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THE EQUIVALENT MORTAR VOLUME METHOD IN THE MANUFACTURING OF RECYCLED AGGREGATE CONCRETE

METODA RÓWNOWAŻNEJ OBJĘTOŚCI ZAPRAWY W WYTWARZANIU BETONU Z KRUSZYWEM Z RECYKLINGU

Abstract

Many studies have observed that the mechanical properties of concrete made of recycled aggregate are worse than for concrete made of natural aggregate; this is mainly due to the mortar that is attached to the recycled aggregate. In literature, an equivalent mortar volume method in the manufacturing of recycled aggregate concrete has been proposed. This method treats the attached mortar as new mortar. The application of this method can reduce the use of natural materials while maintaining mechanical properties and eliminate the additional processes required for the production of recycled aggregates. The aim of this paper is to briefly describe the recent application of this method, present gaps in current research and anticipated directions for further research.

Keywords: concrete, recycled aggregate, equivalent mortar volume method, sustainable development

Streszczenie

Wiele badań wykazało, że właściwości mechaniczne betonu wykonanego z kruszywem pochodzącym z recyklingu są gorsze niż właściwości betonu wykonanego z kruszywa naturalnego, głównie ze względu na zaprawę zespoloną z kruszywem z recyklingu. W związku z tym w literaturze zaproponowano metodę równoważnej objętości zaprawy w wytwarzaniu betonu z kruszywem z recyklingu. Ta metoda traktuje dołączoną zaprawę jako nową zaprawę. Zastosowanie tej metody może zmniejszyć zużycie materiałów naturalnych przy jednoczesnym zachowaniu właściwości mechanicznych betonu i wyeliminować dodatkowe procesy wymagane do produkcji kruszyw z recyklingu. Celem tego artykułu jest krótki opis najnowszych zastosowań tej metody, przedstawienie luk w obecnych badaniach i przewidywanych kierunków dalszych badań.

Słowa kluczowe: beton, kruszywo z recyklingu, metoda równoważnej objętości zaprawy, zrównoważony rozwój

1. Introduction

As the amount of natural aggregates (NA) used for building and road construction increases, so does the amount of recycled aggregates (RA). With the depletion of natural resources, researchers investigated the possibility of reusing used aggregates [1-6]. However, many studies have observed that the mechanical properties of recycled aggregate concrete (RAC) are lower than those of natural aggregate concrete (NAC), mainly as a result of the mortar attached to the RA [3, 6–13].

Figure 1 presents the cross section of a cylinder specimen made with RA and white cement to show the actual composition of RA. Through simple visual inspection, a form of non-destructive testing, the residual mortar can be distinguished from RA. In the figure, RA is composed of residual mortar (RM) and original virgin aggregate (OVA). Many studies have been conducted to improve the properties of RA and RAC through mechanical, chemical and biological processes [12–21], the addition of fibres [10, 22, 23], and the addition of mineral additives such as fly ash and blast furnace slag [24–26].

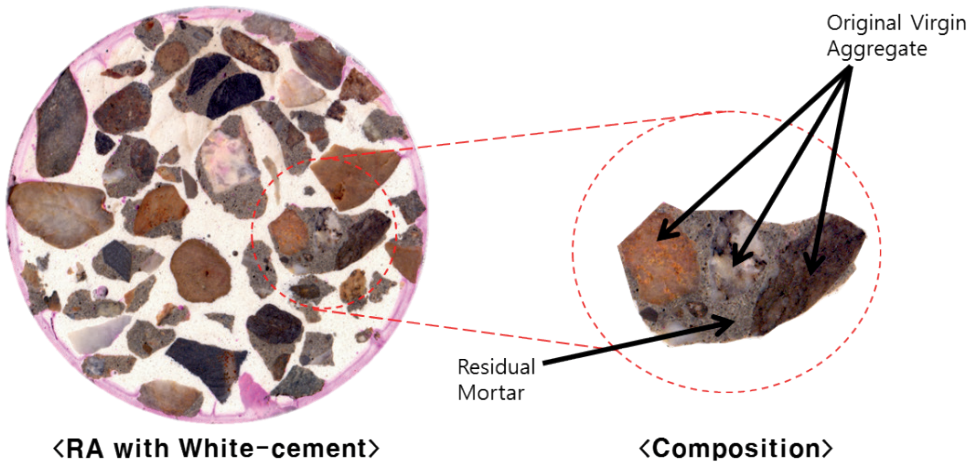


Fig. 1. Example of the composition of recycled aggregate

Although the addition of specific materials and additional processes to improve the properties of RA may be effective, it seems to be somewhat less than ideal in terms of time, economy and eco-friendliness. From this point of view, it is hard to consider it a fundamental solution. With this in mind, a new mix design for RAC was proposed by Fathifazl et al. [27]. While the conventional concrete mix design (CMD) did not take into account the mortar attached to the RA, the proposed method treats the attached mortar as mortar (Fig. 2). Therefore, the application of the equivalent mortar volume (EMV) method not only reduces the amount of new input material but also eliminates the time and economic factors for processing RA.

The purpose of this paper is to review the recent applications of the EMV method in the manufacturing of RAC by comparing RAC mixed by the EMV method with CMD concrete.

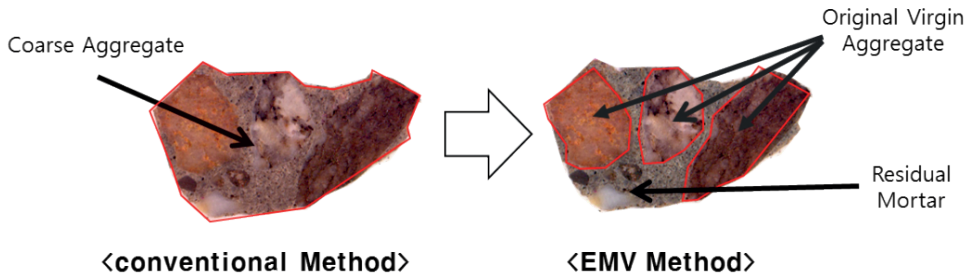


Fig. 2. Concept of RA according to CMD (L) and EMV method (R)

2. Recycled aggregate

Although it makes a little difference, waste concrete is produced as RA after several crushing, screening, and cleaning processes (Fig. 3) [28]. The produced RA contains a certain percentage of already hardened mortar (also named attached mortar, residual mortar, or adhered mortar). Figure 4 shows the absorption rate and specific gravity of the RA used in many different research projects. Specially processed RA such as HCI were excluded. As shown in Fig. 4, the water absorption rate of NA ranges from 0.26% to 1.2%, while RA have a range of 1.4-9.68%. In addition, as the absorption rate increases, the specific gravity tends to decrease.

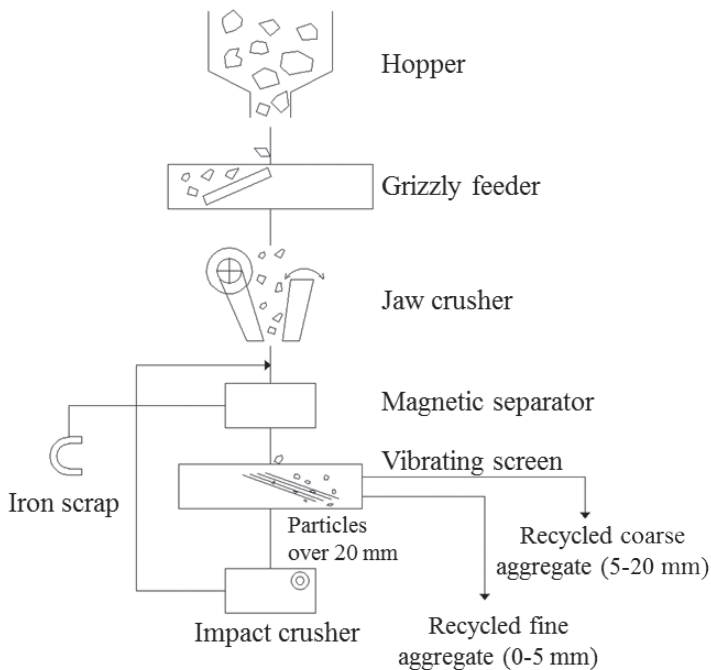


Fig. 3. General flowchart for RA production

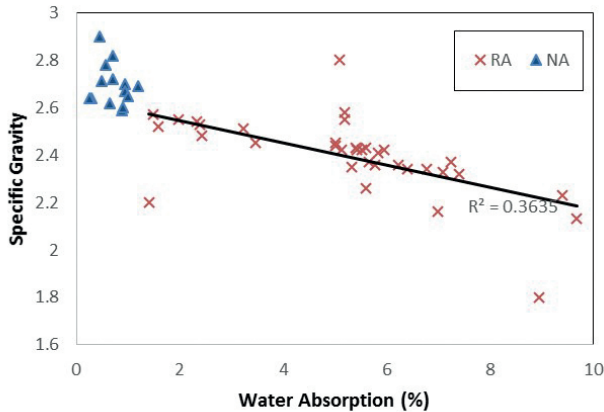


Fig. 4. Correlation between specific gravity and absorption rate of RA and NA (data from [6, 13, 16, 17, 22–24, 26, 29–36])

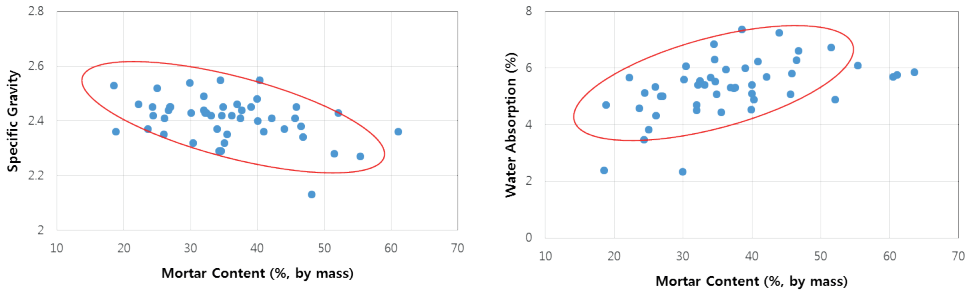


Fig. 5. Correlation between the RMC and specific gravity (L), Water absorption (R) (data from [3, 13, 33, 35, 36, 38–44])

The presence of RM adversely affects the basic properties of RA by, for example, lowering the specific gravity and increasing the water absorption rate compared to NA, which leads to a degradation of the properties of the RAC [3, 6, 10, 13, 37]. Figure 5 shows the relationship between the residual mortar content (RMC) on RA and the density and water absorption of RA investigated in other studies. There may be differences depending on production processes and the impurities contained in aggregates, in general, as the RMC increases, the specific gravity decreases and the water absorption rate tends to increase [3, 13, 33, 35, 36, 38–44].

3. Mixing methods

3.1. Conventional mix design (CMD) method

Many studies related to RAC have used the national standard mix design [45, 46] or standard ASTM/ACI mix design [47, 48]. However, these mix designs have a fixed amount of newly added materials irrespective of the type and characteristics of the corresponding

aggregate [49–58]. When using the monotonous concrete mix method which has the same amount of water, cement, and sand with RA, the actual mortar content of RAC increases due to RM on RA (Fig. 8 (a) & (b)).

Figures 6 and 7 show the compressive strength and elastic modulus as a function of the RA replacement ratio. Due to variables such as water/cement ratios and admixture use, the range of the mechanical properties of compressive strength and elastic modulus of RAC varies somewhat; the same concrete mixing design, i.e. the same amount of cement and sand, was employed for each group of RA. The results showed that the mechanical properties decrease as replacement ratios of RA increase.

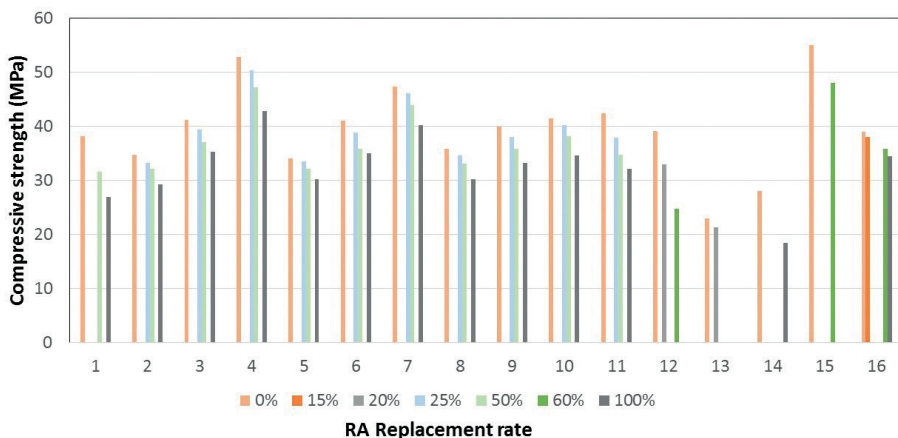


Fig. 6. Relationship between compressive strength and RA replacement rate (data from [6, 10, 15, 22, 24, 29, 32, 36, 37])

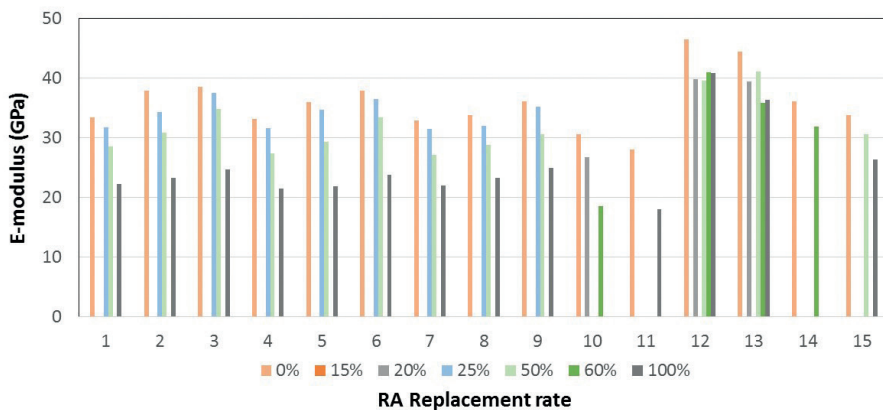


Fig. 7. Relationship between elastic modulus and RA replacement rate (data from [6, 15, 29, 36, 37, 59])

3.2. EMV methods

3.2.1. Original equivalent mortar volume (EMV) method

Fathifazl et al. [60] claimed that the observed inferior physical properties of RAC may be responsible for the mix design, and this can be overcome by the proper mix design method. Therefore, the proposed EMV method equates RM with newly added mortar, and reduces the amount of new cement, sand, and water by as much as the volume amount of RM. Based on this, the total mortar volume of the RAC is kept the same as the mortar volume of NAC (Fig. 8 (a) & (c)).

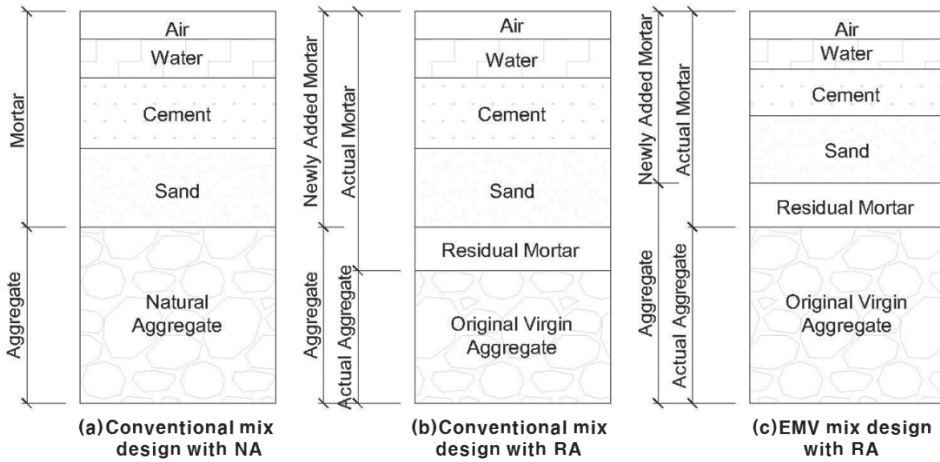


Fig. 8. Comparison of concrete mix design

The process of this mixing method is as follows.

RAC consists of a mixture of RA and NA, where the NA is replaced with the same volume of RM as the volume of RA. Thus, the NA input ratio, R , can be defined as the follows (Eq. (1)):

$$R = \frac{V_{NA}^{RAC}}{V_{NA}^{NAC}} = \frac{V_{RM}^{RAC}}{V_{RA}^{RAC}} \quad (1)$$

Where R = proportion of NA; V_{NA}^{RAC} = volume of NA in RAC; V_{NA}^{NAC} = volume of NA in NAC; V_{RM}^{RAC} = volume of RM in RAC; V_{RA}^{RAC} = volume of RA in RAC.

In addition to the above, Eq. (2) and (3) should be satisfied to equalise the volume of mortar and aggregate in RAC and NAC.

$$V_{TM}^{RAC} = V_M^{NAC} = V_{RM}^{RAC} + V_{NM}^{RAC} \quad (2)$$

$$V_{TNA}^{RAC} = V_{NA}^{NAC} = V_{OVA}^{RAC} + V_{NA}^{RAC} \quad (3)$$

Where V_{TM}^{RAC} = total mortar volume in RAC; V_M^{NAC} = mortar volume in NAC; V_{RM}^{RAC} = RM volume in RAC; V_{NM}^{RAC} = new mortar volume in RAC; V_{TNA}^{RAC} = Total NA volume in RAC; V_{NA}^{NAC} = NA volume in NAC; V_{OVA}^{RAC} = OVA volume in RAC.

Because the NA volume of the RAC and the NA volume of the NAC should be equal, the volume of the OVA of NAC should be calculated; this can be obtained from the RMC and the apparent density of the OVA (4). RMC in RA can be obtained by subtracting the OVA weight from RA (5).

$$V_{OVA}^{RAC} = V_{RA}^{RAC} \times (1 - RMC) \times \frac{SG_b^{RA}}{SG_b^{ova}} \quad (4)$$

$$RMC\% = \left[\frac{W_{RCA} - W_{OVA}}{W_{RCA}} \right] \times 100 \quad (5)$$

Where SG_b^{RA} and SG_b^{ova} = bulk specific gravity of RA and OVA, respectively.

Many studies have been conducted on the estimation of RMC in RA to obtain OVA (thermal treatment [11], soaking in acids [61-63], microwave heating [64]), but there are no standard regulations yet. Fathifazl et al. [60] used the following method, as presented in [65, 66]. The approximate process of the test is as follows: sampling the aggregate, drying the sample for 24 hours in 105°C oven, immersing it in a 26% sodium sulphate solution for 24 hours. The freeze-thaw test is repeated for five cycles with sodium sulphate (-17°C for 16 hours, 80°C for 8 hours).

Figure 9 shows the before and after RMC calculation test of RA used in [67]. The right side of Fig. 9 (b) shows the RM after passing through a 4.75 mm sieve following the test.

Using the Eqs. (1), (3) and (4), presented above, the volumes of RA and NA for RAC can be obtained (6), (7).

$$V_{RA}^{RAC} = \frac{V_{NA}^{NAC} \times (1 - R)}{(1 - RMC) \times \frac{SG_b^{RA}}{SG_b^{OVA}}} \quad (6)$$



Fig. 9. RCA sample before (a) and after (b) RMC determination [67]

$$V_{RA}^{RAC} = V_{NA}^{NAC} \times R \quad (7)$$

V_{RM}^{RAC} to be calculated to satisfy Eq. (2) can be obtained by subtracting V_{OVA}^{RAC} from V_{RA}^{RAC} (8), and the amount of mortar to be newly added is as shown in Eq. (9).

$$V_{RM}^{RAC} = V_{RA}^{RAC} \times \left[1 - (1 - RMC) \times \frac{SG_b^{RA}}{SG_b^{OVA}} \right] \quad (8)$$

$$V_{NM}^{RAC} = V_M^{NAC} - V_{RM}^{RAC} \quad (9)$$

By substituting Eq. (1) and Eq. (3) into Eq. (6), Eq. (10) can be derived, i.e. Eq. (11)

$$V_{RA}^{RAC} = V_{NA}^{NAC} \quad (10)$$

$$V_{RA}^{RAC} = V_{NA}^{NAC} = \frac{W_{OD-NA}^{NAC}}{SG_b^{NA} \times 1000} \quad (11)$$

Where, W_{OD-NA}^{NAC} = oven-dried weight of NA in NAC; SG_b^{NA} = bulk specific gravity of NA.

Once V_{RA}^{RAC} is determined, the mass of the material to be used is given by Eqs. (12)-(17).

$$W_{OD-RA}^{RAC} = V_{RA}^{RAC} \times SG_b^{RA} \times 100 \quad (12)$$

$$W_{OD-NA}^{RAC} = V_{NA}^{RAC} \times SG_b^{NA} \times 1000 \quad (13)$$

$$W_W^{RAC} = W_W^{RAC} \times \frac{V_{NM}^{RAC}}{V_M^{NAC}} \quad (14)$$

$$W_C^{RAC} = W_C^{NAC} \times \frac{V_{NM}^{RAC}}{V_M^{NAC}} \quad (15)$$

$$W_{OD-FA}^{RAC} = W_{OD-FA}^{NAC} \times \frac{V_{NM}^{RAC}}{V_M^{NAC}} \quad (16)$$

$$W_{TM}^{RAC} = W_W^{RAC} + W_C^{RAC} + W_{OD-FA}^{RAC} + \left(W_{OD-RA}^{RAC} \times RMC \times \text{Acceptance ratio} \right) \quad (17)$$

Where, W_{OD-RA}^{RAC} , W_{OD-NA}^{RAC} , W_{OD-FA}^{RAC} = oven-dry weights of RA, NA, and FA in RAC, respectively; W_W^{RAC} , W_C^{RAC} , W_{TM}^{RAC} = weights of water, cement, and total mortar, respectively.

3.2.2. Modified Equivalent Mortar Volume (M-EMV) methods

If RA has a high amount of RMC, it may not be possible to replace 100% NA with RA. Thus, concrete mixed by the EMV method has a minimum proportion of NA (18). According to [60], it is assumed that the OVA of RCA is similar to NA, and when bulk specific gravity

of RA = 2.31, RMC = 41%, and bulk specific gravity of NA is 2.7, the minimum required NA proportion is 21%. In other words, 21% of the volume of RAC must be NA, and new mortar equivalent to the corresponding proportion is required.

$$R_{\min} = 1 - \frac{(1 - RMC)}{V_{DR-NA}^{NAC}} \times \frac{SG_b^{RGA}}{SG_b^{NA}} \geq 0 \quad (18)$$

Where, = dry-rodded unit volume of NA in NAC.

Some studies have shown poor performance in slump and workability due to the lack of cement when the replacement ratio of RA increases [38, 68-72]. Therefore, the modified EMV methods (M-EMV) were introduced.

Yang et al. [69] introduced the parameter S-factor, which regulates the effective residual mortar content, assuming that some of the RM contained in RA acts as aggregate and rest acts as mortar (Fig. 10 (d)). Thus, the NA input R is as shown in Eq. (19), and the other equations are the same as in study [60].

$$R = 1 - \frac{V_{RCA}^{RAC}}{V_{NA}^{NAC}} \times \left(1 - \frac{1}{S} \times RMC \right) \times \frac{SG_b^{RGA}}{SG_b^{NA}} \quad (19)$$

In [69], S-factor 2 was applied for a 100% replacement rate of RA containing 11.6% of RMC, and in the case of RMC, 35.5%, 2 and 3 were applied to the 50% and 75% replacement rate, respectively. In other words, as the content of the RA was increased, the mix design was adjusted in such a way as to reduce the effective ratio of the RMC. Studies [41-43, 67, 68] were performed using the M-EMV method, the test results obtained from the studies showed properties that were either similar to or higher than those of CMD concrete.

Ahimoghadam et al. [38] notes that in the original EMV method, RM in RA is considered to behave as fresh mortar, but in practice, the RM is already hardened, and this difference causes poor performance in the fresh state of the RAC mixed by the EMV method. Therefore, the equivalent volume (EV) method based on having the same volume of aggregate and cement was proposed (Fig. 10 (a), (b)), while the EMV method had the same volume of aggregate and mortar as the CMD (Fig. 10 (b), (c)). In [38], the ratio of sand and cement of RM was determined on the basis of the concrete composition volume ratio (with regard to sand, cement, aggregate) by the ACI mix design, and afterwards, the new mortar content was determined.

In some mixtures prepared in [72], the phenomenon of mortar not completely covering the coarse aggregates was observed due to a lack of new mortar, thus modifying the EMV method by reducing the sand and increasing the cement content was tried in an attempt to improve the properties of fresh concrete.

Rajhans et al. [33] analysed the property difference by applying the two stage mixing approach (TSMA) [73], which divides the input materials and the order of input during the concrete mixing process. In this way, compressive strength at twenty-eight days was improved by 9.5% in comparison to the conventional aggregate-cement-water mixture.

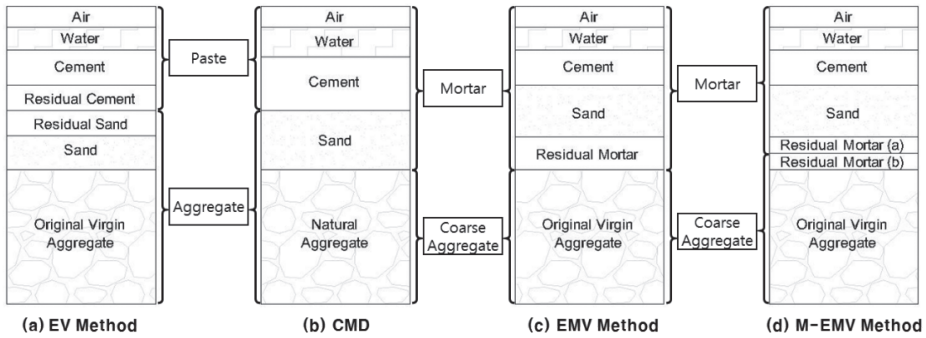


Fig. 10. Comparison of concrete mix design

4. Results and Discussion

Table 1 summarises the research on EMV based methods. As shown in the table, the mechanical properties of RAC using the EMV and M-EMV methods showed similar or higher values in comparison to conventional natural aggregate concrete. Yang et al. [42] and Abbas et al. [74] investigated EMV-based RAC and found it comparable to or superior than NAC in terms of durability as well as mechanical properties such as compressive strength and elastic modulus.

In study [68], two types of RA with different RMC were produced by regulating the process of waste concrete crushing from the same source; the compressive strength and elastic modulus of RAC made from these RAs were analysed. In the study, the results of experiments with the same mortar volume of two RAs with different RMC showed less variation than the results obtained from the CMD concrete. If the source of RA was the same, regardless of the amount of RM, the compressive strength range of the M-EMV concrete was 29.3-31.5 MPa and the elastic modulus was 22.2-23.4 GPa, whereas the CMD concrete represented a scattered distribution of 23.6-30.9 MPa and 17.4-23.6 GPa, respectively. In addition, for CMD concrete, the mechanical properties decreased significantly as a function of increasing volume of total mortar. However, M-EMV concrete did not cause a decrease in the mechanical properties because it had the same volume of the total mortar. In this regard, the author claimed that the volume of the entire mortar in the concrete had a direct effect on the mechanical properties.

The proper use of supplementary cementitious material (SCM) such as blast furnace slag (BFS) and fly ash (FA) can further reduce the amount of cement injected [60] and have a higher resistance to chloride penetration [74]. Rajhans et al. [75] stated that the addition of the FA and the adjustment of the mixing order improved the compressive strength by 21.7% compared to CMD, and Abbas et al. [74] stated that using the FA can make the carbonation coefficient of EMV concrete lower than or similar to that of the CMD concrete.

In [76-78], shear tests on a beam with and without a stirrup showed no significant difference in failure mode, cracking, or shear performance from CMD concrete beams. In

[79], a life-cycle assessment analysis of the EMV method was analysed, and it was evaluated to be better than CMD concrete in terms of CO₂ emissions, ozone layer depletion, and eutrophication, etc.

Table 1. Selected studies and highlights on the EMV-based method

Ref	Method	Highlight
[33]	EMV TSMA	<ul style="list-style-type: none"> Compressive strength increased up to 9.5% than normal mix design
[38]	EV	<ul style="list-style-type: none"> Equivalent volume (EV) method was proposed
[49]	EMV	<ul style="list-style-type: none"> Slump decreased by 33-65% Air content decreased by 15-26.5% than ACI mix design Compressive strength was similar Elastic modulus increased by 18-24% Cement 21-24%, water approximate 40 litres less than ACI mix design
[40]	EMV	<ul style="list-style-type: none"> Rheology test was investigated Slump decreased and yield stress increased EMV influence on plastic viscosity Cement reduced by 14%
[41]	M-EMV	<ul style="list-style-type: none"> Slump decreased by 33-47% Compressive strength was similar -3-+4.8% Elastic modulus increased by 8.7-13% Drying shrinkage decreased Cement reduced by 8.5-14%
[42]	M-EMV	<ul style="list-style-type: none"> Drying shrinkage decreased by 3-27% by day 585 Freeze and thaw was similar Cement reduced by 10-16.7%
[43]	M-EMV	<ul style="list-style-type: none"> Compressive strength decreased by 11-20% Elastic modulus decreased by 6-10% Flexural strength decreased by 8-16% at RA replacement ratio 100%, increased by 4-10% at RA 50% Tensile strength decreased by 9-17%
[44]	EMV	<ul style="list-style-type: none"> Compressive strength and secant modulus of elasticity investigated
[60]	EMV	<ul style="list-style-type: none"> Compressive strength range -6.67-+0.83% Elastic modulus increased by 4.5-11.4% Proper use of SCMs can further reduce amount of cement
[68]	M-EMV	<ul style="list-style-type: none"> Verification of the correlation of the total mortar volume in concrete with mechanical properties; two types of RA from the same source but different RMC were used For the RA replacement ratio 25, 50, 100%, the compressive strength range of the E-EMV concrete was 29.3-31.5 MPa and the elastic modulus was 22.2-23.4 GPa; the CMD concrete represented 23.6-30.9 MPa and 17.4-23.6 GPa, respectively Cement reduced by 2.7-10%

[69]	M-EMV	<ul style="list-style-type: none"> Compressive strength increased by 6.7-8.8% by day 7 Elastic modulus increased by 2-8.7% by day 7 Introduced the parameter S-factor, which regulates the RMC
[72]	M-EMV	<ul style="list-style-type: none"> By reducing sand and adding cement, the performance of fresh concrete was improved RA containing impurities such as clay and asphalt reduce the mechanical strength of concrete
[74]	EMV	<ul style="list-style-type: none"> Strong resistance to freeze-and-thaw Lower apparent chloride diffusion coefficients than CMD concrete High resistance to chloride penetration achieved through the use of EMV with SCM. Use of FA making the carbonation coefficient of EMV concrete lower than or similar to CMD concrete
[75]	EMV TSMA	<ul style="list-style-type: none"> By adding FA and changing the material input order, compressive strength increased by 21.7%
[76]	EMV	<ul style="list-style-type: none"> Higher shear strength
[77]	EMV	<ul style="list-style-type: none"> No significant difference in failure mode, cracking patterns, shear performance of concrete beam with stirrup compared to CMD concrete Higher ultimate shear stress resistance than CMD concrete
[78]	EMV	<ul style="list-style-type: none"> No significant difference in failure mode, cracking patterns, shear performance of concrete beam without stirrup compared to CMD concrete More ductile behaviour than CMD concrete
[79]	EMV	<ul style="list-style-type: none"> Based on ISO14040 [82], life-cycle assessment of ACI, Bolomey, and EMV compared EMV method praised for being more ecologically friendly in the fields of Co2 emissions, ozone depletion, Eutrophication, etc. Reuse of concrete waste improved through the application of EMV
[80]	M-EMV	<ul style="list-style-type: none"> Compressive strength increased by 1.2-11.9% Elastic modulus increased by 4.8-8.9% Drying shrinkage lower
[81]	EMV	<ul style="list-style-type: none"> Compressive strength decreased by 15-17% Flexural strength increased by 8.5-16% Tensile strength decreased by 9.7-38% Elastic modulus range -18.9-+28.7% UPV decreased by 5.7-6%

5. Conclusions and Perspectives

In this paper, the effectiveness of RAC mixed by the EMV-based method treated residual mortar attached on recycled aggregate as new mortar has been reviewed by comparing it with concrete produced using a conventional mix design. From the results of this review, the following conclusions and perspectives can be drawn.

RAC using CMD has shown a tendency to degrade mechanical properties as the ratio of RA is increased, and through the application of the EMV and M-EMV methods, the mechanical properties and durability of RAC can be comparable to those of NAC.

It is worth mentioning that the application of the EMV method is environmentally friendly because it can reduce the use of cement, sand and water while maintaining mechanical properties, and it can eliminate the additional processes required for the production of recycled aggregates.

Since the EMV method was introduced around ten years ago, various studies have been conducted, but the accumulation of data remains insufficient. Moreover, the fact that many studies are focused on its mechanical properties such as compressive strength, tensile strength, and elastic modulus can be an indicator of the direction of future research. In addition, considering EMV-based RAC is a mixture of hardened residual mortar and new mortar, the study of early-aged properties is also considered important.

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