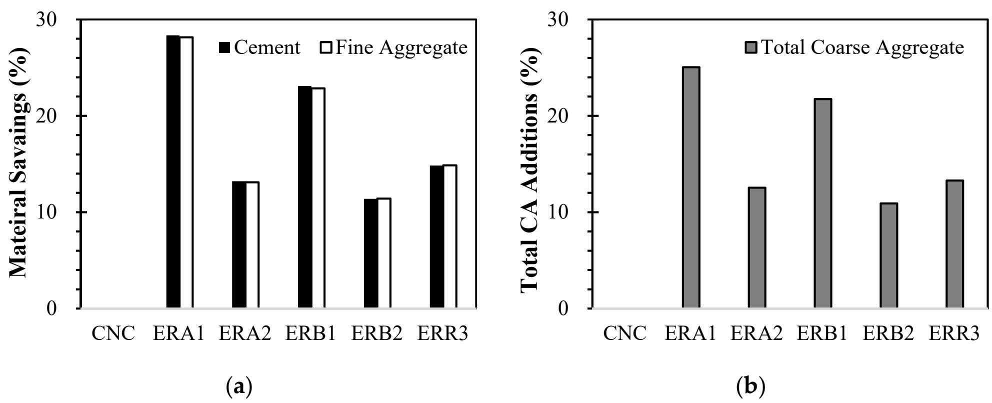


Figure 3. Material quantity change: (**a**) savings in cement and fine aggregate and (**b**) additions in total coarse aggregate.

Sixty-liter volume capacity of pan mixer was utilized at the laboratory located in Hongik University of South Korea. The superplasticizer in the mixing water was thoroughly dispersed, before the addition of water. Portland Type I cement was subsequently added and the mixer was operated for approximately one minute and thirty seconds. Then, the remaining water was added while the pan mixer was operating and the concrete was mixed for another two minutes.

3.2. Test Preparation

All mechanical strengths were the average of three specimens. The compressive strength and Young's modulus were tested according to ASTM C 39 [38] and ASTM C 469 [39], respectively, at 7 and 28 days. The flexural strength and split tensile strength of each mixture were tested at 28 days only.

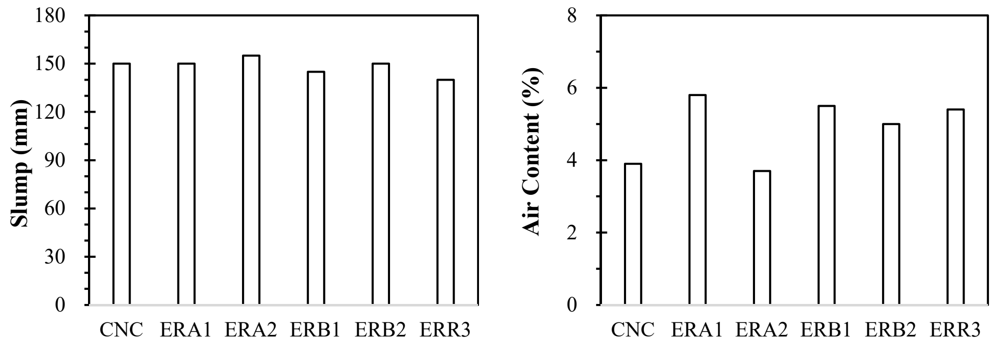
Drying shrinkage tests were measured with a dial gauge suggested by the KS standard [40], which is similar to ASTM C 157 [41]. Rectangular samples of 100 × 100 × 400 mm were used.

The shrinkage strain was evaluated by an absolute digimatic indicator (ID-S112 model made from Mitutoyo in Japan) with an 0.001 mm resolution. The samples were maintained in an environmental chamber (20 °C and 60% Relative Humidity).

4. Experimental Test Results

4.1. Results of Slump, Air Content and Density

Figure 4 shows the test results of concrete properties at the fresh state such as slump, air content. The mixtures slumps ranged between 140–155 mm and are depicted in Figure 4a. It was explained by Fathifazl [5] that, primarily because of higher water content, concrete mix with NCA resulted in bigger slump, comparing to the EMV mixture, and this usually results in slump loss. In this study, however, the slump loss was adjusted by the superplasticizer.



(**a**) slump (**b**) air content

Figure 4. Test values of slump and air content by different mix design methods.

The air contents values of the mixtures ranged between 3.7–5.8% depicted in Figure 4b. Air content of the control mix was 3.9%, whereas that of the modified EMV mixtures ranged from 5.0 to 5.8%, except for the ERA2 mix. It was noted in a previous study [28] that higher air content in the modified EMV mixes may be a result of entrapped air because of its rough mixture and smaller mortar amount. Nonetheless, it appears that the ERA2 mix with a smaller admixture amount, compared to the ERA1 mix, results in the lowest air content value.

Figure 5 shows the density variation of each mixture at the fresh state and hardened states, compared to the CNC mixture. Figure 5 shows that as concrete hardened, its density showed little gain. Figure 5 indicates that the relative densities at the hardened state of the EMV mixtures (excluding 92.8% of ERA2) ranged from 95.6–97.6, compared to the CNC mix. The density of the ERA2 mix dropped about 3% more in both the fresh and hardened states. It is suspected that specimens of the ERA2 were inappropriately made.

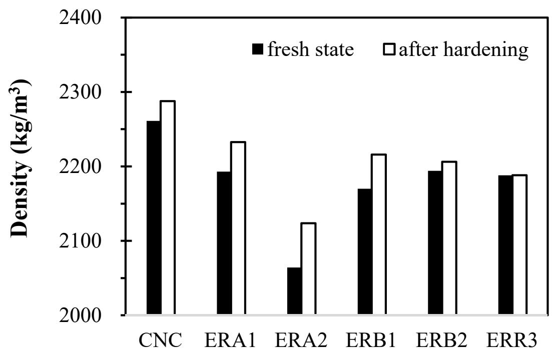


Figure 5. Test values of density by different mix design methods.

4.2. Compressive Strength

Figure 6a presents the average compressive strengths of concrete samples at 7 days and 28 days. In addition, the relative strength ratio of the ERA series, ERB series, and ERR mix are shown in Figure 6b–d, compared to the compressive strength of the control specimens (CNC).

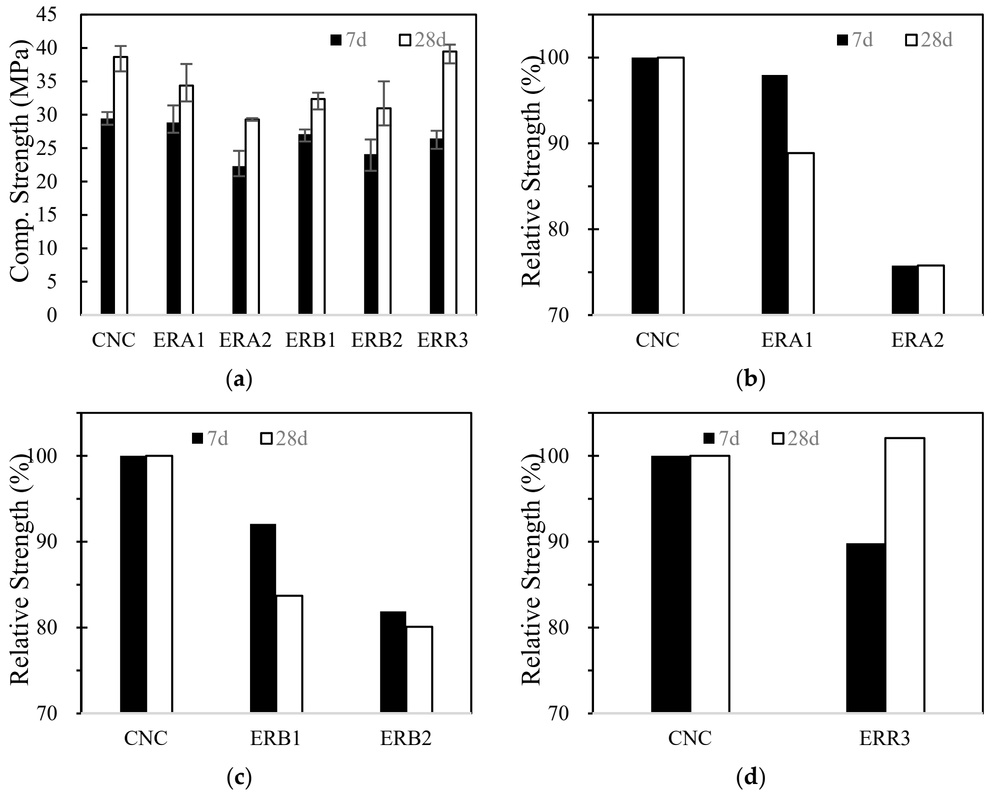


Figure 6. Compressive strength results of concrete samples (**a**) strength, (**b**) relative value of ERA series, (**c**) relative value of ERB series, and (**d**) relative value of ERR mix.

In Figure 6b,c, the relative strengths of the ERA concrete series and ERB concrete series are compared to the CNC concrete, respectively. Test results showed that the compressive strengths decreased by 24% in the ERA2 mix (S = 2), compared to the control CNC mix and ERA1 mix (S = 1). It should be noted that the water-cement ratio, slump, and air content were kept to be almost the same in these mixes in Table 3 and Figure 4a,b, thus not affecting compressive strengths. However, the FA/a ratio (see Table 3) of ERA1 and ERA2 is 32.4% and 38.7%, respectively, whereas that of ERB1 and ERB2 is 34.3% and 39.5%. Because of variation of the FA/a ratio, the compressive strength was ERA1 > ERA2 and ERB1 > ERB2. Obviously, poor water absorption of the RA (3.82%) and RB (6.61%) aggregates resulted in a decrease in the compressive strength, whereas the NA aggregate showed good water absorption (0.37%).

Comparing the test results between the ERA series and ERB series in ‘S = 1’, the compressive strength was ERA1 > ERB1. Once again, the same water-cement ratio, slump, and air content were employed. A lower FA/a ratio of ERA1 might account for greater compressive strength gain. Ho et al. [42] found an increase of compressive strength of RCA concrete at early ages of 3 days and 7 days with greater replacement of RCA up to 100%. They asserted that the mortar strength of this concrete was likely superior to that of the control mixes, due to the reduction of the effective W/C ratio in the RCA mixes. An increase of compressive strength of RCA concrete with up to 30% replacement of RCA was also reported by Paul et al. [43], while equivalent compressive strength of RCA concrete was attained with 50% replacement and 100% replacement of RCA by Paul [44].

Next, in 'S = 2', however, the compressive strength was ERA2 < ERB2. Very poor density of ERA2 in Figure 6, which might be ascribed to it having the lowest density (see Figure 5), yielded the converse test result.

Test results in Figure 6d indicates that the compressive strength of the ERR mix is superior to that of the control CNC mix. It is due to the high quality of the RCA manufactured from the PC concrete sleepers. This was explained in the author's former study [28]: RCA produced from wastes of precast structural concrete is of high quality and clean.

4.3. Young's Modulus

Figure 7 shows the average Young's modulus of concrete samples at 7 days and 28 days with the traditional mixture and the modified EMV mixtures.

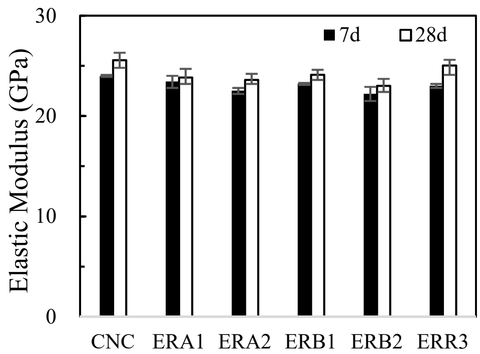


Figure 7. Young's modulus results of concrete samples.

Figure 7 shows that all the other RCA mixes, regardless of having different mix designs, yielded 2–7% decreases in the Young's modulus value at seven days. At 28 days, this gap is enlarged to range from 6–10%. Comparing the relative compressive strength drop of 11–20% in Figure 6b,c, the 6–10% decrease in the relative modulus of the modified EMV concrete mixes might be the result of the characteristic in the modified EMV method. It was explained by Fathifazl et al. [8] that modulus is proportional to the volume of total mortar; however, strength is mostly dependent on the strength of the mortar and the ITZ. Ho et al. [42] reported equivalent modulus test results of RCA concretes with replacement levels of 30%, 50%, and 100% of RCAs. It was pointed out that the modulus of RCA is lower than that of NA and, consequently, due to the porous nature of RCA, the difference in the modulus of RCA and hardened cement paste will be smaller than that of NA and hardened cement paste.

Meanwhile, the ERR mix, which contained high-quality RCA produced from PC concrete sleepers, resulted in only a 2% decrease in the elastic modulus value, compared to the control CNC mix. It is very clear that the strength decrease of concrete produced with RCA is due to the porous interface transition zone (ITZ) surface. Further studies are needed to enhance the strengthening of ITZs and their surroundings by using minerals such as silica fume, slag or ashes.

4.4. Flexural Strength

Figure 8a presents the average flexural strength of concrete samples at 28 days with the traditional mixture and the modified EMV mixtures. In addition, the relative strength ratios of the ERA series, ERB series, and ERR mix are depicted in Figure 8b–d, respectively, compared to the flexural strength of the control specimens (CNC). Compared to the remarkable drop in the compressive strength of as much as 24% in the ERA2 mix, the difference in the flexural strength was reduced to 16% in the ERA2 mix. Two studies explained [45,46] that the flexural strength of RCA concrete is not greatly affected by the presence of RCA, compared to flexural behavior of NA concrete because of the interfacial bond and better mechanical interlocking resulting from rough-textured as well as angular RCA. This trend also can be explained by the relation between flexural strength (modulus of rupture: MOR) and compressive strength. Price [47] suggested from his tests that the MOR of concrete to compressive strength is 14.5% with a compressive strength of 27.6 MPa and 12.8% with 41.4 MPa. However, test results in the ERB series show that the MOR to compression is about 18%, as shown in Table 4. Therefore, either ERB1 or ERB2 mix may be preferred for concrete pavements, where the pavement is loaded in bending.

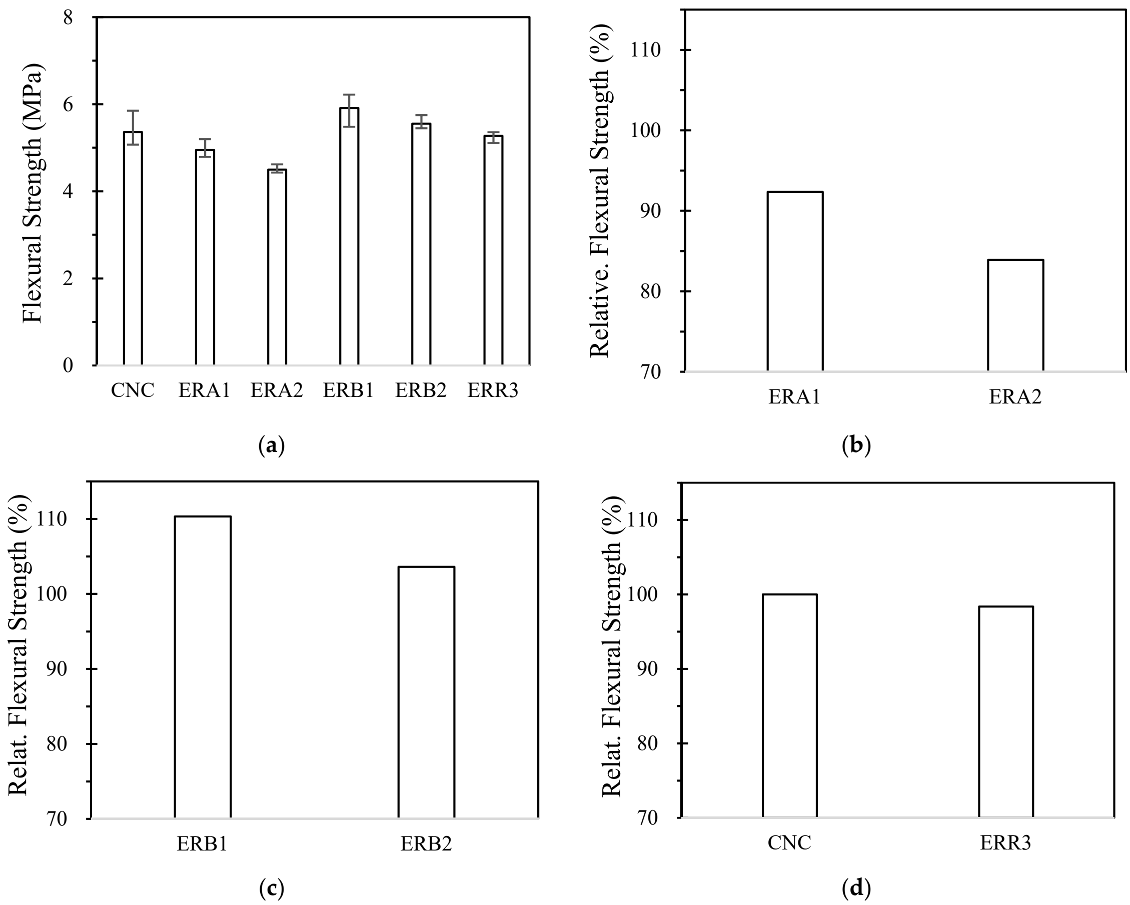


Figure 8. Flexural strength results of concrete samples (**a**) strength, (**b**) relative value of ERA series, (**c**) relative value of ERB series, and (**d**) relative value of ERR mix.

Table 4. Relation between compressive, flexural, and split tensile strength of concrete; Mix-Id: mixture identification.

Mix-Id	Average Strength of Concrete (MPa)			Ratio (%)	
	Compression	Flexure	Split Tension	Flexure to Compression	Split Tension to Compression
CNC	38.7	5.36	3.72	13.9	9.6
ERA1	34.4	4.95	3.40	14.4	9.9
ERA2	29.3	4.50	3.05	15.3	10.4
ERB1	32.4	5.91	3.47	18.3	10.7
ERB2	31.0	5.55	3.31	17.9	10.7
ERR3	39.5	5.27	3.30	13.4	8.4

It is seen in Figure 8b,c that at the same water-cement ratio, slump, and air content, EMV mixtures with S = 1 (ERA1 and ERB1) have higher flexural strength than those with S = 2 (ERA2 and ERB2). The lower FA/a ratio of the ERA1 and ERB1 mixes, compared to the ERA2 and ERB2 mixes, contributed to higher flexural strength.

Next, comparing test results between the ERA series (Figure 8b) and ERB series (Figure 8c), it was observed that flexural strength is decreased as RCA replacement content is increased. Hundred percent of RCA was replaced in the ERA series, while only 50% RCA was replaced in the ERB series. Thus, the relative strength value of the ERB series (104–110%) is far greater than the ERA series (84–92%). It was pointed out by Tripura et al. [48] that failure through old residual mortar (here in ERA series) might result in lower flexural strength and a more irregular failure pattern.

Test results in Figure 8d indicates that the flexural strength of the ERR mix is similar to that of the control CNC mix. The high quality of the RCA, which was produced from PC concrete sleepers, may be one of the main reasons for this.

4.5. Split Tensile Strength

Figure 9a shows the average split tensile strength of concrete samples at 28 days. In addition, the relative strength ratios of the ERA series, ERB series, and ERR mix are shown in Figure 9b–d, respectively, compared to the split tensile strength of the control specimens (CNC). In contrast with the relation of the MOR to compressive strength, the split tension to compressive strength lineally follows the compressive strength trend. In Price's study [47], the split tension of concrete to compressive strength was suggested to be 8.5% with a compressive strength of 4000 psi (27.6 MPa) and 7.7% with 6000 psi (41.4 MPa). Test results in Table 4 shows that the split tension to compression ranges from 9.6–10.7%, except for the ERR3 with a value of 8.4%. Overall, except for the ERR3 mix, a slightly higher split tensile strength values than expected were obtained.

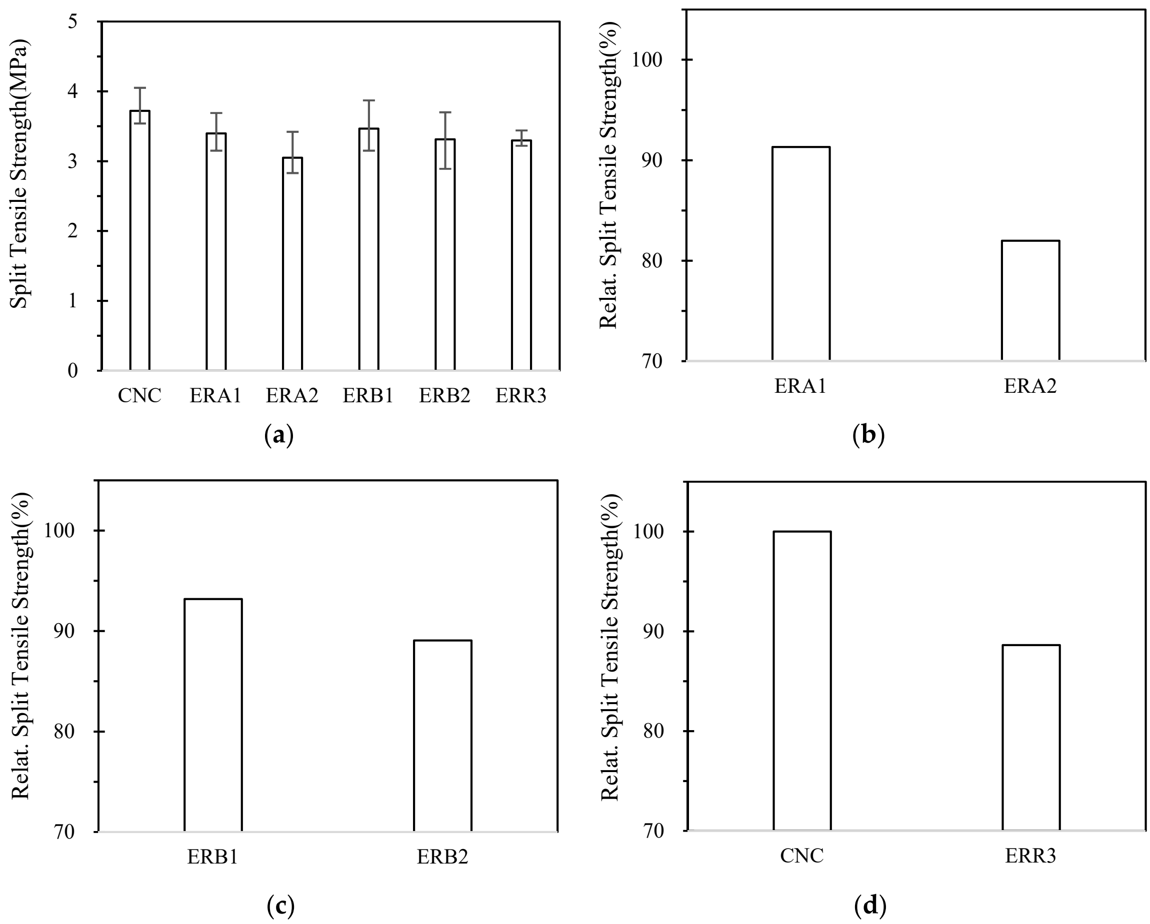


Figure 9. Split tensile strength results of concrete samples (**a**) strength, (**b**) relative value of ERA series, (**c**) relative value of ERB series, and (**d**) relative value of ERR mix.

From Figure 9b,c, the relative split tensile strengths of the ERA concrete series and ERB concrete series were compared to the CNC concrete, respectively. As discussed before, due to variation in the FA/a ratio, split tensile strength was ERA1 > ERA2 and ERB1 > ERB2. Poor water absorption of the RA

(3.82%) and RB (6.61%) aggregates resulted in a decrease of 9–11% (except for 18% of the ERA2) in the split tensile strength results, in contrast to the good water absorption of the NA aggregate (0.37%). It is plainly seen that the strength gap in the split tension narrowed relative to the reference mix, compared to the values of 11–20% (except for 24% of the ERA2) in the compressive strength results.

Comparing the test results between the ERA series and ERB series, except for the ERA2 mix, very similar tensile strength trends were observed. Once again, very poor density of ERA2 in Figure 9 might result in it having the lowest tensile strength.

Test results in Figure 9d shows that the ERR3 mix exhibited 90% of the relative tensile strength to the control mix. According to Price's interpretation of the relation between the tensile strength of concrete to compression, other mixes (9.6–10.7%) had somewhat greater tensile strength gains, in comparison to the compressive strength gains, than the ERR3 mix (8.4%), as tabulated in Table 4.

4.6. Drying Shrinkage

Test results of drying shrinkage are shown in Figure 10a, and their relative drying shrinkage to that of the reference specimen CNC is shown in Figure 10. Finally, at 50 days, the shrinkage strain of the control specimen CNC was 851 μ m/m. Compared to that of the control mix, the drying shrinkage values of the ERA1, ERA2, ERB1, ERB2, and ERR mix were 814 μ m/m, 922 μ mm/mm, 919 μ mm/mm, 1057 μ mm/mm, and 871 μ mm/mm, respectively, indicating roughly a 4% decrease, 8% increase, 8% increase, 24% increase, and 2% increase.

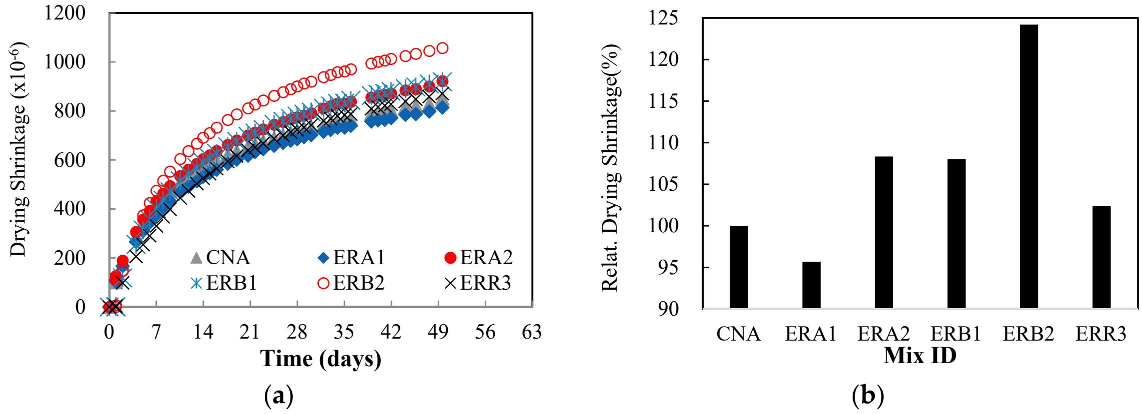


Figure 10. Test results of drying shrinkage of concrete samples (**a**) shrinkage, (**b**) relative value.

Using the ACI equation [49], the drying shrinkage difference between the ERA1 and ERA2 mixes can be analyzed. Influencing factors are air content, slump, cement contents, and fine aggregate ratio. Due to the very similar test results for the slump and air content in all mixes, it can be inferred by the ACI 209 equation that combined correction factors from slump and air content do not affect the final drying shrinkage values of all mixes. However, correction factors for fine aggregate ratios of ERA1, ERA2, ERB1, ERB2, and ERR3 dramatically varied at 0.75, 0.84, 0.78, 0.85, and 0.83, respectively. Similarly, cement content changes the correction factor but only slightly. Thus, the drying shrinkage values by the ACI equation were expected to range in the order of ERA1 < ERB1 < ERR3 < ERA2 < ERB2. In a very similar manner, the test results were ERA1 < ERR3 < (ERB1, ERA2) < ERB2. The second best drying shrinkage value from the ERR3 mix may be attributed to be the good quality of the RCAs manufactured from the PC concrete sleepers. Except for the ERB2 mix, the modified EMV mixes are viable against the drying shrinkage, compared to the reference CNC mix.

5. Conclusions

This study assessed the influence of the revised EMV mix proportion method on mechanical strength and drying shrinkage properties of RCA concretes, which are proportioned to have the same W/C ratio, slump and air content. This experimental study used three grades of RCAs with different water absorption ratios, where two different RCAs (water absorption ratio of 3.82% and 6.61%) were crushed from the same source of old concrete. The third RCA was produced from old PC concrete sleepers.

Six mixes were studied for typical structural concrete where the control concrete contained natural coarse aggregate mixed according to the traditional ACI method and the others were prepared with the revised EMV method. From this study, the following conclusions are drawn. Here the test results of ERA2 mix were excluded in the concluding discussion due to low mechanical strength values, which may be ascribed to its low density.

(1) Due to the nature of a lower slump problem that often occurs in the modified EMV method, all the mixture slump values were controlled by using a superplasticizer to range between 140–155 mm and air contents values with 3.7–5.8%.
(2) Except for the split tensile strength, test results showed that the ERR mix with 100% RCA replacement, which was produced from old PC sleepers mixed by the revised EMV mix method, exhibited equivalent compressive strength, Young's modulus, and flexural strength values to the companion reference mix of natural aggregate. In addition, the relative drying shrinkage increased only 2% to the companion control mix.
(3) In other mixes (except for ERR mix), compared to the drop of 11–20% of the compressive strength, the modulus of the modified EMV mixes resulted in only a 6–10% decrease to the companion control mix, which is the result of the characteristic in the revised EMV method.
(4) In the modified EMV mixes with RCA replacement of 100%, the flexural strength of concretes decreased by 8–16%. However, with 50% replacement of RCA mixes, the strength increased by 4–10% and thus may be preferred for concrete pavements, which are loaded in bending.
(5) Although a 7–11% decrease was observed in the modified EMV mixes, the split tension to compressive strength of concrete lineally follows the compressive strength trend.
(6) At 50 days, test results revealed that drying shrinkage of the modified RMV mixes with RCA exhibited a 4% drop to only an 8% increase. There was one, except for the ERB2 mix with a 24% increase, and this might be affected by relatively higher fine aggregate ratio and cement content, compared to the other EMV mixes.

Further studies should be carried out to enhance strengthening ITZs of RCA and their surroundings by using minerals such as silica fume, slag, or bottom ashes. The equivalency of mechanical strength properties then may be more clearly acquired by the revised EMV proportioning method with any RCA source.

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