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Research Article

An investigation on effect of aggregate distribution on physical and mechanical properties of recycled aggregate concrete (RAC)

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ABSTRACT

The aim of this study was to optimize the aggregate gradation curve (AGC) for recycled aggregate concrete (RAC). Five different gradation curves such as three AGCs defined in TS802 (A16, B16, C16) and two proposed AGCs named G1 and G2 were employed. The concretes designed with AGCs consist of different mortar phases and included coarse aggregates such as coarse NA and coarse RA. Thus, three stages were considered and were progressed in the experimental program: the 1st stage included the evaluation of the properties of the mortars, and the effect of AGC on the mortar phase of the concrete was investigated. The mortars had the components of concrete such as cement, water, and fine aggregate (<4 mm) representing the mortar phase of concretes. The 2nd stage was the evaluation of the test results of the fresh and the hardened concretes and, in this stage, the effect of AGC on the properties of concrete was diagnosed. Also, an additional stage was the 3rd stage and was made on the experimental data to define the weights of the parameters of the concretes by using the Entropy Method and to select the best AGC with the help of a decision-support instrument, TOPSIS. Separately evaluation of the test results showed that C16 resulted in a durable RAC in terms of low water absorption capacity with high compressive strength. Besides, the results of the Entropy Method presented exciting findings, and the coarse aggregate ratio in the mix was found to be the most effective parameter among the investigated parameters. When all parameters were investigated together using the TOPSIS method, the best AGC was found as G2 for RAC, but A16 can be preferred instead of G2 according to the similar TOPSIS scores. In addition, this paper opens a path in the literature regarding the need for the development of AGC in RAC and further investigations should be made.

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1. INTRODUCTION

The sustainability approach gains importance around the world day by day and seems to be the savior of future resources. Recycling of construction wastes, especially recycling of waste concrete (WC), is one of the sustainability approaches, and sustainable economic growth and saving resource policies, nowadays, are on the policymakers' agenda [1].

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Regulations on recycled aggregate (i.e., Technical Code for Application of Recycled Aggregate Concrete (DG/TJ07-008) [2]) and higher consumption advisory policies (i.e., Directive 2008/98/EC [3]) are some of the actions on WC. However, although many regulations have been made, the construction and demolition waste (CDW) amount has been increased due to urban renewals [4–8], natural disasters [9, 10] and wars [11] especially happened in the recent decades and 1950s. The solution to the mentioned problem by advanced techniques and approaches was an obligation and a necessity. The utilization of a higher amount of WC in a widely used material such as concrete sounds good and inspires many researchers to evaluate the effect of the use of WC as recycled aggregate (RA) in concrete [12, 13]. However, the most important criterion preventing the usage of RA in new concrete is the higher water absorption capacity of RA compared to natural aggregate (NA) [14] and it decreases not only the physical and mechanical performance of recycled aggregate concrete (RAC) but also the durability performance of RAC [15]. Thus, some measures (use of mineral additions [16], mixing methods (i.e., double-mixing method [17] and triple mixing method [18]), RA treatment methods (Shi et al., 2016), etc.) [19] have been developed and suggested by researchers in their studies. At this point, it was commonly stated that the use of 20~30% RA had a minor effect on the properties of RAC [20] and treatment may have increased the optimum utilization ratio of RA (i.e., up to 60% RA treated with optimized ball mill method [10, 21–24] and up to 50% RA with new combination method [25]). Thus, it is meaningful to consider RA with a treatment method instead of the use of RA in the mix only and it has advantages, as expected.

Besides, although many papers focused on the effect of RA on concrete properties increasing the optimum ratio of RA in the mix, few papers aimed to present the effect of design methods especially considering the aggregate properties (aggregate size, particle packing, etc.) (i.e., [26–30]). Duan et al. [31] proposed a modified design method for RAC, and the scatter of the compressive strength and the porosity of RAC were investigated. The size of RA such as 5–10 mm, 10–20 mm, and 5–20 mm was considered to have an aggregate gradation effect on RAC and aggregate gradation re-adjustment was suggested stating satisfactory test results [31]. Bui et al. [25] developed a new combination method and replaced natural aggregate (NA) with RA in consideration of the different sizes of aggregates, and the methodology resulted in a new and increased optimum ratio as 50%. McGinnis et al. [32] investigated the gradation effect of RA considering the average particle size of RA such as ASTM #8 (1.18–12.5 mm) and ASTM #57 (2.36–37.5 mm) and also used the literature data such as INDOT #8. It was found that the gradation impact of coarse NA and RA was similar, and a smaller average aggregate size made RAC stronger and also stiffer [32]. Based on the experiments of concretes including NA, it was also found that "5–10–14–18" mm and "5–10–18–22" mm bands result in better concrete in consideration of compressive strength and workability [33]. Although the studies considered the aggregate size effect and also gradation effect on the properties of RAC [25, 31, 32], the effect of AGC on the properties of RAC was rarely studied. The theoretical research (i.e., particle packing, random aggregate distribution in a unit volume/section) and author examinations on this topic showed that AGC affected the aggregate concentration of unit volume. Also, it was stated that the decrease of aggregate concentration in concrete decreased the mechanical performance of concrete [34] and it should have been considered in the mix design.

To fill the gap in the literature, optimization of AGC considering the standard curves such as A16-B16-C16 compatible with TS 802 [35] and two proposed curves (G1 and G2) were examined in consideration of the properties of the mortar phases of concrete and the concretes such as NACs and RACs. The concretes consisted of different mortar phases (M-G1, M-A16, M-B16, M-C16, and M-G2) due to the different AGCs and, also coarse aggregates such as coarse NA and coarse RA. Thus, three stages were considered and were progressed in the experimental program: The 1st stage included the evaluation of the properties of the mortar phase of the concretes, and the effect of AGC on the mortars was investigated. The mortars include the components of concrete representing the mortar phase of concretes. The 2nd stage was the evaluation of the test results of concretes such as the air content of fresh concrete, the density of the hardened state of concrete, the water absorption, and the compressive strength, and in this stage, the effect of AGC on the fresh and the hardened properties of concrete were determined. Also, an additional stage was the 3rd stage and was made on the findings and the parameters to define the weights of the parameters of the concretes by using the Entropy Method and to select the best AGC with the help of a decision-support instrument, TOPSIS.

2. MATERIAL AND METHOD

2.1. Materials

General-purpose CEM I 42.5 R compatible with TS EN 197-1 was utilized in the mixes (Table 1).

In the mixes, coarse NAs and RAs were employed. NA was a crushed calcareous stone. River sand (0–2 mm) and crushed stone (0–4 mm) as a fine aggregate were utilized (Table 2). RA was sourced from low strength WC (<20 MPa) [36]. Superplasticizer was used to enhance the low workability of fresh concretes (Table 3). S2 slump class (50–90 mm) was selected for whole mixes.

2.2. Method

In the design of concrete, TS 802's AGCs for maximum aggregate size of 16 mm (A16, B16, and C16) [35] and two proposed AGCs (G1 and G2) were considered (Table 4). AGC development studies usually have been dependent on Fuller's Curve, and AGC was developed for concrete mixtures to achieve optimum performance. The aim of the proposal of

Table 1. Properties of cement

Contents	Cement
SiO_2 (%)	18.9
CaO (%)	64.7
SO_3 (%)	3.42
Al_2O_3 (%)	4.8
Fe_2O_3 (%)	3.4
MgO (%)	1.4
K_2O (%)	0.4
Na_2O (%)	0.7
Density (g/cm^3)	3.11
Chlorine ratio (%)	0.0241
Specific surface area (m^2/kg)	3840
Loss on ignition (%)	1.82
Activity index (%)	–

G1 and G2 gradation curves was to be observed the effect of non-consideration of the gradation curves given in TS 802. The ingredients of the designed mixtures were presented in Table 5. The specimens were produced under standard laboratory conditions according to TS EN 12390-2 [37]. Then, the freshly produced mixtures were cast in the molds and 15×15×15 cm cubic specimens were maintained in the molds for 24 hours for hardening purposes. Also, the fresh concrete was sieved through a 4 mm mesh sieve and the passing mixture was placed in 4x4x16 cm prismatic molds when the concretes including NA were produced. Thus, the mortar phases of the concretes were obtained. The specimens were cured in 22±2 °C water for 28 days according to TS EN 12390-2 [37]. At the age of 28 days, the experiments such as water absorption, density, and compressive strength tests for hardened concrete specimens, and bending and compressive strength tests for the mortars were conducted and compatible with the related standards [38–40].

The strength class of RACs and natural aggregate concretes (NACs) are determined according to Eq. 1–2 detailed in TS EN 206-1+A2 [41]:

$$f_{c,\,avg} \geq f_{ck}+1.0 \tag{1}$$

$$f_{c,\,min} \geq f_{ck}-4.0 \tag{2}$$

Here, f_{ck} is the characteristic compressive strength of group (MPa), $f_{c,\,avg}$ is the average compressive strength of group (MPa), and $f_{c,\,min}$ is the minimum compressive strength of group (MPa).

2.2.2. Entropy Method

The Entropy Method [42] was used to evaluate the weight factors of the experimental findings such as density, water absorption, coarse aggregate ratio, air content of fresh concrete, natural aggregate concentration, and fineness modulus and compressive strength. According to the method, the following calculation steps are considered.

Table 2. The properties of natural aggregates and recycled aggregates

Notation	Density, g/cm^3	Water absorption %	LA abrasion value %	Residual content %
Sand	2.56	0.64	–	–
Crushed sand	2.62	0.85	–	–
NA (11-16 mm)	2.70	0.32	26	–
NA (4-11 mm)	2.65	0.42	–	–
RA (11-16 mm)	2.21	8.10	46	45
RA (4-11 mm)	2.23	8.90	–	54

Table 3. The properties of superplasticizer

Content	Superplasticizer
Structure of material	Polycarboxylic ether
Color	Amber
Density (kg/l)	1.08-1.14
Alkaline ratio (%)	<3
Chlorine ratio (%)	<0.1

If *i*; 1, 2, 3, …, m are alternatives, *j*; 1, 2, 3, …, n are evaluation criteria, x_{ij}=the value of ith alternative at jth evaluation criterion,

$$X=\begin{bmatrix} x_1(1) & \cdots & x_1(n) \\ \vdots & \ddots & \vdots \\ x_m(1) & \cdots & x_m(n) \end{bmatrix} \text{ and i = 1, 2, …, m and j= 1, 2, …, n} \tag{3}$$

Here, X is the matrix included alternatives and criteria. The first calculation is the normalization of the values of X matrix as follows:

$$p_{ij}=\frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}} \tag{4}$$

Here, p_{ij} is the normalized value of ith alternative and jth criterion. In this method, the value of entropy E_i of the ith alternative is defined as [42]:

$$E_i=-\frac{\sum_{j=1}^{n} p_{ij}\cdot\ln(p_{ij})}{\ln n} \tag{5}$$

Here, E_i is between 0 and 1. Then, the determination of weight w_i can be done as:

$$w_i=\frac{1-E_i}{\sum_{j=1}^{n}(1-E_i)} \tag{6}$$

Also, weight w_i is between 0 and 1, and the sum of w_i is 1.

Table 4. Aggregate gradation curve details for standard curves such as A16, B16, and C16 [35], and proposed curves such as G1 and G2

Sieve size, mm	**G1**	**TS 802**			**G2**
		C16 (Upper AGC)	**B16 (Ideal AGC)**	**A16 (Lower AGC)**	
0.125	13	11	7	3	2
0.25	27	20	13	6	4
0.5	40	30	20	10	6
1	54	41	28	15	10
2	67	52	37	22	15
4	78	64	49	33	20
8	91	77	63	48	30
11.2	95	90	79	68	55
16	99	99	92	85	79
32	100	100	100	100	100

Table 5. Mix design of concretes

Parameters	**Natural aggregate concretes**					**Recycled aggregate concretes**				
Mixes	**NAC-G1**	**NAC-C16**	**NAC-B16**	**NAC-A16**	**NAC-G2**	**RAC-G1**	**RAC-C16**	**RAC-B16**	**RAC-A16**	**RAC-G2**
Components										
River Sand (0–2 mm), kg/m^3	759	541	380	199	126	759	541	380	199	126
Crushed Stone (0–4 mm), kg/m^3	808	698	533	349	276	808	698	533	349	276
Coarse Aggregatea (4–11 mm), kg/m^3	207	489	546	716	603	169	400	447	586	494
Coarse Aggregate (11–16 mm), kg/m^3	56	111	388	590	850	47	93	326	497	715
Cement, kg/m^3	350	350	350	350	350	350	350	350	350	350
Water, kg/m^3	175	175	175	175	175	175	175	175	175	175
Mix details										
Natural aggregate concentration, %	70.2	70.1	70.1	69.9	69.9	64.3	56.4	49.3	41.0	38.3
Attached old mortar content, %	0	0	0	0	0	6.0	13.7	20.8	28.9	31.6
Fresh properties										
Slump class	S2	S2	S2	S2	S2	S2	S2	S2	S2	S2
Air content of fresh concrete, %	1.1	1.3	1.3	1.4	1.5	1.3	1.7	1.8	2.0	1.7

2.2.3. Decision-Making Method: Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is one of the multi-criteria decision-making methods [10, 24, 43–47]. The method works with many matrixes and the data is entered in the decision matrix in the first part. Also, it goes on objectively and, in the progress the method forms positive and negative ideal solutions. However, only weights of the criteria are subjectively formed in the system and the user selects the weighting coefficients for each data.

Decision matrix includes alternative values with i×j dimensions. Lines in the matrix are decision points and columns in the matrix are factors (Eq. 7).

$$A_{ij} = \begin{bmatrix} a_{11} & \cdots & a_{1j} \\ \vdots & \ddots & \vdots \\ a_{i1} & \cdots & a_{ij} \end{bmatrix} \tag{7}$$

Table 6. The test results of mortars

Notations	Air content of fresh mortar, %	Bending strength, MPa			Compressive strength, MPa		
		Average	Minimum	Standard deviation	Average	Minimum	Standard deviation
M-G1	2.4	9.17	9.07	0.12	45.2	43.0	1.57
M-A16	3.0	9.63	9.26	0.32	46.0	44.8	0.98
M-B16	3.1	9.09	8.60	0.43	44.8	43.2	1.40
M-C16	3.5	8.72	7.52	1.15	46.7	43.4	2.16
M-G2	3.7	8.53	8.16	0.33	44.0	43.0	0.65

Table 7. The test results of concretes

Notations	C_{NA}, %	C_{CNA}, %	I_m, mm	A_{fresh}, %	d, g/cm^3	WA, %	f_c, MPa			
							Mean	Min.	Std. Dev.	Str. Class
NAC-G1	70.2	14	3.36	1.1	2.26	3.1	43.1	41.6	1.56	C30/37
NAC-C16	70.1	32	4.16	1.3	2.32	3.0	44.1	43.2	0.95	C30/37
NAC-B16	70.1	50	5.12	1.3	2.36	2.5	50.2	49.8	0.34	C35/45
NAC-A16	69.9	70	6.10	1.4	2.38	3.1	53.6	52.7	0.77	C40/50
NAC-G2	69.9	78	6.79	1.5	2.41	3.2	46.5	43.7	2.57	C35/45
RAC-G1	63.6	14	3.36	1.3	2.18	3.5	35.9	34.4	1.30	C25/30
RAC-C16	56.8	32	4.16	1.7	2.22	3.5	38.7	38.0	0.93	C30/37
RAC-B16	49.7	50	5.12	1.8	2.21	3.9	37.4	37.0	0.51	C30/37
RAC-A16	42.0	70	6.10	2.0	2.21	4.3	34.8	33.7	1.42	C25/30
RAC-G2	38.8	78	6.79	1.7	2.23	4.5	34.2	33.5	0.86	C25/30

C_{NA}: Ratio of natural aggregate volume to total volume; C_{CNA}: Coarse aggregate volume to total aggregate volume; I_m: Fineness modulus; A_{fresh}: Air content of fresh concrete; d: Density of hardened concrete; WA: Water absorption; f_c: Compressive strength.

Then, normalized matrix is formed considering decision matrix elements (a_{ij}) (Eq. 8–9).

$$N_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{n} a_{ij}^2}} \quad (i = 1,2,3,\dots,m \ ve \ j = 1,2,3,\dots,n) \tag{8}$$

$$N_{ij} = \begin{bmatrix} n_{11} & \cdots & n_{1j} \\ \vdots & \ddots & \vdots \\ n_{i1} & \cdots & n_{ij} \end{bmatrix} \tag{9}$$

The weighting coefficients are added to normalized matrix (Eq. 10).

$$V_{ij} = \begin{bmatrix} w_1 \times n_{11} & \cdots & w_n \times n_{1j} \\ \vdots & \ddots & \vdots \\ w_1 \times n_{i1} & \cdots & w_n \times n_{ij} \end{bmatrix} \rightarrow V_{ij} = \begin{bmatrix} v_{11} & \cdots & v_{1j} \\ \vdots & \ddots & \vdots \\ v_{i1} & \cdots & v_{ij} \end{bmatrix} \tag{10}$$

According to the problem condition, positive and negative ideal solution values are found considering maximization and minimization (Eq. 11–14). Positive ideal solution values:

$$A^+ = \{(max_i \, v_{ij})\} \tag{11}$$

$$A^+ = \{{v_1}^+, {v_2}^+, \dots, {v_n}^+\} \tag{12}$$

where, A^+ matrix includes maximum values for each column. Negative ideal solution values:

$$A^- = \{(min_i \, v_{ij})\} \tag{13}$$

$$A^- = \{{v_1}^-, {v_2}^-, \dots, {v_n}^-\} \tag{14}$$

where, A^+ matrix includes minimum values for each column. Then the distance from alternatives to negative and positive ideal solutions is calculated (Eq. 15–16). The distance to positive ideal solution:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2} \tag{15}$$

The distance to negative ideal solution:

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2} \tag{16}$$

At the last part, calculation of the relative proximity to the ideal solution is done for alternatives and the values vary between 0 and 1 (1 is absolute positive ideal solution) (Eq. 17).

$$G_i^* = \frac{S_i^-}{S_i^- + S_i^+} \tag{17}$$

3. Results and Discussion

The test results were properly evaluated in the separate sections. In this paper, the effect of AGC on the properties of mortars and the properties of concretes were investigated. The concretes designed by five AGCs such as G1, 16, B16, C16, and G2 consisted of the mortar phases such as M-G1, M-A16, M-B16, M-C16, and M-G2, respectively, and also coarse NA and RA. Thus, three stages were conducted to assess the properties of the mortars and concretes and select the best mix. The test results of the mortars and concretes are given in Tables 6 and 7, respectively.

3.1. The Results of The Stages

The stages of this study have separated evaluation parts as given below. Accordingly, the first stage included the evaluation of the strengths of the mortars in consideration of the effect of AGCs on the mortar phases of the concretes. The mortars included some components of concrete (i.e., cement, water, fine aggregate, admixture, and not coarse aggregate) representing mortar phase of concrete. The second stage was on the test results of concretes (i.e., the air content of fresh concrete, the density of the hardened state of concrete, water absorption, and compressive strength) with fruitful comments, and evaluations. In the third stage, an evaluation was made as an additional stage on the experimental data to select the best AGC for RAC by using a decision-making instrument, it was TOPSIS.

3.1.1. Results of the First Stage of the Experimental Program

The results of the mortars were given in Table 6. The mortar phase was the same for NAC and RAC if the same aggregate distribution curve was used. It has been observed in this study that the strength properties of mortars were dependent on the AGC. it has been determined that the bending strength of mortars decreased as they were changed from the upper aggregate distribution curve to the lower aggregate distribution curve. For example, the bending strength of the M-G1 mixture was determined as 9.17 MPa, while the bending strength of the M-B16 mixture was determined as 9.09 MPa, and the bending strength of the M-G2 mixture was also found to be 8.53 MPa. It is found that the fineness modulus of the mix increased as the aggregate distributions of the mix changed from G1 to G2, and this caused an increase in the fineness modulus (which means that the grain size of aggregates became larger) reduced their bending strength. Considering the effect of the aggregate distribution on all mortar bending strengths, it can be seen that the highest bending strength value was obtained as 9.63 MPa in the M-C16 mixture and the second was M-G1 with 9.17 MPa following the first. On the other hand, the standard deviations of the mortars decreased (except for M-G2) and the air content of the fresh mortar increased when the fineness modulus of the mix decreased. This may be caused due to the increase in the average aggregate size of the mix (the fineness modulus of the mix) and it was reported that the higher aggregate size in the mix caused the settling problem creating gaps in the medium and realized a decrease in the strengths [24, 36]. On the other hand, the compressive strength of mortars was not influenced by the AGC, and the strengths only changed between 44–46 MPa. According to the cement properties obtained from the producer as given in Table 1, the cement has minimum 42.5 MPa compressive strength and the addition of fine aggregate didn't decrease/increase the strength. In addition, it was reported that the fine particles (0.063–4 mm) had a minor influence on the compressive strength of the specimens except for powders (<0.063 mm) if these were added to the cement paste [24, 36]. Accordingly, it can be commented that the bending behavior (bending is the combination of tensile + compressive stresses through the cross-section of the specimen as well-known) may have been influenced by the AGC. Besides, the minimum compressive strength values showed a limited change between 43–44 MPa while the standard deviation of the specimen presented a similar behavior. As a consequence of the results mentioned, AGC had an effect on the bending strengths and, a minor change was observed in the compressive strengths due to the AGC.

3.1.2. Results of the Second Stage of the Experimental Program

The results of the concretes were given in Table 7. According to the physical test results, it was found that when the fineness modulus of the mix increased due to different AGC, the density of NAC and RAC increased from 2.26 to 2.41 g/cm^3 and from 2.18 to 2.23 g/cm^3, respectively, and the increase in the density of RAC was found limited due to the increase in the open porosity. Because the water absorption of RAC was found higher than that of NAC, the inclusion of coarse RA in the mix was the key factor. For instance, the water absorptions of NAC-G2 and RAC-G2 were determined as 3.2% and 4.5% while the same AGC consideration in the mix and the mentioned difference became clearer when the coarse aggregate concentration increased in the mix from 14 to 78%. As reported in the literature, RA had a porous structure with high-water absorption and low-density values [1, 10, 21, 48] and it shaped the resulting concrete properties when RA was used in the mix. On the other hand, it can be indicated that the high fineness modulus the high coarse aggregate

Table 8. Weights of concrete properties

Criteria	Density	Water abs.	Coarse agg. ratio	Air content	Nat. agg. cons.	Fineness mod. of mix	Mean comp. str.
Weight values for NACs	0.0014	0.0207	0.7554	0.0295	0.0000	0.1737	0.0193
Weight values for RACs	0.0001	0.0275	0.6773	0.0480	0.0859	0.1558	0.0054
Weight values for concretes	0.0026	0.0636	0.5865	0.0688	0.0922	0.1349	0.0513

concentration, but the low natural aggregate concentration was observed by changing AGC from G1 to G2. Thus, the skeleton of the RAC became weak compared to NAC, so not only the physical properties but also the mechanical properties of RAC were affected negatively. Hence, the compressive strength of the RAC was obtained lower than NAC while the same AGC was considered.

When different AGCs from G1 to G2 were used with different fineness modulus from 3.36 to 6.79 mm in the mix, the compressive strength increased up to 38.7 MPa for up to 4.16 mm fineness modulus then decreased down to 34.2 MPa for up to 6.79 mm fineness modulus. Hence, the peak/maximum compressive strength of RAC was determined for RAC-C16. It can be stated that RAC-C16 had 56.8% natural aggregate concentration, a low open porosity (3.5%), and a high density (2.22 g/cm^3). However, the results showed that the highest compressive strength of NAC was obtained for RAC-A16 as 53.6 MPa with 69.9% natural aggregate concentration. It can be noted that the coarse aggregate concentration in the RAC caused high entrained air content, high open porosity, and settling problem decreasing the compressive strength while it supported the skeleton of NAC increasing the compressive strength of NAC although increasing a minor air content of the mix. Besides, although the mentioned positive effect of coarse NA on the strength was observed, the comments cannot be made for RA. Because RA had an additional part (AOM) compared to NA, AOM had low physical and mechanical properties compared to NA [21]. Therefore, RA had three ITZ: old ITZ between NA in RA and old AOM, new ITZ between NA in RA and cement paste, and new ITZ between AOM and cement paste [6, 24]. Thus, the inclusion of coarse RA cannot have acted as similar as the coarse NA and the increase in the compressive strength of RAC cannot have been observed due to AOM and the higher ITZ volume compared to that of NAC. In addition, based on the compressive strength test results, the strength classes of concretes were determined according to TS EN 206-1+A2 (Turkish Standards Institution, 2021), and the strength classes of the concretes were given in Table 7. According to the findings, it can be stated that the consideration of RA in the mix decreased not only the compressive strength but also the strength class of concrete. Besides, it is interesting that the strength class of not only NAC but also RAC were dependent on the aggregate type [24, 36] and the AGC. Also, the scatter of test results of compressive strength was observed due to the AGCs. The strength class of NACs was not the same and differed from C30/37 to C40/50. Similar comments can be made for RACs.

Thus, the fine particle proportion rather than coarse particle may have a great role in the results of RAC-C16, and AGC influenced RAC and NAC in a different way. Hence, the parameters mentioned above can be considered properly while the design of the RAC mix.

3.1.3. The Results of the Third Stage of the Experimental Program

In this section, the properties of concretes were evaluated in a holistic manner. First, the weights of the concrete results were determined using the Entropy Method and the importance of the parameters according to their weights was examined. In addition, considering the concrete results and parameters examined in the article, the best concrete series was determined using TOPSIS. Then, the results were compared together.

3.1.3.1. Entropy Method Results

The Entropy Method is a weighting method working objectively and is widely used in many areas from management to engineering. The output data of the method (weights) eases and accelerates decision-making with a low decision time. Hence, the weights of the parameters of concretes such as density, water absorption, coarse aggregate ratio, air content of fresh concrete, natural aggregate concentration, fineness modulus, and compressive strength were calculated to compare the importance level of each parameter in this study (Table 8). As a result, the weights of the properties of concretes were determined in consideration of the mentioned parameters.

The effect of the AGC on the properties of concretes was investigated in this study and the most important first and second criteria among the mentioned properties were determined by the Entropy Method such as that the first was the coarse aggregate ratio in the mix and the second was the fineness modulus of the mix aggregate. As mentioned in the previous section, it was found that the physical and the mechanical properties of not only NAC but also RAC were influenced by the coarse aggregate ratio of the mix and the natural aggregate concentration, and the findings were given in Table 8 proved these statements.

In addition, the comparison of the weights of the properties of NAC and RAC showed that the influence of the

Table 9. Weights of criteria (Scale from 1 to 10 imply that higher is important)

Criteria	Mortar		Concrete						
	Bending strength	Compressive strength	Coarse aggregate concentration	Natural aggregate concentration	Fineness modulus	Density	Water absorption	Air content	Compressive strength
Weights[a]	3	9	7	7	7	5	9	9	9

[a]: High is important.

Table 10. TOPSIS results

Concretes	NAC-G1	NAC-C16	NAC-B16	NAC-A16	NAC-G2	RAC-G1	RAC-C16	RAC-B16	RAC-A16	RAC-G2
Gi[a]	0.535	0.567	0.618	0.641	0.635	0.514	0.539	0.554	0.564	0.573

[a]: High is good.

AGC on the compressive strength of NAC was higher than that of RAC while a relatively minor influence of the AGC on the density of RACs and the natural aggregate concentration of NACs was found. Besides, when the weights of the concrete properties were compared, the weights of the water absorption and the air content of fresh concretes were nearly the same.

3.1.3.2. TOPSIS Results

TOPSIS is a method to determine the effectiveness and the suitable choice considering the criteria of the choices with their weights. Hence, when TOPSIS is intended to use, the weights of the criteria of the choice. In this paper, accordingly, the weights of criteria were determined as given in Table 9 and the results were evaluated in the TOPSIS using the weights which weights were formed according to the author's experiences. The scale for weights was performed from 1 to 10, and here the higher was more important. The mechanical performance and the durability performance were kept at the forefront. Hence, compressive strength and open-pore related properties such as the water absorption and the air content in the fresh concrete were decided as more important and 9 was specified. Besides, it is well-known that the natural aggregate concentration influences the mechanical performance of concrete [34] and 7 was specified for the concentrations.

After an examination of the parameters in TOPSIS, the results were found as given in Table 10. Separately evaluation of the test results showed that A16 resulted in a denser NAC with higher compressive strength, while C16 resulted in a durable RAC in terms of low water absorption capacity with higher compressive strength. However, when all parameters were investigated together using the TOPSIS the best AGCs were found as A16 for NAC and G2 for RAC, respectively. According to the TOPSIS results, RAC-G2 and RAC-A16 had 0.573 and 0.564 scores, respectively, and it can be noted that RAC-A16 can also be preferred instead of RAC-G2 due to the similar TOPSIS scores. When the TOPSIS results of RACs were compared with that of NAC, although RAC-G2 was the best in RACs, it is interesting that RAC-G2 was superior to the worse concrete among NACs.

4. CONCLUSION

In this paper, the effect of aggregate gradation curves (AGCs) detailed in TS 802 (A16, B16, and C16) on recycled aggregate concrete (RAC) was investigated. Also, two AGCs (G1 and G2) were proposed to examine the effect of the rest of the region detailed in TS 802 (A16, B16, and C16). Accordingly, a comprehensive experimental program was conducted including three stages for the evaluation of the properties of the mortar phase of concrete, the concrete, and the selection of the best concrete mix. Hence, after conducting the several tests on the specimens, the following conclusions and discussions were made based on the evaluations of the test results:

1) AGC had an effect on the bending strengths, and a minor change was found in the compressive strengths due to the effect of AGC.
2) Different AGCs required different fine and coarse aggregate proportions in the mix and five AGC were employed in the mix design of concretes. Accordingly, the fine particle ratio in the mix rather than the coarse particle ratio in the mix may have a great role in the results of RACs, and AGC affected RAC and NAC in a different manner. Thus, the parameters investigated in this paper can be considered properly in RAC mix design to achieve a high compressive strength value.
3) The Entropy results showed that the influence of the AGC on the compressive strength of NAC was higher than that of RAC while a relatively minor influence of the AGC on the density of RACs and the natural aggregate concentration of NACs. Also, the most important criterion was found as the coarse aggregate ratio in the mix and the fineness modulus of the mix aggregate followed the first.

4) Separately evaluation of the test results and holistic evaluation of all results presented different findings for RAC but the same for NAC. Accordingly, a separate evaluation of the test results showed that A16 resulted in a denser NAC with higher compressive strength, while C16 resulted in a durable RAC in terms of low water absorption capacity with higher compressive strength. However, when all parameters were investigated together using the TOPSIS the best AGCs were found as A16 for NAC and G2 for RAC, respectively. RAC-A16 can also be preferred instead of RAC-G2 due to the similar TOPSIS scores.

5. FURTHER ASPECTS

A16 AGC resulted in a denser NAC with higher compressive strength and can be suitable to use for NAC. However, further investigations should be conducted including the durability tests. C16 AGC can be offered to decrease the open pore content of RAC in terms of water absorption and thus this can lead to durable concrete. However, further investigations including durability parameters should be conducted. Because RA has pores, this leads to a weak link in the medium.

The Entropy Method, in this paper, gives the important level of the parameters and emphasizes that the coarse aggregate ratio in the mix was an important parameter and can be considered in the design of RAC. Besides, the importance level of the investigated properties of concretes should be enlarged by adding the other physical, mechanical, and durability properties. Thus, more comprehensive, understandable, and comparable findings can be achieved. Also, the weights of the concrete properties can be determined by using other weighting methods (i.e., SWARA, CILOS, IDOCRIW) and the results of the methods can be compared to each other. Also, the advantages and the disadvantages of the methods in the current area can be argued.

The AGCs such as A16, B16, and C16 considered in this paper were selected according to the maximum aggregate size (it was 16 mm). However, the effect of AGCs for the maximum aggregate sizes such as 8 mm, 32 mm, and 64 mm as given in TS 802 can be investigated in further studies RAC. Besides, in this paper, RA was sourced from low strength (<20 MPa) waste concrete. The medium strength (20–40 MPa) and the high strength (40 MPa>) waste concrete sources can be examined to observe the difference in the effect of the AGCs.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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PEER-REVIEW

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