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Experimental investigation on properties of recycled aggregate concrete with optimized Ball Milling Method

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HIGHLIGHTS

- Mechanical treatment method (Ball Milling Method) is applied to RA with an optimization process.
- Initial RA water absorption value (8.95%) is decreased 0.84% after oBMM.
- The optimum 'enhanced' RA use in concrete is found as 60%.

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ABSTRACT

Numerous research studies were conducted to improve the weak properties of recycled aggregate as a construction material during the last two decades. Most of these studies mainly focused on minimizing the undesired characteristics of the recycled aggregate through various treatment techniques to strengthen the attached old mortar or remove it from the recycled aggregate. Mechanical Treatment Methods (MTMs) used to remove the attached mortar from the aggregates were evolved over the years. Among available methods of treatments in the literature, the number of studies investigated the MTMs with an optimization process is limited. In lack of proper optimization process with rubble quality identification, mechanical treatment methods may be ineffective to provide concretes with sufficient properties, and they may yield to extra energy consumption and carbon emission. In other words, the optimization of treatment methods and determination rubble quality are two essential steps for having satisfactory results on the recycled aggregate.

In this study, an optimization process is applied using the Los Angles test machine through the conducted Ball Milling Method (BMM). During the BMM process, various combinations of rotation (R) (100–200-300-400-500) and the steel ball (S) (0-2-5-7-10-12) applied to the recycled aggregate. Analysis results demonstrated the effectiveness of reducing the 8.95% water absorption value of the untreated recycled aggregate to 0.84% after the optimization process of BMM.

Then, seven concrete specimens including 0-20-40-60% recycled aggregate (RA) and improved recycled aggregate (RA-i) mixes produced in the framework of the experimental study. For comparison purposes, engineering properties of 28 days concrete are determined. The use of RA-i up to 60% in concrete has not influenced the physical and mechanical properties, distinctively. After the optimization process, the RA use in concrete increased up to 60% which is twofold of the optimum RA value in the literature. As a result, optimized BMM improved the mechanical and physical characteristics of RA and increased the use of RA ratio in concrete mixes without any trade-off.

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1. Introduction

Using aggregates from recycled Construction and Demolition Waste (CDW) in concrete is critical to minimize the consumption of limited resources and fulfill the sustainability in the construction industry. During the CDW process and utilization of recycled aggregate (RA), engineers confront with several issues due to two phases of recycled aggregate namely natural aggregate (NA) and attached old mortar (AOM) are described [1]. Even though natural aggregate (NA) has better material characteristics compared to AOM, it still has a lower density, elasticity modulus, and compressive strength with a higher water absorption capacity due to its ITZ

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cracks [1–5]. As a result, such undesired properties limit the widespread use of RA in concrete works. Most of the research studies based on recycled aggregate concrete (RAC) report that RA influences the mechanical properties and workability and impairing durability of concrete unfavorably [6–10]. Therefore, most of the research studies focused on improving these material properties of RA to make its use feasible in the production of concrete [11–13]. The mechanical grinding and the acid treatment methods are used to remove AOM while the polymer and the pozzolan slurry emulsion methods are generally used to strengthen AOM [11]. Removal of AOM and strengthening process aim to improve the RA considering lower strength capacity, high porosity, and higher water absorption properties. However, when these treatment methods have taken into account, energy consumption, CO_2 emission and their detrimental effects on the environment should be considered [14]. In this respect, the mechanical/microwave and various mechanical treatment methods are one step ahead for being environmentally friendly. Among mechanical treatment methods, mechanical abrasion treatment is the most successful method based on its impact on the environment and required energy consumption [14]. The Ball Milling Method (BMM) is one of the well-known mechanical abrasion treatment methods applies to RA. BMM method can be applied by itself or together with other available methods.

The performed studies using BMM in the literature are classified into three major groups as follows:

1) Methods disregard the former concrete properties (i.e., mechanical properties) while applying BMM/BMM together with another treatment method to RA without performing any optimization process on the treatment [13,15–19].
2) Methods considering the former concrete properties (i.e., mechanical properties) while applying BMM/BMM together with another treatment method to RA without performing any optimization process on the treatment [20–23].
3) Methods considering the former concrete properties (i.e., mechanical properties) while applying BMM/BMM together with another treatment method to RA with an optimization process on the treatment [24].

The number of studies considering the former concrete characteristics with an optimization process was limited in the literature, and its unfavorable consequences such as carbon emission, energy consumption and a waste of time have given in the context of this study. Moreover, additional cracks usually form due to applied mechanical treatments [25,26]. The rubble quality is an important factor determining the concrete properties, especially the impact of low-quality rubble becomes more apparent in the freshly poured new concrete [27].

This research study aims to close the gap in the literature while providing important outcomes about the use of recycled aggregate at a higher percentage in an efficient way for the concrete industry. In this experimental study, RA used in concrete mixes is obtained from the low strength concrete (20 MPa) [27,28], and the physical and the mechanical tests were applied on the former concrete to define its rubble quality. Then, for determining the optimum rotation (R)–steel ball (S) value of the BMM, 30 different combinations of R-S, 100-200-300-400-500 rotations with 0-2-5-7-10-12 steel balls, are applied using a standard Los Angeles abrasion test machine. The criterion established for the optimum combination was to reduce water absorption ratios of the RA less than 1%. Concretes produced in the laboratory are classified into three main groups as follows; (1) conventional concrete with NA (as control ones), (2) recycled aggregate concrete with untreated RA and (3) recycled aggregate concrete with treated RA by using the optimized BMM. The physical tests (density and water absorption), the mechanical tests (compressive, splitting tensile and flexural strengths and elasticity modulus) and SEM analysis are conducted on the concrete specimens at 28th day.

2. Framework of the experimental study

2.1. Material properties

CEM-I type cement meets the requirements of TS EN 197-1:2012 [29] standard is used in the content of the concrete mix during the experimental study. Properties of the CEM-I cement are listed in Table 1.

Properties of NA used in this study are demonstrated in Table 2. Both fine and coarse natural aggregates (NA) used in the produced concrete mixes. CDW used in this study belongs to a demolished building in Istanbul/Turkey. The properties CDW are given in Table 3. One of the important criteria to obtain RA was to use CDW without any impurities, such as bricks, marble, and tile. RAs were obtained by crushing CDW in the laboratory. Properties of RA used in this study are demonstrated in Table 4. The particle size distribution tests carried out in compliance with TS 706 EN 12620:2009 [30] for aggregates.

Experimental study was conducted in five stages: *In the first stage of the study*, physical and mechanical tests were performed to determine the quality of the source material for RA. Water absorption and density tests were performed for defining the physical properties on concrete samples belonging to former concrete whereas the compressive strength tests were performed to determine mechanical properties of the samples. The average compressive strength for 16 cylindrical cores that has a dimension of 100 mm diameters and 100 mm height found to be 8.05 MPa (Table 3). According to the literature, the source quality classifications of the concrete wastes, such as low quality for 15–25 MPa, medium quality for 35–45 MPa and high quality for 65–75 MPa, and the strength classifications of the concrete types, such as low strength for <20 MPa, moderate strength for 20–40 MPa and high strength 40–60 MPa, are defined clearly [27,28]. Since the average compression strength is less than 20 MPA, the RA incorporated in this study corresponds to low-strength classification. According to Pedro et al. [27] when the source quality of the RA in the concrete mix varies between high-quality to medium quality, loss in the performance of concrete described as negligible. Thus, in lack of RA treatment methods, the properties of former concrete in this study were expected to affect the properties of recycled concrete.

In the second stage of the study, the CDW is crushed into small pieces by using a laboratory jaw crusher in order to obtain RAs having size fractions smaller than 35 mm. RA stack was separated and stored in containers for three fraction ranges with 0–4 mm, 4–11.2 mm, and 11.2–22.4 mm. The physical and mechanical properties of the RA ranging from 11.2 mm to 22.4 mm confirmed the requirements of TS-EN 1097-6:2013 [31] and TS EN 1097-2:2015

Table 1
The contents of cement.

Contents	Value
SiO_2 (%)	21.9
CaO (%)	65.0
SO_3 (%)	2.6
Al_2O_3 (%)	6.0
Fe_2O_3 (%)	3.5
MgO (%)	0.9
Density (g/cm^3)	3.14
Specific surface area (m^2/kg)	3520
Loss on ignition (%)	1.1

Table 2
The properties of natural aggregates.

Notation	Density (g/cm^3)	Water absorption (%)	LA abrasion value, %
Sand	2.74	1.2	–
NA (11.2–22.4 mm)	2.67	0.67	21
NA (4–11.2 mm)	2.62	0.78	–

Table 3
The average compressive strength, the water absorption and the density of the origin concrete.

	Density (g/cm^3)	Water absorption (%)	Compressive strength (MPa)
Average	2.00	10.11	8.05
Standard deviation	0.11	1.80	2.54

Table 4
The properties of treated and untreated recycled aggregates.

Aggregate	Water absorption (%)	Density (g/cm^3)	LA abrasion value, %
RA (11.2–22.4 mm)	8.95	1.80	55
Natural aggregate in RA (11.2–22.4 mm)	0.56	2.78	–
RA-i (11.2–22.4 mm)	0.84	2.47	28

[32]. Therefore, RAs separated into 0–4 mm and 4–11 mm were excluded from this study.

In the third step, optimization process of Ball-Milling Method is performed on RA using standard Los Angeles abrasion machine, and standard steel balls were used to reduce the water absorption property below 1% level. In the optimization process, the number of drum rotations (R) and the number of the steel balls (S) were set to 100-200-300-400-500 and 0-2-5-7-10-12, respectively, and, each 5 kg of RA within the range of 11.2–22.4 mm subjected BMM. Series of BMM tests with 30 different combinations applied to the RA with various drum rotation number and steel ball values as shown in Tables 5 and 6. Following each BMM test, RAs were put in bags with name tags describing the applied procedure on the RA. For instance, if the name tag of the RA shows 300R-2S, the numbers in front of the letters represent the rotations and steel balls, respectively.

In the fourth step, the processed RA samples separated into three groups with fraction sizes of 0–4 mm, 4–11.2 mm and 11.2–22.4 mm. Water absorption and the density tests were carried out on the processed RA with only fraction sizes of 4–11.2 mm and 11.2–22.4 mm. Test results were showed that rise in the number of R and S not only increases the density of RA but also reduces the water absorption of RAs. The rise in the number of rotations and steel ball not only increased the density but also reduced the water absorption of RAs based on test results (Tables 5 and 6). For the low strength RA, the optimum drum rotation and steel ball combination selected as 500R-10S depending on the water absorption values of RA. Prior to the optimization process of RA in the BMM, the only criterion for the optimum combination is to have a water absorption value less than 1%. During the BMM process, the amount of 0–4 mm RA started to increase with the selected rotation number and steel ball number while the amount of AOM in RA significantly decreased (Fig. 1).

Hereinafter 500R-10S RA sample will be named as improved RA (RA-i). Los Angeles abrasion test is applied on RA-i in accordance with the requirements of TS EN 1097-2:2015 [32] and LA abrasion value was found as 28%. The RA-i is also used to prepare the required amount of fraction size for 4–11 mm, and 11.2–22.4 mm range *in the fifth step*. Powder and shell content, Los Angeles abrasion loss, water absorption, density, unit weight, attached old mortar content, shape index, flatness index, sand equivalence, aggregate volume stability, freeze-thaw resistance of aggregates were determined and the test results carried out on aggregates are given in Table 7.

2.2. Production of concrete

Concrete designs were prepared in the laboratory regarding the absolute volume method for 0–20–40–60% RA and improved RA (RA-i) mixes. Designated concrete samples and their contents were given in Tables 8 and 9. During the casting of fresh concrete, the cast-in-place concrete was vibrated until seeing the occurrence of air bubbles on the surface.

Angularity and surface roughness in terms of texture in RA compared with rounded and smooth NA as shown in Fig. 2. Workability of the concrete mixes was expected to be in the lower range. Before the use of RA in the concrete production, RAs were soaked into 20 ± 2 °C water in the laboratory for 24 h. Furthermore, polycarboxylic ether based superplasticizer was used to achieve the constant workability (S4) in the mixtures. However, after the application of BMM, RA had smoother and rounded shapes, and lower-workability characteristic has overcome for the RA-i concrete mixes. Hence, approximately the same amount of superplasticizer is used to fulfill the requirements of TS EN 206-1:2019 [33] as shown in Table 9.

2.3. Test specimens and curing procedure

Based on the specifications of TS EN 12390-2:2010 [34], two cylindrical specimens with an aspect ratio (h/d) of 2 and prismatic specimens with an aspect ratio of 5 were stored in lime-saturated water at 20 ± 2 °C until 28-day.

2.4. Tests

Water absorption, density, and tensile splitting strength tests were conducted on the cylindrical specimens with a 100 mm diameter and aspect ratio of 2 in accordance with the requirements

Table 5
The density of RA after the application of BMM.

	RA (4–11.2 mm) (g/cm^3)						RA (11.2–22.4 mm) (g/cm^3)					
	0 S	2 S	5 S	7 S	10 S	12 S	0 S	2 S	5 S	7 S	10 S	12 S
100 R	2.00	1.96	1.68	1.85	2.43	2.26	2.04	1.78	1.77	2.16	2.32	2.34
200 R	2.19	2.15	2.13	2.10	2.32	2.37	1.75	2.24	2.32	2.32	2.51	2.41
300 R	2.15	2.03	2.27	2.22	2.29	2.28	2.32	2.28	2.23	2.37	2.32	2.36
400 R	2.03	2.03	1.82	2.31	2.44	2.34	2.08	2.09	2.22	2.18	2.43	2.73
500 R	2.29	2.19	2.20	2.45	2.49	2.40	2.38	2.41	2.38	2.42	***2.47***	2.47

Table 6
The water absorption values of RA after the application of BMM.

	RA (4–11.2 mm) (%)						RA (11.2–22.4 mm) (%)					
	0 S	2 S	5 S	7 S	10 S	12 S	0 S	2 S	5 S	7 S	10 S	12 S
100 R	8.43	9.97	7.81	6.28	5.62	7.67	13.34	8.19	6.16	6.17	4.73	3.77
200 R	6.38	7.53	7.57	7.25	4.36	4.03	7.14	6.52	2.71	3.37	3.50	1.63
300 R	6.48	6.58	5.26	5.93	3.99	3.46	4.48	5.34	4.29	3.14	3.08	3.48
400 R	7.14	6.41	6.36	6.00	2.66	2.05	5.71	6.77	4.08	9.96	1.45	1.24
500 R	4.24	6.31	5.68	2.56	2.00	2.14	2.82	1.98	2.03	1.14	***0.84***	0.96

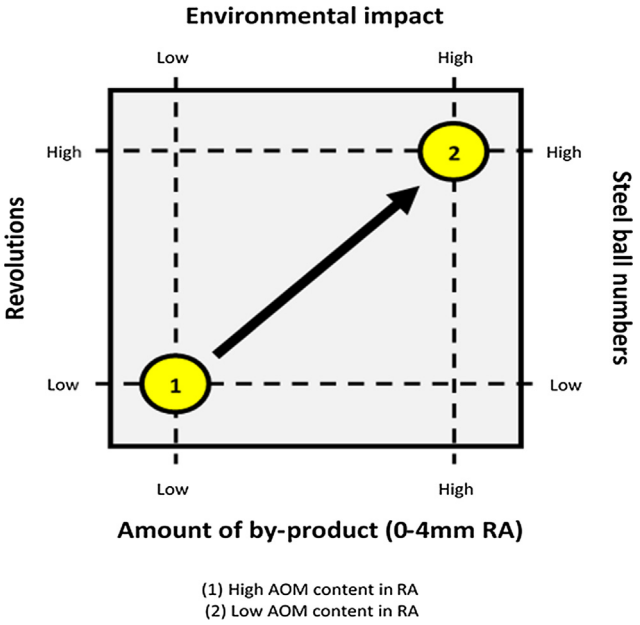


Fig. 1. The amount of 0–4 mm RA obtained during BMM.

of TS EN 12390-6:2010 and TS EN 12390-7:2010 [31,35] whereas the compressive strength and the elasticity modulus tests performed on the cylindrical specimens with a 150 mm diameter and aspect ratio of 2 regarding TS EN 12390-3:2010 [36],

ASTM C469:2014 [37], respectively. Similarly, flexural strength and inclination angle determination tests performed on prismatic specimens (short edges 100 mm, height 500 mm) in accordance with the TS EN 12390-5:2010 [38–41]. The tests are given in Table 10.

Table 8
The notations of concrete mixtures.

Notation		Definition
Concretes with NA	NAC	Concrete containing 20% NA (4–11.2 mm aggregate size) and 40% NA (11.2–22.4 mm aggregate size)
Concretes with untreated RA	RA1C	Concrete containing 20% RA (4–11.2 mm aggregate size) and 40% NA (11.2–22.4 mm aggregate size)
	RA2C	Concrete containing 20% NA (4–11.2 mm aggregate size) and 40% RA (11.2–22.4 mm aggregate size)
	RA12C	Concrete containing 20% RA (4–11.2 mm aggregate size) and 40% RA (11.2–22.4 mm aggregate size)
Concretes with treated RA	RA1C-i	Concrete containing 20% RA-i (4–11.2 mm aggregate size) and 40% NA (11.2–22.4 mm aggregate size)
	RA2C-i	Concrete containing 20% NA (4–11.2 mm aggregate size) and 40% RA-i (11.2–22.4 mm aggregate size)
	RA12C-i	Concrete containing 20% RA-i (4–11.2 mm aggregate size) and 40% RA-i (11.2–22.4 mm aggregate size)

Table 7
Aggregate test results.

Properties	Aggregate type					
	NA		RA		RA_i	
	4–11.2 mm	11.2–22.4 mm	4–11.2 mm	11.2–22.4 mm	4–11.2 mm	11.2–22.4 mm
Powder content (<0.063 mm), %	1.2	0.9	2.6	2.2	0	0
Shell content, %	0	0	0	0	0	0
Los Angeles abrasion loss, %	–	21	–	55	–	28
Water absorption, %	0.78	0.67	8.80	8.95	1.40	0.84
Density, g/cm^3	2.62	2.67	2.06	2.00	2.58	2.47
Unit weight, g/cm^3	1.44	1.35	1.23	1.15	1.35	1.27
Attached old mortar content, %	–	–	39.2	52.5	6.7	9.6
Shape index, %	10.6	5.5	13.5	10.4	2.3	3.2
	Average = 8.0		Average = 11.9		Average = 2.7	
Flatness index, %	1.10	0.95	3.20	2.85	1.10	0.90
	Average = 1.03		Average = 3.03		Average = 1.00	
Sand equivalence, %	73	76	68	70	–	–
	Average = 74.5		Average = 69		–	
Aggregate volume stability, %	0.0737		0.0947		0.0842	
Freeze-thaw resistance, %	4 mm 8 mm	16 mm	4 mm 8 mm	16 mm	4 mm 8 mm	16 mm
	1.5 1.6	1.1	19.1 25.8	35.4	4.5 3.9	2.4
	Average = 1.4		Average = 26.8		Average = 3.6	

Table 9
The components of mixtures.

Notation		Cement, kg/m^3	Slump class	Super plasticizer, %	Water, kg/m^3	NA (4–11.2 mm), kg/m^3	NA (11.2–22.4 mm), kg/m^3	Crushed sand, kg/m^3	Natural sand, kg/m^3	Recycled aggregate, kg/m^3			
										16 mm	11.2 mm	8 mm	4 mm	2 mm
Concretes with NA	NAC	350	S4	0.60	175	369	737	780	467	–	–	–	–	–
Concretes with untreated RA	RA1C	350	S4	0.60	175	–	737	780	467	2	43	119	128	0
	RA2C	350	S4	0.55	175	369	–	780	467	233	311	61	5	37
	RA12C	350	S4	0.65	175	–	–	780	467	235	354	180	133	37
Concretes with treated RA	RA1C-i	350	S4	0.60	175	–	737	780	467	2	43	119	128	0
	RA2C-i	350	S4	0.55	175	369	–	780	467	233	311	61	5	37
	RA12C-i	350	S4	0.40	175	–	–	780	467	235	354	180	133	37

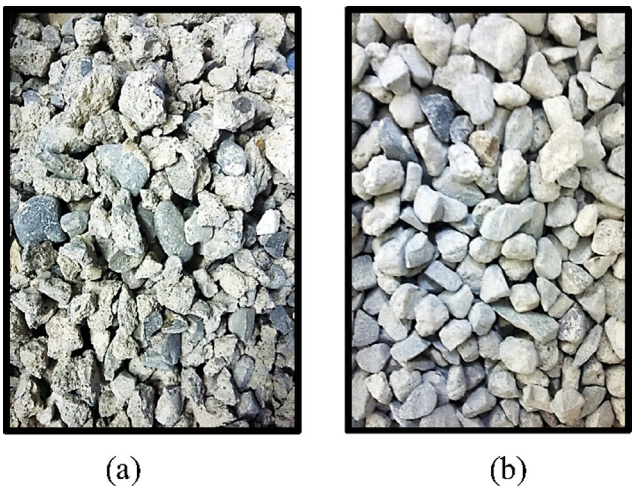


Fig. 2. Appearance of aggregates: RA (a) and RA-i (b).

Table 10
The tests conducted.

Test	Reference	Specimen details
Compressive strength	TS EN 12390-3:2010 [36]	Cylindrical specimen (diameter 150 mm, height 300 mm)
Flexural strength	TS EN 12390-5:2010 [38]	Prismatic specimen (short edges 100 mm, height 500 mm)
Inclination angle	[39–41]	Prismatic specimen (short edges 100 mm, height 300 mm)
Tensile splitting strength	TS EN 12390-6:2010 [35]	Cylindrical specimen (diameter 100 mm, height 200 mm)
Elasticity modulus	ASTM C469:2014 [37]	Cylindrical specimen (diameter 150 mm, height 300 mm)
Density	TS EN 12390-7:2010 [31]	Cylindrical specimen (diameter 100 mm, height 200 mm)
Water absorption	TS EN 12390-7:2010 [31]	Cylindrical specimen (diameter 100 mm, height 200 mm)

3. Test results and discussions

Physical (density and water absorption) and mechanical (compressive and splitting and flexural strengths, elasticity modulus, and inclination angle determination) test results of the 28-day concrete are shown in Tables 11 and 12.

3.1. Compressive strength

Test results confirmed the anticipated reduction of compressive strength due to the use of varying ratios of RA in concrete mixes (Tables 11 and 12 and Fig. 3). Even though compressive strengths of RA1C, RA2C, and RA12C reduced substantially, the amount of reduction in RA1C-i, RA2C-i, and RA12C-i kept at negligible levels as demonstrated in Tables 11 and 12.

The variation in the compressive strength in RA12C-i sample was promising due to having a slight change regardless of the 60% RA-i content. Moreover, the compressive strength of the concretes produced from the low strength source materials shifted to the moderate-strength concrete range (20–40 MPa) with 20–40–60% RA contents. It is evident that RA-i material after the optimization process changes the compressive strength in the recycled

Table 11
The test results of concrete specimens.

Notation		RA, %	Density (g/cm^3)	Water absorption (%)	Compressive strength, MPa	Splitting tensile strength, MPa	Elasticity modulus, MPa	Flexural strength, MPa
Concretes with NA	NAC	0	2.37	3.93	39.1	2.71	30,490	5.52
Concretes with untreated RA	RA1C	20	2.28	5.00	32.9	2.89	26,658	5.68
	RA2C	40	2.20	6.92	27.9	2.14	22,070	4.53
	RA12C	60	2.09	8.49	24.8	1.90	18,492	4.17
Concretes with treated RA	RA1C-i	20	2.34	3.77	39.5	2.64	29,413	5.33
	RA2C-i	40	2.31	4.03	38.3	2.45	25,012	4.44
	RA12C-i	60	2.28	4.35	38.2	2.59	25,636	5.03

Table 12
The relative test results of concrete specimens to NAC.

Notation		Density	Water absorption	Compressive strength	Splitting tensile strength	Flexural strength
Concretes with NA	NAC	–	–	–	–	–
Concretes with untreated RA	RA1C	−4%	+27%	−16%	+7%	+3%
	RA2C	−7%	+76%	−29%	−21%	−18%
	RA12C	−12%	+116%	−37%	−30%	−25%
Concretes with treated RA	RA1C-i	−1%	−4%	+1%	−3%	−3%
	RA2C-i	−3%	+3%	−2%	−9%	−20%
	RA12C-i	−4%	+11%	−2%	−4%	−9%

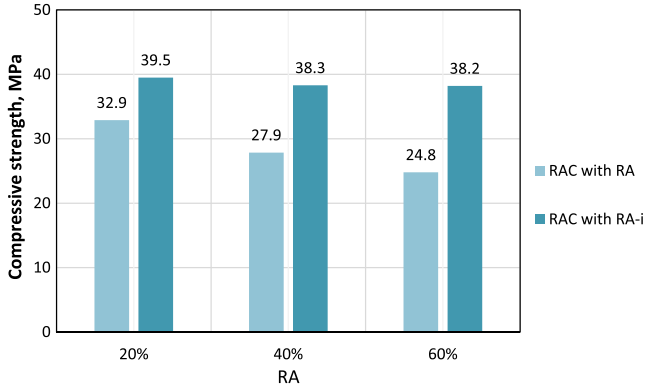


Fig. 3. The compressive strengths of concretes.

concrete, marginally. In contrast, the optimum recommended value of RA content is 30% corresponding to half of the findings of this study [1,42].

Following the mechanical tests, visual inspections were conducted on specimens to examine the crack pattern in concretes. It was observed that crack paths in concretes included RA passed through old ITZ while crack paths in concretes including RA-i passed through aggregates itself which indicated that the weakest point of RAC was AOM. Besides, the amounts of AOM in 4–11.2 mm and 11.2–22.4 mm RA decreased 39.2% to 6.7% and 52.5% to 9.6%, respectively, as shown in Table 7.

Formation of discontinuities in the texture of the RA attributed to crushing process decreases the compressive strength of the concrete. However, the removal of AOM content in RA by the optimization process of BMM contributes to the performance improvement in the concrete particularly for compressive strength (Tables 4 and 6 and Fig. 2).

3.2. Splitting tensile strength

Test results based on the splitting tensile strength are presented in Table 11. Regarding test results when the RA ratio in concretes increases, the splitting tensile strength decreases like in the tendency of compressive strength test. Despite using RA-i in concrete mixtures, reduction in splitting tensile strength was marginal. There are two common approaches in the literature to interpret the results of the splitting tensile test [1,7,43–45]. One approach takes into account the ratio of the splitting tensile strength to the compressive strength while the other approach only considers the splitting strength value. The evaluation can be performed either incorporating methods stated above or conducting regression analysis between splitting tensile and compressive strength value. In the scope of this study, all three available methods were examined properly as in the order described.

3.2.1. Evaluation 1: The ratio of the splitting tensile strength to the compressive strength of concretes

The ratio of the splitting tensile strength to the compressive strength is an indicator of the brittleness of the material, while this ratio increases brittleness decreases [1].The ratio of the splitting tensile strength to the compressive strength in RA1C, RA2C, and RA12C are found higher than RA1C-i, RA2C-i, RA12C-i and NAC (Table 13) where the ratios of RA1C-i, RA2C-i, and RA12C-i approximately found same as the ratio of NAC.

Hence, utilization of the RA-i and RA affects brittleness of the material. Ductility of concretes using RA is the highest compared to RA-i and NAC, particularly the concrete designated with RA1C with 20% RA content. On the other hand, when the lower and the upper bound ratios are a concern, the ratios of concrete specimens of RA and RA-i with varying ratios (20–40–60%) range in the order of 7.7–8.8% and 6.4–6.8%, respectively. The difference between the

Table 13
The ratio of the tensile splitting strength to the compressive strength according to RA content in concretes.

Notation		RA, %	Ratio
Concretes with NA	NAC	0	0.069
Concretes with untreated RA	RA1C	20	0.088
	RA2C	40	0.077
	RA12C	60	0.077
Concretes with treated RA	RA1C-i	20	0.067
	RA2C-i	40	0.064
	RA12C-i	60	0.068

upper and lower bound ratios of RA found higher than concretes containing RA-i. Jau et al. [46] found the range of upper and lower bound values of concrete specimens with RA higher than the NA counterparts. Concretes containing RA-i had a narrower upper and lower bound range compared to concretes prepared from RA. Thus, it is worth mentioning that after the application of BMM, the higher scatter range avoided, and values ranged for a narrower bounding ratio.

3.2.2. Evaluation 2: The splitting tensile strength of concretes

The splitting tensile strength of RA1C, RA2C, and RA12C are varied +7%, −21% and −30% compared to its NAC counterparts given in Tables 11 and 12 and Fig. 4. For RA1C-i, RA2C-i, and RA12C-i variation from the tensile splitting values of NAC are found −3%, −9% and −4%, respectively. Based on the given results in Tables 11 and 12, concrete mixes containing 20% RA increases the splitting tensile strength value that is compatible with a previous study carried out in the literature stating RA use up to 40% increases the splitting tensile strength whereas beyond that ratio the strength value reported reducing [1]. Also, another important finding from test results is the changes in the splitting tensile strength of RA1C-i, RA2C-i and RA12C-i are negligible and approximately the same as the values of NAC. Among three samples RA12C-i comprised of 60% RA-i variation from the results of NAC found −4%. As a result, the impact of optimized BMM on the splitting tensile strength of concretes for RA1C-i, RA2C-i and RA12C-i, was satisfying and the use of 60% RA-i has slightly changed the splitting tensile strength compared to the splitting tensile strength value of NAC.

3.2.3. Evaluation 3: Correlations between the splitting tensile strengths and the compressive strengths of concretes

Compressive and the splitting tensile strength relationship of concretes were given in Fig. 5. Correlation coefficients of concretes for NA, RA-i, and RA calculated as 0.6354, 0.6076 and 0.3917, respectively. The highest and lowest correlation coefficients in Fig. 5 belong to the conventional concrete and recycled aggregate concretes, respectively. There are similar studies in the literature supporting the finding of the lowest correlation coefficient belonging to RAC less than 50% [1,7]. In the same study, the reason for the low correlation coefficient of RAC attributed to RA due to its effect on changing the splitting tensile strength more than the compressive strength.

Benefits of removing AOM content in RA through the optimizing process of BMM justified the change of behavior of RA close to NA. Thus, the increase in the correlation coefficients of recycled aggregate concretes from 0.3917 to 0.6076 verifies the statements above and another proof of the optimization process.

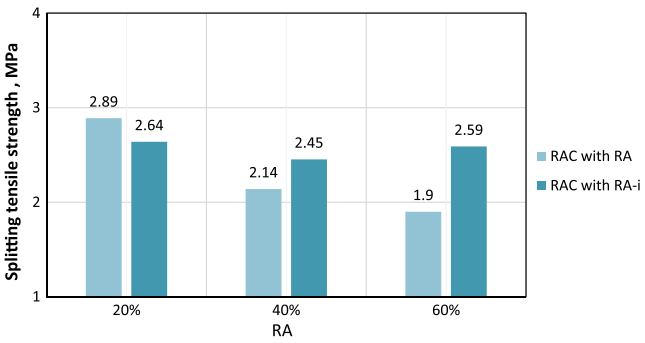


Fig. 4. The splitting tensile strengths of concretes.

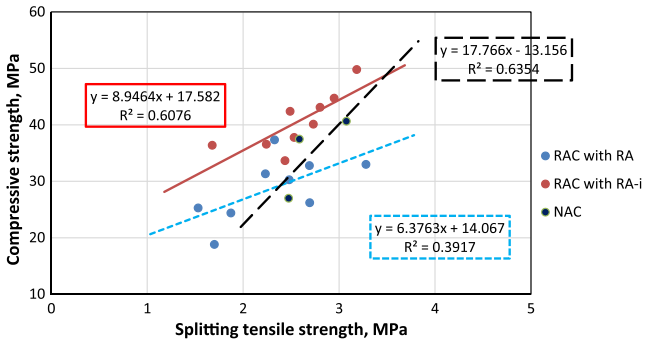


Fig. 5. Relations between the compressive strength and the splitting tensile strength of concretes (Coefficients of correlation are 0.6354, 0.6076 and 0.3917 for specimens including NA, RA-i and RA, respectively).

3.3. Statistical evaluation of compressive and splitting tensile strengths

The statistical evaluation of concrete specimens in terms of compressive and the splitting tensile strengths was given in Table 14. The highest standard deviation of the compressive strength and the splitting tensile strength calculated for the concretes with RA and RA-i content, respectively [47].

3.4. Static elasticity modulus

Test results based on the determination of elasticity modulus are presented in Table 11 and Fig. 6, and the elasticity modulus of concretes included RA and RA-i are lower than NAC taken as reference. The elasticity modulus reduces with the increase of RA and RA-i content in concretes. Among recycled aggregate concretes, concretes with RA-i content has a higher modulus of elasticity than their counterparts with RA content.

Due to compressive strength and the elasticity modulus test results, of NAC and RA1C-i with 20% RA-i content had approximately the same values of compressive strength and elasticity modulus. As a result, mechanical behavior of the concretes with NA and RA-i content are approximately the same, and the 20% RA-i use in concretes has a negligible effect on the elasticity modulus. Also, when a closer look is given to Fig. 6, the relative elasticity modulus values of RA1C-i, RA2C-i and RA12C-i become 0.96, 0.82 and 0.84, respectively. The change of elasticity modulus in concretes due to the type of aggregates is apparent where the maximum change in the elasticity modulus found −18% for RA2C-i. In Eurocode 2 (EC2), the use of sandstone and limestone compared to NAC were allowed to be −30% and −10% modulus of elasticity of concrete, respectively [48]. In this perspective, the limits of EC2 on RA-i can be accepted as appropriate, and it is valid for RA due to the poor results (Fig. 6). However, according to Paine and Dhir [48], the application on RA is found inappropriate based on limits of EC2, and in their research study, there has been no performance enhancement observed. In addition, Paine and Dhir [48] state that it is possible to achieve approximately the same strength values for RAC NAC, and after employing a water/cement ratio correction it is possible to obtain 15% lower elasticity modulus. In this study, after employing the optimized BMM, experimental results were found similar to given values in the literature [48].

Generally, elasticity modulus is related to the phases of the concrete structure [49]. The elasticity modulus of aggregate significantly affects the elasticity modulus of concretes [1,50]. In other words, the elasticity modulus of RAC are considerably influenced by the content of aggregate types (e.g. herein NA, RA and RA-i are used). Therefore, RA utilization in concrete mixes yields comparatively lower elasticity modulus, higher porosity, and cracks

Table 14
The statistical values of strengths of concretes.

Test	Statistical value	Specimens included						
		NA	RA1	RA2	RA12	RA1-i	RA2-i	RA12-i
Compressive strength	Standard deviation	3.15	5.83	5.29	4.69	5.42	3.41	3.86
	Mean value	39.1	32.9	27.9	24.8	39.5	38.3	38.2
Splitting tensile strength	Standard deviation	0.06	0.28	0.20	0.41	0.40	0.56	0.16
	Mean value	2.71	2.89	2.14	1.90	2.64	2.45	2.59

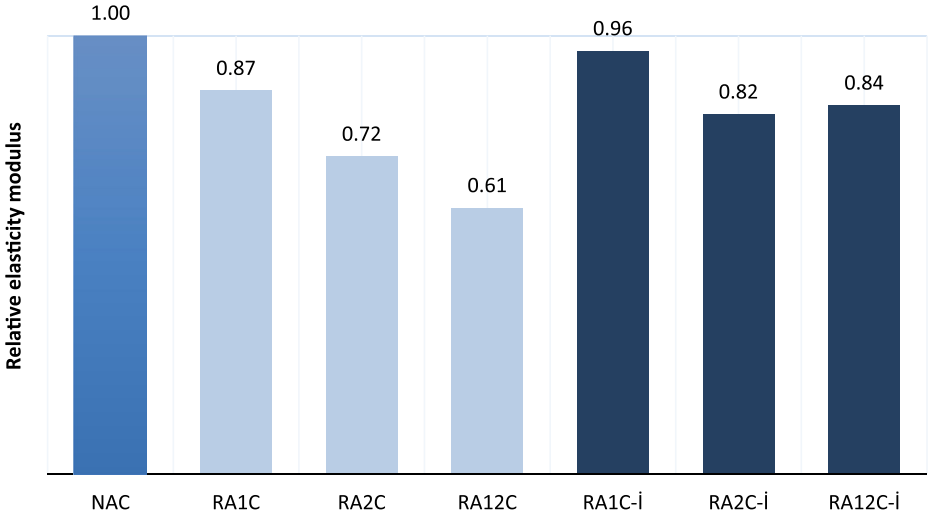


Fig. 6. Relative elasticity modulus of concretes.

etc. Although RA-i has better properties than RA, it may still have some cracks and discontinuities in its structure due to the applied loads on RA-i during the production process and the application of BMM (BMM has crushing and polishing mechanisms when recycled aggregates abraded from the drum, and mostly crushing process is the reason for crack formations [20]). Test results given in Table 4 supports the comments mentioned above. Regarding Table 4, natural aggregate used in RA has the water absorption and the density values like 0.56% and 2.78 g/cm^3, respectively, and after the application of BMM, RA-i has the water absorption and the density values as 0.84% and 2.47 g/cm^3, respectively. AOM may still has a roll on the variation of properties between aggregates given in Table 4 for the source of natural aggregate in RA and RA-i. Because AOM could not be totally removed but mostly removed (Fig. 2). Since AOM could not be totally removed but mostly removed, AOM may still have a roll on the variation of properties between aggregates given in Table 4 (Fig. 2).

3.5. Flexural strength

The flexural strength results were given in Tables 11 and 12 and Fig. 7. Regarding previous studies, the flexural strength is negatively affected by RA [3,10]. When concentrated on Tables 11 and 12, the same expression is valid for the splitting tensile strength. The flexural strengths of RA1C, RA2C, and RA12C are changed as +3%, −18% and −25% compared to NAC. Likewise, the flexural strengths of RA1C-i, RA2C-i and RA12C-i varied −3%, −20% and −9% compared to NAC. 20% RA content use in concrete mixes increases the flexural strength and the splitting tensile strength. The loss of strength in concretes with RA-i is observed at marginal level.

3.6. Failure behavior of concrete specimens under compression

The *inclination angle* is described as the angle between the vertical loading plumb and the macro crack. The tests are applied to 10 × 10 × 30 cm prismatic specimens for the 28 day-concrete. At the early stage of the loading, for all specimens no cracks were seen. At the early stage of the loading, no cracks were seen in all specimens. Due to the increase of stresses on the specimen, small vertical micro-cracks were observed. Gradually formed micro-cracks are combined with inclined cracks after the loading reached the peak value where the macro-cracks is thickened on the observed surface. The differences in the failure patterns of the test specimens with NA, RA, and RA-i were observed after exceeding the peak load. For concretes with RA, short and thin micro cracks occurred in the form of branches whereas inclined micro-cracks form rapidly after exceeding the peak load. In concretes with NA and RA-i content, short macro cracks with vertical discontinuities are formed.

Inclination angel of macro-cracks on the surfaces of concretes produced from NA is the range of 61–68°. Among test specimens, NAC has the smallest inclination angle while the highest inclination angles belong to the concrete RA-i as shown in Table 15. Failure plains of the concretes containing RA and RA-i are larger than the NAC taken as reference.

The experimental results show that the recycled aggregate concrete failure plain is in shear mode, and the similar results were found in Ref. [40]. According to Xiao et al. [40] the inclination angles of conventional concrete and recycled aggregate concrete were found 58-64° and 63–79°, respectively. Regarding to Table 15, the mean inclination angle were found dependent on the aggregate type, such as NA, RA, and RA-i, regardless of recycled aggregate ratio. For instance, the mean values of inclination angles and RA contents for RA1C, RA2C and RA12C are 77°, 74° and 76°, and 20%, 40% and 60% respectively.

On the other hand, considering 40% RA and RA-i utilization in the mixes, the difference between the upper and the lower bound values of the inclination angle were found higher, where the mean values of the inclination angle were found lower in comparison to 20% and 60% RA and RA-i utilization in the mixes.

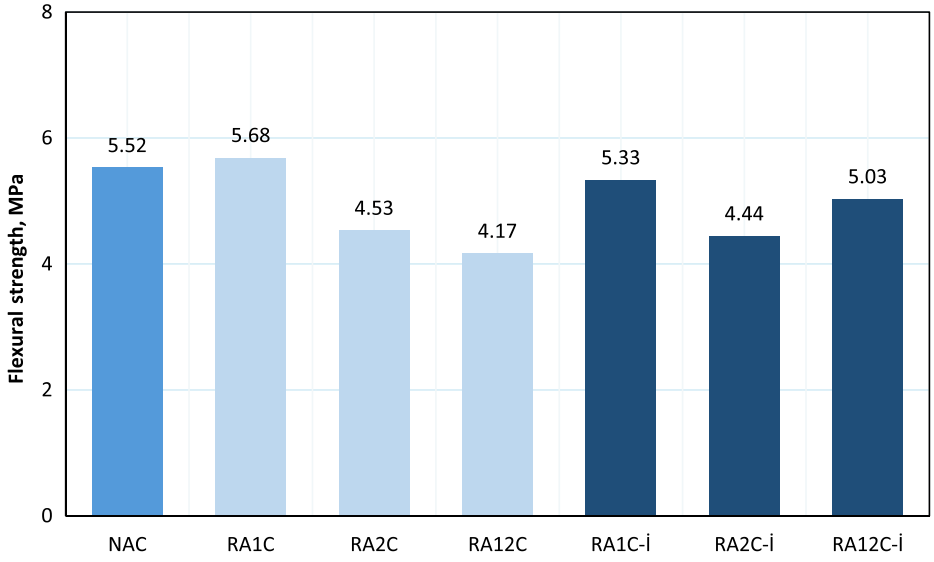


Fig. 7. The flexural strengths of concretes.

Table 15
The inclination angles of specimens.

Notations		RA, %	Mean	Min.	Max.	Difference between max. and min.
Concretes with NA	NAC	0	65°	61°	68°	7°
Concretes with untreated RA	RA1C	20	77°	71°	81°	10°
	RA2C	40	74°	66°	80°	14°
	RA12C	60	76°	73°	80°	7°
Concretes with treated RA	RA1C-i	20	82°	80°	84°	4°
	RA2C-i	40	80°	74°	86°	12°
	RA12C-i	60	82°	77°	83°	6°

3.7. Density and water absorption

The results of the water absorption and density are presented in Tables 11 and 12 and Figs. 8, 9 for concrete mixtures containing NA, RA and RA-i. Each reported value is the average of three samples. As shown in Table 7, RA has higher water absorption capacity and open pores than NA due to the AOM. Hence, RA utilization in the mixes causes the concretes more porous, a decrease in density and an increase in water absorption [1,26,51,52]. However, the disadvantages of RA with poor properties of AOM was improved by BMM process.

Tables 11 and 12 indicate that the relative water absorption of RA1C-i, RA2C-i and RA12C-i are −4%, +3% and +11% while those of RA1C, RA2C and RA12C are +27%, +76% and +116%, respectively, in comparison to those of NAC. Also, the density of RA1C-i, RA2C-i and RA12C-i are 2.34, 2.31 and 2.28 g/cm^3, respectively, similar to the density of NAC (2.37 g/cm^3).

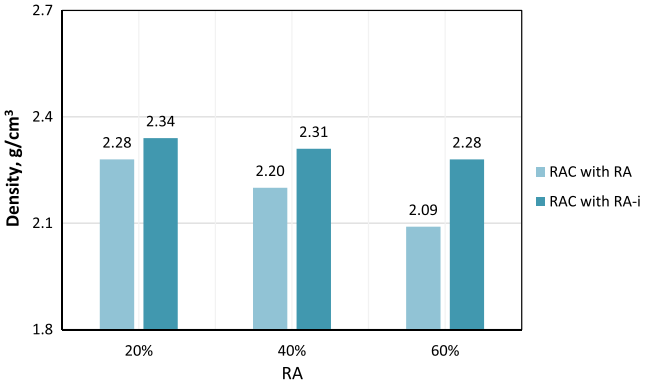


Fig. 8. The density values of concretes.

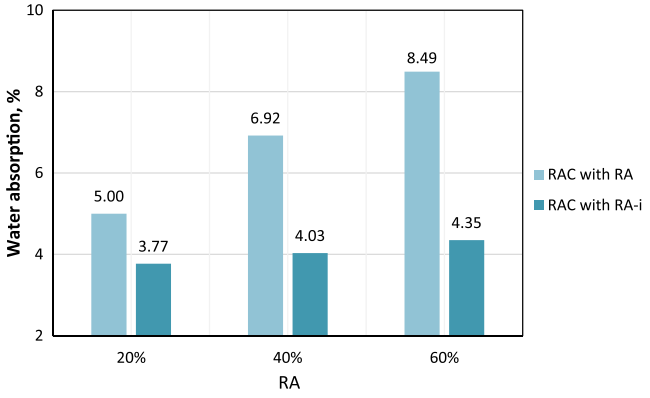


Fig. 9. The water absorption values of concretes.

3.8. Microstructure analysis

Microstructure analysis is conducted in order to better observe better effect of BMM process on the modification of RA. In the microstructure observation, Scanning Electron Microscope (SEM) was used to investigate ITZ regions of concretes including RA and RA-i. Under 5000× magnification, the appearance differences of AOM and new cement paste was clearly observed as shown in Fig. 10. The presence of AOM cracks, discontinuities and a slightly

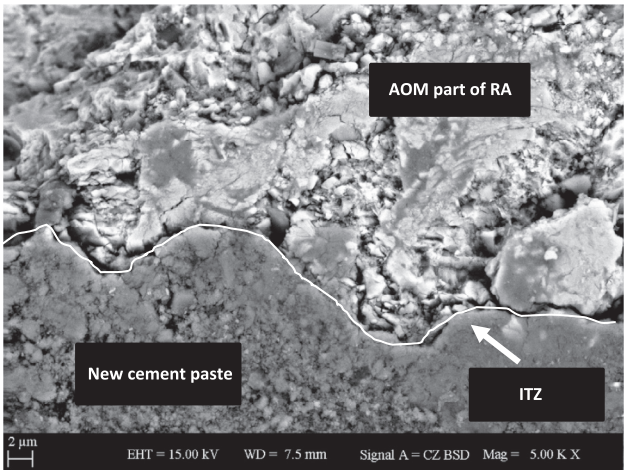


Fig. 10. RA, new cement paste and ITZ in concrete.

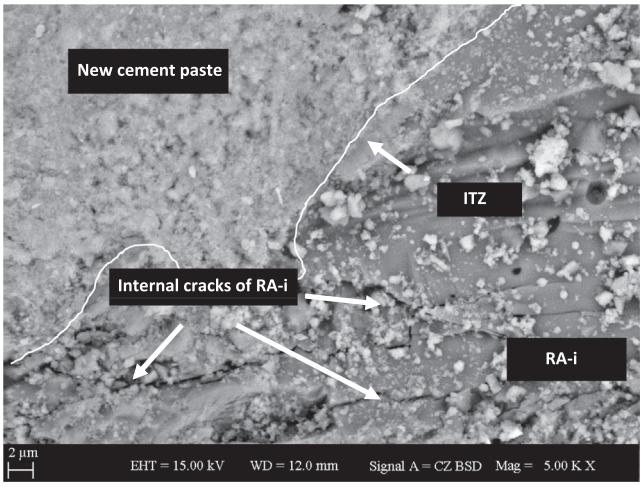


Fig. 11. RA-i, new cement paste and ITZ in concrete.

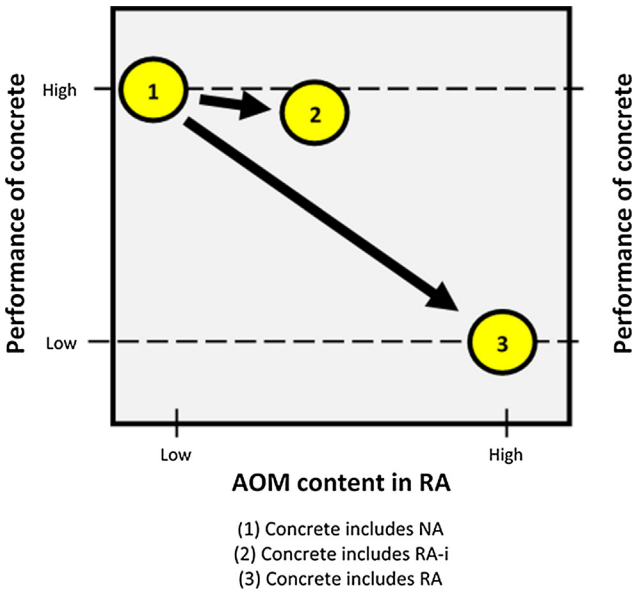


Fig. 12. The influence of aggregates (NA, RA, RA-i) on the concrete performance.

loose structure can be clearly observed. Furthermore, ITZ between RA and new cement paste presents poor adhesion between AOM and new cement paste. When taking into account the adhesion of RA-i to new cement paste as shown in Fig. 11, observation results revealed that concretes including RA-i achieve denser microstructure. This proofs that BMM process effectively improves not only the pore structure, but also weak AOM structure of concretes containing improved recycled aggregate.

According to the test results, it can be summarized that the mechanical and the physical performance of RAC are increased with the decrease of the amount of AOM in RA by applying BMM (Fig. 12).

4. Conclusions

In this study, experimental results for the physical, the mechanical and the microstructural properties of concretes including treated and untreated RA are presented and discussed. Based on the study, the following conclusions can be drawn:

- The optimum number of drum rotations (R) and the steel balls (S) combination in the optimization process is found as 500R-10S which results tenfold reduction in water absorption. The water absorption of recycled aggregate is significantly reduced from 8.95% to 0.84% after BMM process.
- The compressive strength decreases, as the recycled aggregate ratio in concretes increases. However, the compressive strength of RA12C and RA12C-i decrease 37% and 2%, respectively, in comparison to NAC.
- The splitting tensile strength decreases as the recycled aggregate content increases similar to the compressive strength test results. The splitting tensile strength of RA12C decreases 30% while the splitting tensile strength of RA12C-i decreases 4% in comparison to NAC. Moreover, the flexural strength of RA12C and RA12C-i decrease 25% and 9%, respectively, in comparison to NAC.
- The ratios of the splitting tensile strength to the compressive strength of concretes including untreated recycled aggregate are determined as 0.077–0.088 while those of concretes with natural aggregate and treated aggregate are determined approximately same as 0.064–0.069.
- The elasticity modulus of concretes decrease as the recycled aggregate content increases. The elasticity modulus of RA12C and RA12C-i decrease 39% and 16%, respectively, in comparison to NAC.
- The water absorption values of recycled aggregate concretes increase with the increase of recycled aggregate content. However, the water absorption value of treated recycled aggregate concretes are similar with NAC even in higher recycled aggregate content.
- SEM analysis indicates that the treated recycled aggregate concretes have a denser ITZ and thus encourages the performance of the physical and the mechanical properties.

Conflict of interest

None.

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