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Review

Effect of Treated/Untreated Recycled Aggregate Concrete: Structural Behavior of RC Beams

Ayman Abdo [1], Ayman El-Zohairy [2,*], Yasser Alashker [3], Mohamed Abd El-Aziz Badran [1] and Sayed Ahmed [1]

[1] Structural Engineering Department, Zagazig University, Zagazig 44519, Egypt; aabdo@zu.edu.eg (A.A.); eng_moh.badran@yahoo.com (M.A.E.-A.B.); m.sayed@zu.edu.eg (S.A.)
[2] Department of Engineering and Technology, Texas A&M University-Commerce, Commerce, TX 75429, USA
[3] Department of Civil Engineering, College of Engineering, King Khalid University, P.O. Box 394, Abha 61411, Saudi Arabia; yalashgr@kku.edu.sa
* Correspondence: ayman.elzohairy@tamuc.edu

Abstract: Using recycled concrete aggregates from construction and demolition wastes on structural concrete is a sustainable solution to reduce the consumption of natural resources and the detrimental effects of concrete production on the environment. This paper has collected much data from the literature to study fresh, mechanical properties and durability of concrete made of treated/untreated recycled aggregate (RA). Furthermore, the flexural and shear behavior of recycled aggregate concrete (RAC) beams was studied. This study discussed the distinctions and similarities between reinforced RAC beams and reinforced natural aggregate concrete (NAC) beams. The results of this review's analysis clearly show that reinforced RAC beams with different RAC ratios perform structurally on par with or slightly worse than reinforced NAC beams, demonstrating the viability of RAC for structural applications. Emphasis is placed on carefully choosing and adjusting material models for recycled aggregate concrete. Ultimately, guidelines for future inquiries in this field are delineated and deliberated upon. The review will be advantageous for academics and professionals who aim to acquire a comprehensive comprehension of the behavior of RAC beams. It addresses several practical concerns connected to the numerical modeling of these components, which have not been adequately covered in existing literature.

Keywords: recycled aggregate concrete (RAC); mechanical properties; durability; reinforced concrete beams; structural behavior

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1. Introduction

In recent years, the amount of waste produced during the construction and demolition of structures and other civil engineering projects has increased. Wasted concrete, ceramic waste, plastic, and glass are only a few of the recyclable aggregates that may be used in concrete to make the building sector more eco-friendly. Moreover, using recycled aggregates (RA) in concrete production would lessen the strain on non-renewable natural aggregate supplies, lead to the use of waste disposed of in landfills, and aid in developing a circular economy [1–7]. Waste concrete can come from various sources, such as demolished buildings, abandoned precast members, batching plant leftovers, and lab-tested samples [8–11]. Therefore, using RA from construction and demolition waste as a replacement for natural aggregate has become urgently necessary to conserve non-renewable natural resources (i.e., sand and gravel) and environmentally friendly ways to reduce waste. RA are classified as recycled concrete aggregate (RAC), recycled brick aggregate, and recycled mixed aggregate. Meanwhile, RA contains a range of components, including wood blocks, glass, paper fragments, plastics, and other pollutants [10,12,13]. Nowadays, recycled concrete aggregate is the most often used type of recycled coarse aggregate in construction [12,14–16]. Therefore, Using RA from construction and demolition waste as a partial or total replacement for NA in concrete can increase sustainability in construction [17].

Unfortunately, natural aggregate concrete (NAC) is more durable than recycled aggregate concrete (RAC). Hence, RAC is not widely used in structural applications. The surface of NAC and RAC is quite different in that RAC has more porous spots and fine cracks than NAC, and because of this, RAC has a higher absorption rate than NA (0.5–14.7% vs. 0.3–3.0%) and a lower specific gravity (7–20%, respectively) [18].

According to Figure 1, It was discovered that most research investigating the subject of employing RAs in concrete was conducted only in the last 20 years, and most of this research was performed in the previous decade only. Several nations have made more historical and present-day contributions to this field of study. This map was created to help scientists understand where RA-using concrete buildings could be most effective. In this review article, we discuss the use of RAC and its properties on the mechanical properties and durability and the effect of using treated and untreated RAC on the behavior of RC beams in flexural and shear. Figure 2 shows the structure and subsections of the con-tents of this review article, along with the sections' descriptions. Figure 3 also shows the existing research gaps in the recycling field and future studies on this topic.

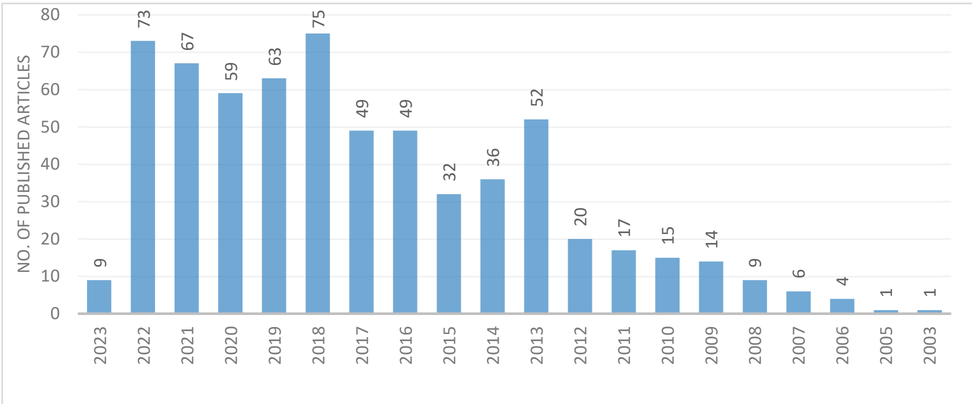


Figure 1. Number of published articles per year.

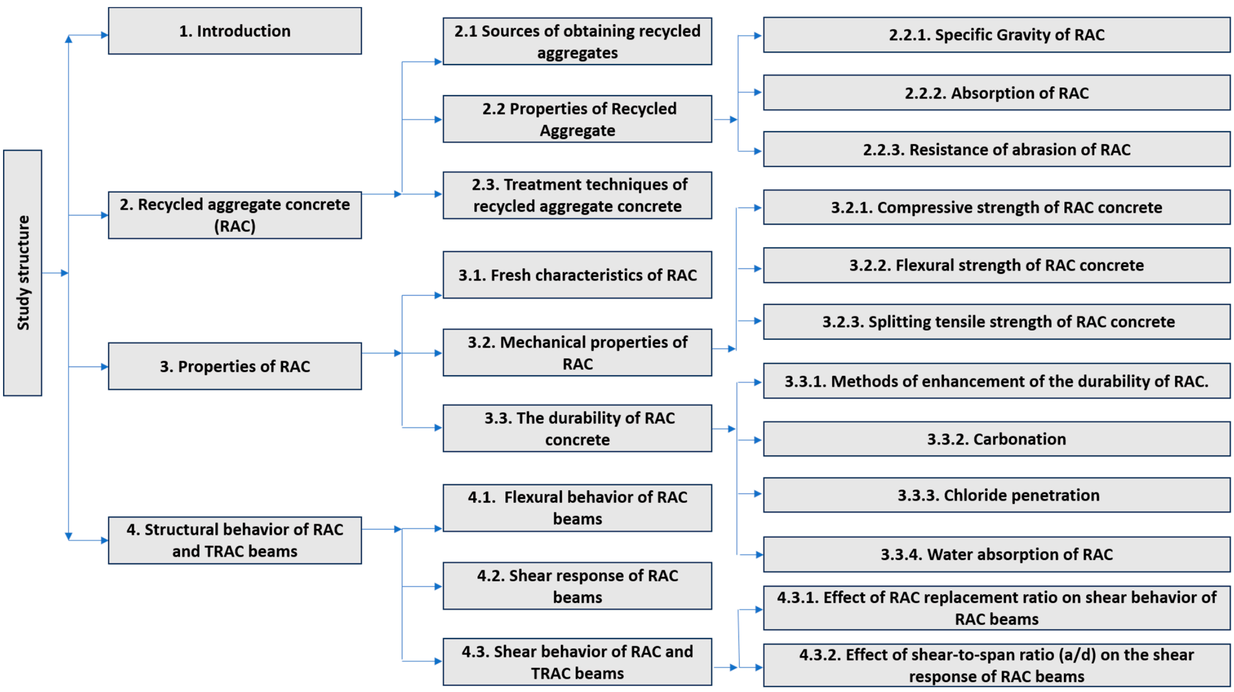


Figure 2. The structure of this review article, along with the sections' descriptions.

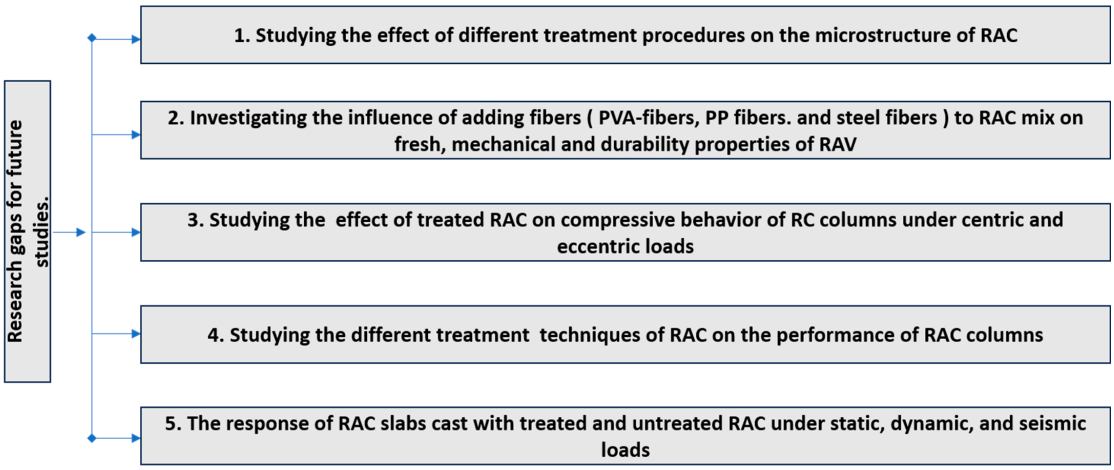


Figure 3. Research gaps that exist in this context, which could be the topics of future research.

The use of supplemental cementitious materials (SCMs), such as fly ash (FA), ground granulated blast furnace slag (GGBFS), silica fume (SF), nano silica (NS), metakaolin (MK), etc., is strongly recommended to improve the properties of RAC [12,19–21]. As a result, using SCMs, which are typically industrial byproducts or waste materials, improves the sustainability of concrete production. Guo et al. [22] proved that the mechanical properties of the produced concrete with RCA decreased as the replacement ratio of RCA increased, demonstrating that the addition of RCA harmed the hardened properties of SCC. Furthermore, combining fly ash and slag improved the mechanical properties of concrete. Sadeghi-Nik et al. [23] examined the influence of using MK and NS as additives to cement to produce concrete with RCA, and the results showed that adding up to 20% of MK to cement with 2% NS improved the mechanical properties. Wang and Baolong Zhu [24] studied the addition of NS by 3% of cement weight and PVA fibers by 3.6 kg/m^3 to SCC mixes. The results revealed an improvement in the mechanical properties of SCC. Using SCMs such as FA, GGBFS, and SF to partially replace cement in RAC has greatly increased its resistance to chloride diffusion [25,26]. Majhi and Nayak [27] investigated that chloride ion ingress decreased in RAC with a high volume of GGBFS. Furthermore, adding SF in RAC significantly decreased the chloride ion penetration. Adding 20% superfine phosphorous slag to RAC reduced the chloride diffusion coefficient by 20% compared to using RA alone [27].

Unfortunately, RAC is less strong than natural aggregate concrete (NAC). Hence, RAC is not widely used in structural applications. The subqualities of RA make it crucial to investigate the endurance of structures made using RAC. Porosity must be controlled during (i) material selection (bonding materials, combination, and water cement ratio), (ii) operation of mixing and casting, and (iii) curing schedules for a durable result to be guaranteed. Moreover, concrete must have structured permeability properties that restrict the introduction of hazardous substances [28–30]. It has been shown that several therapy approaches may ameliorate RA subtypes. Two examples are [1,31–34] deadhesion and strengthening of cement mortar. To name only a few examples of treatments: carbonization [34–42], microwave heating [43,44], pre-soaking RA in nano silica solution [45,46], water-repellent treatment [16,47], impregnation with polyvinyl alcohol [32], HCl [48], sodium hexameter phosphates [49], and organosilicon modifiers [44,50]. Evidence suggests that cured RA has good properties, making manufacturing concrete with desired attributes possible.

2. Recycled Aggregate Concrete (RAC)

RAC is recycling old concrete to create recycled aggregates to produce a new concrete mix [3]. It is an approach that has been widely used around the world in the last twenty years. On a global scale, concrete is a commonly used building material in civil engineering structures [7,15,51–55]. Its use is increasing with the expansion of construction projects because of growing populations [44,56–59]. Concrete consists of three essential components: aggregates, cement, and water. Among these components, aggregate is crucial since it makes up 65–75% of the concrete volume [60]. In 2017, China generated 5.51 billion tons of concrete, used 5.00 billion tons of non-renewable resources and natural aggregates, and released 0.83 billion tons of carbon dioxide (CO_2) [16,22].

In addition, extraction and crushing of natural aggregate (NA) use energy and increase CO_2 emissions [44,61]. Concrete manufacture and transportation contribute about 10% of the CO_2 in nature, which causes pollution issues [16,62]. One option is recycling the wasted concrete from CDW to produce RAC through crushing and sieving processes [63,64] to minimize the demand for non-renewable natural resources, limit CO_2 emission, and help to solve the problem of construction sanitary landfills.

2.1. *Sources of Obtaining Recycled Aggregates*

Urbanization has caused an exponential rise in construction and demolition waste (CDW), which has led to numerous environmental issues, such as greater energy use, emissions of CO_2, noise pollution, traffic congestion, loss of agricultural land, and problems caused by natural coarse and fine aggregates [17,65]. Aggregate resulting from the recycling of CDW is an alternative source for natural aggregates [66,67]. Many sources of CDW concrete, such as construction waste and concrete samples, have undergone laboratory testing [8–11].

Three criteria are used to classify recycled aggregate (RA): recycled mixed (concrete and brick) aggregate, RAC, and recycled brick aggregate [10,12,13]. RAC is the most commonly utilized form of RCA in concrete structures [14,15,68–70].

2.2. *Properties of Recycled Aggregate*

Working with RAC can be difficult because the specifications of the original concrete source are sometimes unavailable [62]. RAC is highly heterogeneous, has porosity, and contains a lot of impurities. This makes modeling and predicting the resulting concrete properties complex [63].

2.2.1. Specific Gravity of RAC

The ASTM defines specific gravity or relative density as the proportion of a material's density to distilled water's density at a particular temperature. The process for determining specific gravity is ASTM C 128. The specific gravity of virgin aggregate is 2.7, whereas RAC's is 2.40. The density of the oldest mortar attached to the RA is the cause of this discrepancy [71,72]. The specific gravities of coarse RA at saturated surface dry situations range between 2.2 and 2.6. As the particle size drops, so does this value. The specific gravity of fine RA is 2.0 to 2.3 for saturated surface dry settings [71]. The specific gravity of RAC and NCA from earlier experiments is presented in Table 1.

Table 1. Specific gravity of RAC and NCA.

Author	Specific Gravity %	
	RAC	NCA
[73] G. Fathifazl1 et al.	2.42 to 2.5	2.71 to 2.74
[74] Shi Cong Kou et al.	2.33 to 2.37	2.62
[75] K.Y. Ann et al.	2.48	2.63
[76] C.S. Poon et al. (Granite)	2.33 to 2.37	2.62
[77] J.M.V. Gómez-Soberón	2.17 to 2.28	2.59 to 2.67
[78] J. F. Liang et al.	2.52	2.82

2.2.2. Absorption of RAC

According to the ASTM, absorption is the gradual rise in aggregate mass caused by water penetrating the particles' pores over time.

2.2.3. Resistance of Abrasion of RAC

It has been found that RAC is weaker when old mortar is attached to it. This difference is because of the RAC's raised absorption of the old mortar, RAC has a more significant proportion of abrasion than NA, according to several types of study. Los Angeles abrasion (LA abrasion) determines how well an aggregate will hold up to wear from impact or abrasion. According to the Los Angeles test, abrasion increases as attached mortar content does [53]. According to other studies, abrasion loss for RAC ranges from 15% to 51.50%. As shown in Table 2, NA exhibits loss due to abrasion ranging from 15% to 45%. Losses of under 15% are possible in natural aggregate (9.1%) [79], and Table 2 shows that the maximum abrasion loss amount, which is dependent on NA quality, may be substantial. RAC's abrasion resistance range is 20–45%, with a maximum range of 50% [80].

Table 2. LA abrasion results by other studies.

Reference	LA Abrasion Results (% Mass Reduction)	
	NCA	RAC
[81] Yehia and Abdelfatah	19–25	21–35
[82] Verian et al.	29–31	34–36
[83] A.M. Amer et al.	38.90	51.50
[84] Kudra et al.	28	43
[85] Khaliq and Taimur	15.60	23.10
[86] Abedalqader et al.	26.40	40.40

Equation (1) illustrates the ratio decreases as a ratio of the initial weight of the sample:

$$\%\text{Loss} = \frac{\text{M original} - \text{M final}}{\text{M original}} \quad (1)$$

where M original is the mass of the initial sample (gm) and M final is the final sample weight (gm).

2.3. Treatment Techniques of Recycled Aggregate Concrete

Because the cement adhered to its surface, compared to natural aggregates (NA), RA is less dense and more porous [87] because the proportion of porous areas and microcracks in RA is higher than in NA [88,89]. As a result, RA has a greater absorption of water rate than NA (0.5–14.7% against 0.3–3.0% for NA) [18]. It is necessary to improve the ITZ and weak region on the surface of RA [90] to enhance the quality of RA and the effectiveness of RAC. The poor qualities of RA can be improved in two ways: physically and chemically [90].

- Physical improvement entails improving the absorption rate for water and streamlining the ITZ by removing adherent mortar (AM) from used concrete surfaces and enhancing RA particle form. Mechanical grinding or thermodynamic embrittlement frequently removes AM from the aggregate's surface and creates RA [89,91]
- Chemical improvement modifications decrease the water absorption rate while enhancing hardened characteristics and durability by eliminating or strengthening the AM on the surface of the RAC. The most popular improvement methods include carbonizing solidified AM, polymer-impregnated RA, chemical reagent prepreg RA, and treating RA surfaces with cement slurry [92,93].

Furthermore, using supplementary cementitious materials (SCMs) such as fly ash (FA), slag (SL), silica fume (SF), metakaolin (MK), limestone powder (LM), nano silica (NS), and others is strongly advised to enhance the qualities of RAC [19–21,94].

In addition to treatment methods, researchers also offered several ways for creating the best possible mixes, including the modified equivalent mortar volume (EMV) method [95,96], two-stage mixing approach (TSMA) [92,93], and triple mixing approach (TMA) [97,98].

3. Properties of RAC

3.1. Fresh Characteristics of RAC

The fresh property of RAC is explored using slump flow. The workability of RAC concrete is influenced by the following factors: water-to-cement ratio (w/c), the gradation and shape of the aggregates, concrete mix proportion, and the temperature of the concrete mix [99]. Concrete mix, including RAC as CA, has a smaller slump value than NCA at the same mix proportion. Compared to concrete mixes with NCA and the same w/c, the slump lowers because adhered mortar needs more water and increases absorption [80]. The reduced slump impacts how workable fresh concrete is regarding placement and density. The alternative is to increase the mixing water in the concrete by 5% to 15% or to include a superplasticizer as an additive in the mix proportion [18,19]. ASTM C143 slump test can gauge concrete's workability [100].

A greater slump generally denotes a much more malleable concrete mix, while a lower slump indicates a stronger, less pliable concrete proportion. Several studies claim that at the same w/c ratio, slump value is influenced by the inclusion of RAC in the concrete mixes [101,102]. Because of the adhesive mortar attached to the RAC, as indicated in Table 3, water absorption in RAC is greater than in NAC. As a result, NA concrete has a larger slump than 100% RAC concrete at the same w/c ratio. Furthermore, it has been established that slump loss occurs more frequently in oven-dried RAC than in air-dried RAC or saturated surface dry RAC [103,104].

Table 3. Absorption results of RAC and NCA.

Reference	Absorption %	
	RAC	NCA
[77] J. Gómez-Soberón	5.83 to 8.16	0.88 to 1.49
[73] G. Fathifazl1 et al.	3.3 to 5.4	0.54 to 0.89
[74] Shi Cong Kou et al.	2.49 to 2.57	2.62
[75] K.Y. Ann et al.	4.25	0.73
[76] C. Poon et al.	6.28 to 7.56	1.24 to 1.25
[78] J. F. Liang et al.	9.25	0.4

3.2. Mechanical Properties of RAC

The mechanical characteristics of RAC, such as compressive strength, tensile split strength, and flexural strength, are discussed in this section. Because of its limited results and applications, RAC concrete is still poorly understood. According to some studies, concrete's generic properties, including RAC, are comparable to or almost identical to the characteristics of NAC with the same mix design [71,105].

3.2.1. Compressive Strength of RAC Concrete

Several investigations have demonstrated that the ITZ, the bonding in the concrete mix between the mortar and the ITZ region, and the aggregate surface significantly impact the strength. In natural aggregate concrete, the aggregate's surface is covered with mortar. In contrast, In RAC concrete, ITZ considers the bonds between the old and new mortars used to bind the aggregate, which can result in a lower strength for RAC concrete [105–107].

Several studies have demonstrated that RAC has a higher strength than natural aggregate concrete by +25%, especially at 28 days [72]. When compared to the PC, the RAC concrete has greater air entrainment. Many studies have demonstrated that old cement paste attached to RAC interacts with water amount in the fresh concrete properties to enhance the strength of RAC concrete relative to NCA concrete [76,106,107]. In addition, it demonstrated that the natural aggregate replacement level could decrease the concrete compressive strength by 20% when replaced with a 100% RAC [108,109]. Compressive strength is significantly influenced by the w/c ratio as well.

Generally, reducing the w/c ratio improves the compressive strength of concrete. When the w/c is high, not all the water is used to stay hydrated. Then, it can disappear, leaving pore space. Concrete with RAC had a higher compressive strength when the w/c ratio was lower than the w/c ratio of NCA concrete. For example, after curing, concrete with NCA and w/c ratio of 0.480 had a compressive strength of 42 MPa. This crushed concrete made RAC an alternative to the original NA. Compared with normal concrete, the mixture with this RAC can have a compressive strength of 49 MPa and a reduced w/c ratio of 0.38 when employed in the new concrete mixes [107]. Table 4 also displays the differences in compressive strength between the mix with RAC as a coarse aggregate and the same concrete mixes with NA. From the literature, several techniques were used to treat RAC to improve its properties, such as presoaking in water, removal of RA's attached mortar, strengthening of adhered mortar of RA, modification of mixing process, and incorporation of SCMs. Figure 4 depicts various treatment methods used in the literature for recycled aggregate. The most important types of treatment were pre-soaking in water [110], removing RA attached slurry by acid treatment [111] heat treatment [112], strengthening RA attached slurry by carbonization [113], polymer emulsion [114,115], process modification, mixing (two-phase mixing method (TSMA) [116], triple mixing method (TMA) [117]), and embedding in SCMs, such as FA [118,119], slag [120], silica fume [121,122], and nanomaterials [115,123–126], and finally, physical therapy [127]. Figure 5 shows a schematic representation of some treatment methods used to improve the properties of RAC. Table 5 and Figure 6 list the differences in compressive strength between treated RAC and untreated RA. Through this form, it was found that the process of treating recycled aggregate plays an important role in improving the compressive properties of hardened concrete, and this was the general direction of most previous research. From this, the importance was found of using different treatment systems before using recycled aggregates to overcome the negative effect of recycled aggregates on the properties of concrete. From Table 5, it can be seen that the improvement is noticeable for all types of treatment of recycled aggregates on the compressive properties of hardened concrete. The highest percentage of improvement in the compressive properties of hardened concrete was 47% with the use of nano-silica in the research presented by Zhang et al. [128]. We also find that the average increase for all types of treatment in the table was 16%, with a standard deviation of 14.8%.

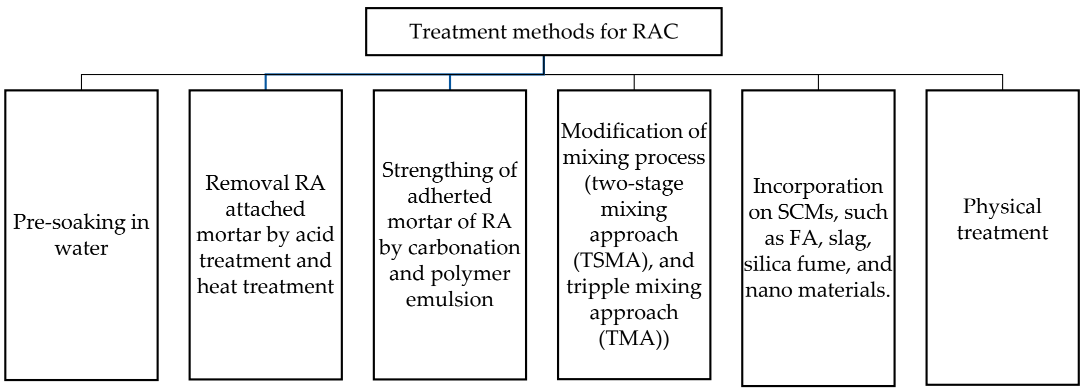


Figure 4. Various treatment methods are used in the literature for recycled aggregate [111–113,115–117,119–127].

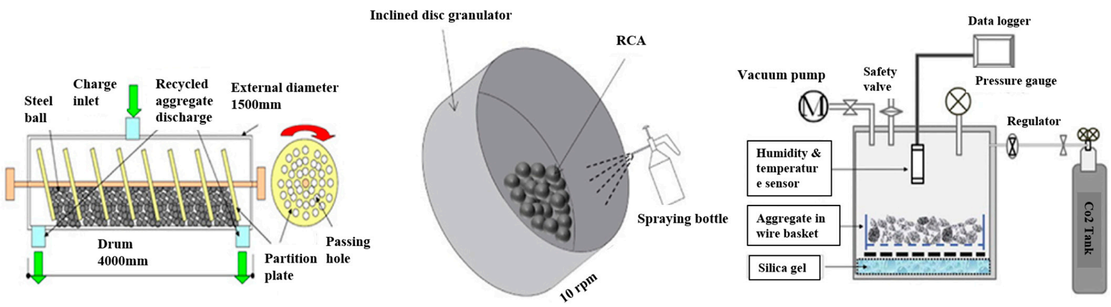


Figure 5. Schematic representation of some treatment methods used to improve the properties of RA [129,130].

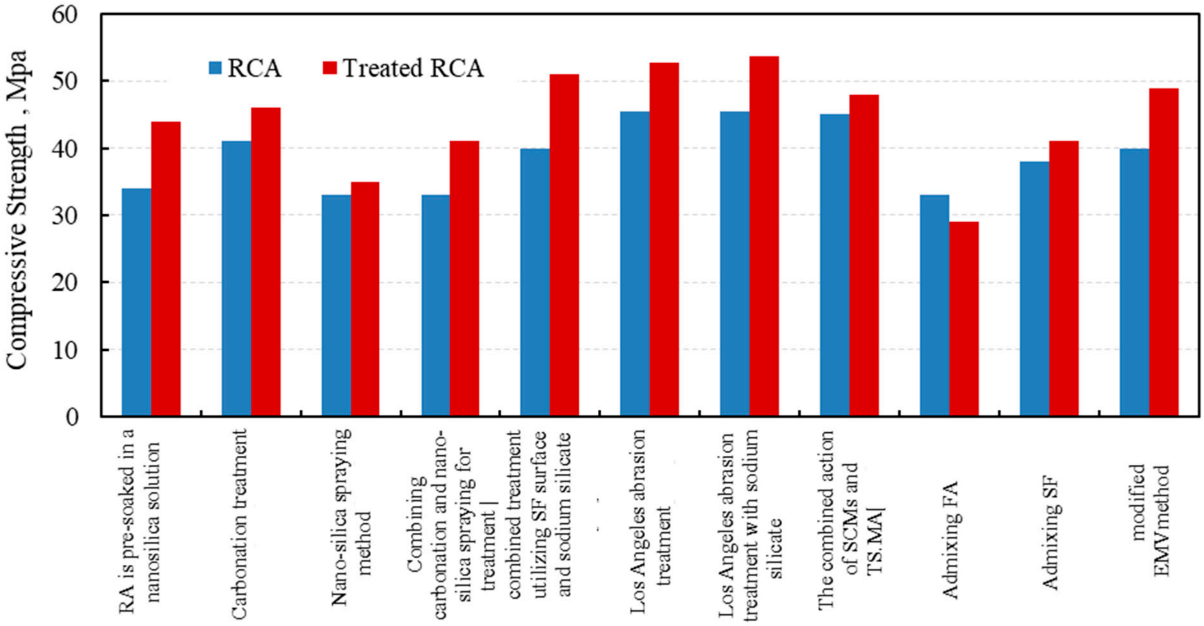


Figure 6. Compressive strength of RAC using different treatment methods [46,95,128–133].

Table 4. 100% RC compressive strength after 28 and 90 days.

Reference	RAC (F28-cu) psi	RAC (F90-cu) psi	NA (F28-cu) psi	NA (F90-cu) psi
[134] Kou et al. (w/c = 0.45)	7555	8920	9690	10,490
[135] Arezoumandi et al. (w/c = 0.40)	4425	N/A	5400	N/A
[136] C. Zhou, Z. Che. (w/c = 0.47)	6420	N/A	6050	N/A
[84] Rawaz et al. (w/c = 0.53)	7540	N/A	8120	N/A
[137] T. Yaowarat.et al. (w/c = 0.40)	6100	N/A	N/A	N/A
[138] Thomas et al. (w/c= 0.50)	4380	N/A	5190	N/A
[83] M. Amer et al. (w/c = 0.5)	6380	7250	N/A	N/A
[139] Butler et al. (w/c = 0.4)	8730	N/A	8980	N/A

Table 5. Compressive strength of treated and untreated concrete with 100% RAC.

Author	Treatment Method	F28-cu at 100% RAC (MPa)	
		RAC	Treated RAC
[46] Shaikh F et al., 2017	RA is pre-soaked in a nano-silica solution.	34	44
[131] R.Faysal et al., 2020	Carbonation treatment	41	46
[129] L. Li et al., 2021	Nano-silica spraying method	33	35
[129] L. Li et al., 2021	Combining carbonation and nano-silica spraying for treatment	33	41
[133] N.K. Bui et al., 2018	combined treatment utilizing SF surface and sodium silicate	40	51
[132] S. Ahmad et al., 2020	Los Angeles abrasion treatment	45.5	52.7
[132] S. Ahmad et al., 2020	Los Angeles abrasion treatment with sodium silicate	45.5	53.7
[131] R. Md. Faysal et al., 2020	The combined action of SCMs and TSMA	45	48
[25] K. Kim et al., 2013	Admixing FA	33	29
[130] M. Koushkbaghi et al., 2018	Admixing SF	38	41
[95] S. Yang, Y. Lim, 2018	modified EMV method	40	49
[128] H. Zhang et al., 2015	nano-silica slurry	15	22

3.2.2. Flexural Strength of RAC Concrete

According to some studies, when compared to NCA, with the same mixture design, concrete manufactured from RAC had a compressive strength reduction of around 25%, but a flexural strength reduction of about 10% [71]. According to a different study, concrete constructed solely of RAC has a flexural strength of 7 to 17% lower than concrete made entirely of natural aggregate. Moreover, raising the w/c ratio decreased flexural strength [138]. The flexural strength of 100% RAC compared with concrete with NAC is summarized in Table 6. Based on this table, it was determined that the treatment of recycled aggregate is crucial in enhancing the flexural characteristics of hardened concrete. This finding aligns with the overall focus of earlier research. It was discovered that applying various treatment methods before using recycled aggregates is crucial to mitigate the adverse impact of recycled aggregates on the characteristics of concrete. Table 6 demonstrates a considerable improvement in the flexural characteristics of cured concrete for all forms of recycled aggregate treatment. S.I. Mohammed and K.B. Najim. [56] demonstrated that the addition of treatment resulted in a significant increase of up to 74% in the flexural characteristics of cured concrete. The table reveals that the mean increase for all treatment types was 28%, accompanied by a standard deviation of 30%.

Table 6. RAC flexural strength at various w/c ratios.

Reference	RAC-28-Day Flexural Strength psi	NCA-28-Day Flexural Strength psi
[135] Arezoumandi et al. (w/c = 0.40)	390	500
[86] A. Abedalqader et al. (w/c = 0.40)	785	1090
[138] Thomas et al. (w/c= 0.50)	563	610
[140] A.S Brand et al. (w/c= 0.42)	1625	2480
[136] C. Zhou, Che. (w/c = 0.47)	735	625
[138] Thomas et al. (w/c= 0.50)	563	610
[137] T. Yaowarat.et al. (w/c = 0.40)	610	N/A
[56] Saif. Mohammed et al. (w/c= 0.44)	435	755

3.2.3. Splitting Tensile Strength (STS) of RAC Concrete

The splitting tensile strength of RAC is similar to the compressive strength. RA concrete has been the subject of numerous prior studies, which have shown that its impact on splitting tensile strength is greater than that on compressive strength [128,141]. On the other hand, according to many investigations, RAC exhibited a greater decline in split tensile strength than normal concrete. According to a study by Surendar et al. [142], adding recycled aggregates up to 25% of the original amount may produce split tensile strength values that are comparable to those of normal concrete. On the other hand, other research found that adding RA to concrete improved its splitting tensile strength. For instance, STS increased by approximately 11% and 9.9%, respectively, with 20% and 50% RAC replacements. The STS values of concrete specimens prepared with 100% RAC and those prepared with NA alone were almost the same [105,118]. Several investigations studied the effect of treating the RAC on SPS [127,128,131,132]. The splitting tensile strength changes in concrete with untreated RAC compared to the treated RAC are summarized in Table 7 and Figure 7. Through this form, it was found that the process of treating recycled aggregate plays an important role in improving the splitting tensile properties of hardened concrete, and this was the general direction of most previous research. From this, we find the importance of using different treatment systems before using recycled aggregates to overcome the negative effect of recycled aggregates on the properties of concrete. Table 7 shows a significant improvement in the splitting tensile properties of finished concrete for every kind of recycled aggregate treatment. N.K. Bui et al. [133] showed that the incorporation of a combined treatment using SF surfaces and sodium silicate led to a substantial enhancement of up to 54% in the splitting tensile properties of cured concrete. The table indicates that the average increase for all methods of therapy was 29%, with a standard deviation of 17.3%.

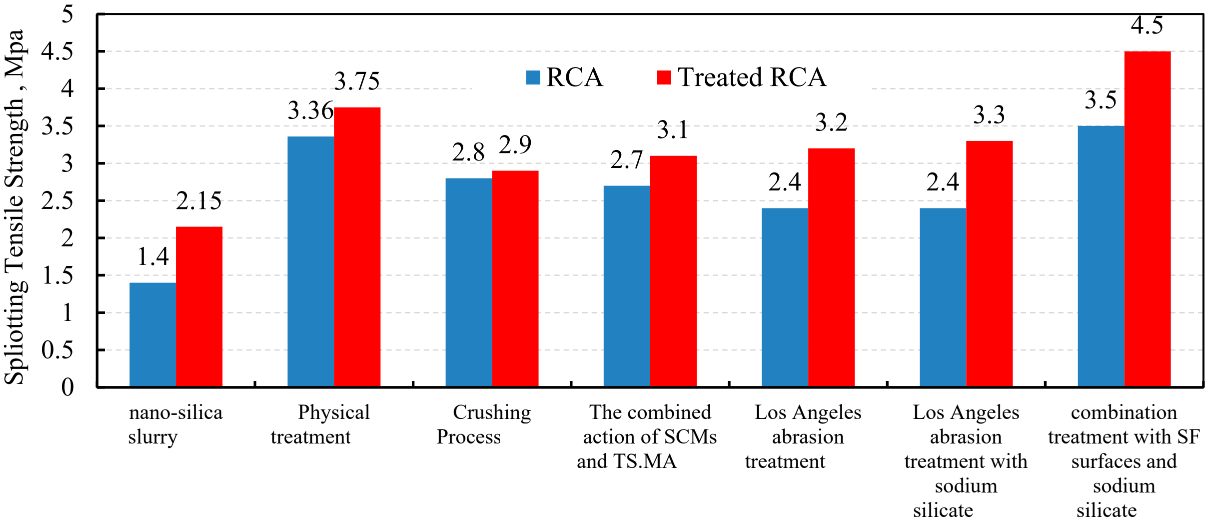


Figure 7. Tensile splitting strength of RAC using different treatment methods. [89,128,130–133,143,144].

Table 7. Tensile split strength of RAC.

Author	Treatment Method	28 days Splitting Tensile Strength at (MPa) RAC	Treated RAC
[128] H. Zhang et al., 2015	nano-silica slurry	1.4	2.15
[89] M. Pepe et al., 2014	Physical treatment	3.36	3.75
[127] D. Pedro and J. de Brito	Crushing Process	2.80	2.90
[145] B. Zhan et al., 2014	CO_2 curing	N/A	N/A
[143] H. Sasanipour, F. Aslani and J. Taherinezhad	The slurry of SF (as a coating treatment for RAs)	N/A	N/A
[131] R. Md. Faysal et al., 2020	The combined action of SCMs and TSMA	2.70	3.10
[144] J. Zhan et al., 2019	Carbonation treatment	N/A	N/A
[129] L. Li et al., 2021	Nano-silica spraying method	N/A	N/A
[129] L. Li et al., 2021	Combining carbonation and nano-silica spraying for treatment	N/A	N/A
[132] S. Ahmad et al., 2020	Los Angeles abrasion treatment	2.40	3.20
[132] S. Ahmad et al., 2020	Los Angeles abrasion treatment with sodium silicate	2.40	3.30
[130] M. Koushkbaghi et al., 2018	Admixing SF	N/A	N/A
[95] S. Yang, Y. Lim, 2018	modified EMV method	N/A	N/A
[133] N.K. Bui et al., 2018	combination treatment with SF surfaces and sodium silicate	3.50	4.50

3.3. *The Durability of RAC Concrete*

The characteristics associated with durability generally include carbonation, chloride penetration, air/water permeability, and porosity as concerns of steel reinforcement corrosion. Resilience to alkali–silica interaction, the presence of sulfates, and thawing–freezing cycles (both with and without de-icing salt) [3].

3.3.1. Methods of Enhancement of the Durability of RAC

Using RAC instead of traditional concrete is possible because it can display durability similar to NAC when prepared with the right technology [146]. To create durable concrete, the less desired RA qualities should be reduced. Table 8 explains the procedures typically used to extend RAC's durability and lists the advantages and downsides of each. These techniques are broken down into four groups: (1) removing mortar that adheres to RA, (2) strengthening mortar that adheres to RA, (3) altering the mixing process, and (4) incorporating SCMs.

Table 8. Treatment options for improving the durability qualities of RAC: benefits and drawbacks [147].

Treated Method	Technique	Advantages	Disadvantages
Removal of RA's attached mortar	Pre-soaking in water	Simple and inexpensive solution.	The adhesive mortar component of RA cannot be erased. Significantly improves the durability properties [110].
	Acid treatment	Beneficial in increasing RA quality [148]. Using HCl and Na_2SO_4 enhances resistance to carbonation and chloride ion penetration [111].	Applying excessive concentrations of acids may increase the presence of harmful ions like chloride and sulfate. It may raise worries about durability [149]. Steep cost [150]
	Heat treatment	Thermal stress causes concrete embrittlement, resulting in the spall of attached mortar [43]. Improves the quality of RA by counteracting the dehydration reaction brought on by heat (i.e., weakening of the old cement paste) [112] RA's water absorption is impaired by 28–74% [151,152].	Increases the amount of energy consumed. On a big scale, inconvenient [150]. Boosts CO_2 emissions.
Strengthening of adhered mortar of RA	Carbonation	Pre-carbonates the RA, increasing their pore space by precipitating a by-product of the carbonation reaction ($CaCO_3$). The ITZ and accompanying mortar are both densified. Increases permeability (bulk electrical conductivity and chloride ion permeability may increase by 15.1, 36.4, and 42.4%, respectively [113]). The corrosion resistance of steel reinforcement improved in the RAC [144]	The alkalinity of RAC can be reduced by reducing the pH [144]. Needs a special device. High cost.
	Polymer emulsion	Producing a hydrophobic coating on the surface of RAs reduces their water absorption [114,115].	On a broad scale, this is inconvenient. The waste solution must be disposed of [151]. Cost-intensive.
Modification of mixing process	Two-stage mixing approach (TSMA)	Enhances RAC's long-term behavior regarding chloride penetration and carbonation depth [116]. Using TSMA with SCMs enhances ITZ quality and boosts corrosion resistance [131].	Time-consuming.
	Triple mixing approach	Increases the resistance of RAC to chloride ion penetration [98,117].	Time-consuming.
Incorporation of SCMs	Fly ash (FA)	Adding FA to RAC blends improves the inferior durability qualities of RAC [19]. Adding FA decreased chloride ion penetration, carbonation, and creep [118,119].	N/A

Table 8. *Cont.*

Treated Method	Technique	Advantages	Disadvantages
	Slag	Slag decreases the chloride diffusion coefficient in RAC mixes [120]. Adding slag to a concrete mixture enhances resistance to attacks from sulfuric acid and sodium chloride [27].	N/A
	Silica fume (SF)	SF reduces water absorption and chloride ion penetration in RAC mixtures. Improve the electrical resistance [121,122].	N/A
	Nanomaterials	Incorporating nanomaterials such as nano-silica enhances the structure of ITZ and C-S-H. It reduces RAC mixes' water absorption and chloride diffusivity [115,123–126]. Permeability, water sorptivity, and chloride ion penetration decreased when RA was pre-soaked in nano silica suspension while improving corrosion resistance [45,46,153].	N/A

3.3.2. Carbonation

A common occurrence called carbonation raises the risk of corrosion for steel reinforcement over time. Almost 0.4% of the atmosphere's mass is made up of CO_2, and when it enters cement paste, it burns Portlandite to produce calcite [3]. This occurrence causes a fall in the concrete's pH, which is reduced from 13 to 8–9, and corrosion begins when the amount of water and O_2 is sufficient. A lot of research has been performed on the carbonation of RAC [154–158]

The RA impact inclusion on carbonation thickness is connected to several aspects, including:

- The quantity of the cement [159];
- The properties of old concrete from which recovered particles are derived [160];
- The grade of the recycled aggregates (including whether they contain concrete, asphalt, bricks, or other building materials) [158];
- The curing [51];
- Using a superplasticizer (SP) to decrease the w/c ratio [161];
- The recycled aggregate replacement ratio [162].

The results acquired from many research in the literature vary; nonetheless, the findings listed below were noted [157]:

- The recovered aggregates from crushed masonry might include various materials (light concrete, bricks, etc.), increasing the carbonation thickness;
- Controlling the water/binder (w/b) ratio and the type of binder makes it feasible to manufacture RAC that is just as resistant to carbonation as normal concrete.

3.3.3. Chloride Penetration

Steel reinforcement corrosion is primarily caused by the entry of chloride ions during carbonation. Much research on this issue has been published in the literature [147,155,158,162–164]. These investigations revealed the following:

o The diffusion coefficient increases as the RAC replacement ratio increases;

- o The chloride diffusion coefficients are greater when recycled fine aggregates are substituted than when recycled coarse aggregates are substituted;
- o Similar to normal concrete, chloride ion migration can be reduced by lowering the w/b ratio or utilizing blast furnaces SL, FA, or SF.

- When fine aggregates recovered from bricks substituted natural sand, the resistance to chloride ion migration improved; this might be attributed to the pozzolanic character of this material.

Some research recommended using polyvinyl alcohol to increase RAC resistance to chloride penetration [162]. According to several research, the chloride diffusion coefficient of their RAC was comparable to that of standard concretes [165,166]. Table 9 lists the impact of several treatment approaches on chloride transportation in RAC and identifies potential enhancing pathways.

Table 9. The impact of treatment methods on chloride transportation of RAC transportation.

Author	Treatment Method	Effect
[26] W. Hu et al., 2019	Admixing GGBFS	The amount of GGBFS varies, and as a result, the chloride diffusion coefficient is decreased by 28.9–67.2%.
[143] H. Sasanipour, F. Aslani and J. Taherinezhad, 2020	The slurry of SF (as a coating treatment for RAs)	The overall charge passed is reduced by 24–41%.
[131] R. Md. Faysal et al., 2020	The combined action of SCMs and TSMA	Reduces total transmitted charge by 13–53%
[144] J. Zhan et al., 2019	Carbonation treatment	After 7 days of carbonation treatment, the chloride diffusion coefficient is reduced by more than 50%, and the total charge transmitted is reduced by 26%.
[129] L. Li et al., 2021	Nano-silica spraying method	Reduces the passing charge by 3.8%.
[129] L. Li et al., 2021	Combining carbonation and nano-silica spraying for treatment	Reduces the charge passed by 24.4%.
[132] S. Ahmad et al., 2020	Los Angeles abrasion treatment	Reduces total charge transmitted by 24%.
[132] S. Ahmad et al., 2020	Los Angeles abrasion treatment with sodium silicate	Reduces total charge transmitted by 47%.
[130] M. Koushkbaghi et al., 2019	Admixing SF	Reduces the total charge passed up to 60%.
[130] M. Koushkbaghi et.al, 2019	Admixing RHA	Chloride ion diffusivity is reduced.
[133] N.K. Bui et al., 2018	Combination treatment with SF surfaces and sodium silicate	Improves chloride ion penetration resistance by 80%.

3.3.4. Water Absorption of RAC

Increasing water absorption of RA is a major issue that affects both the fresh and mechanical characteristics of RAC. The RA's porous, adherent cement mortar absorbs the water from the mixture, making the mixture harsh and dry and increasing the mixing time [3,167]. In addition, RA processing creates microcracks, improving RAC water absorption [116]. As a result, it has been observed that the properties of produced concrete influence RAC porosity more than hardened characteristics [168–171]. Matias et al. [172] proved that water absorption of RAC mixtures made of 100% recycled aggregates ranges from 17.20 to 17.50%, compared with 13.7% of NCA concrete. Evangelista and de Brito [158] demonstrated that the water absorption of concrete made of fine recycled aggregates has a water absorption rate of 45% greater than that of normal concrete. Table 10 lists the influence of various treatment procedures on the water absorption of RAC.

Table 10. An overview of how various treatment procedures affect RAC water absorption.

Author	Treatment Method	Effect
[26] W. Hu et al., 2019	Admixing GGBFS	Decreases water sorption when 40% and 60% GGBFS are added.
[148] H.S. Kim et al., 2017	RAC is pre-soaked in a nano-silica solution	Decreases the water septicity by 58%.
[171] S. Ismail and M. Ramli, 2014	Acid treatment (HCl)	Reduces water absorption significantly.
[143] H. Sasanipour, F. Aslani and J. Taherinezhad, 2020	The slurry of SF (as a coating treatment for RAs)	Water absorption is reduced by 14–22%.
[93] V. Spaeth, A. Djerbi Tegguer	Polymer treatment	Reduces early water absorption; nevertheless, long-term water absorption remains unchanged.
[131] R. Md. Faysal et al., 2020	The combined action of SCMs and TSMA	Reduces early water absorption; nevertheless, long-term water absorption remains unchanged.
[144] J. Zhan et al., 2019	Carbonation treatment	Reduces water absorption by 29%
[129] L. Li et al., 2021	Nano-silica spraying method	Reduces absorption significantly to a degree like that of NAC.
[132] S. Ahmad et al., 2020	Los Angeles abrasion treatment	Water absorption was reduced by 4%.
[132] S. Ahmad et al., 2020	Los Angeles abrasion treatment with sodium silicate	Water absorption was reduced by 8%.
[130] M. Koushkbaghi et al., 2019	Admixing SF	Decrease water absorption by 33–41%.
[130] M. Koushkbaghi et.al, 2019	Admixing RHA	When 20% RHA is utilized, it reduces water absorption.
[133] N.K. Bui et al., 2018	Combination treatment with SF surfaces and sodium silicate	Significantly reduces water absorption.

3.4. Microstructure of RAC and TRAC

Using focused electron beams, SEM captures high-resolution surface pictures of materials at low to high magnifications. SEM was used to evaluate recycled concrete aggregate (RCA) components and examine the microstructure and surface morphology of concrete samples. This modern SEM has a high-resolution electron gun, electromagnetic lenses, and secondary and backscattered electron detectors. Precision imaging and sample integrity required cutting, polishing, and conductive coating. A concentrated electron beam detected secondary and backscattered electrons on the SEM stage in a vacuum chamber to produce high-resolution images of prepared materials [173].

Figure 8 shows 28-day SEM micrographs of several combinations. These micrographs show microstructure-level hydration product development in diverse concrete compositions, strengthening concrete. CSH, ettringite, and calcium hydroxide (CH) are important during hydration. In the micrographs, hexagonal crystals represent CH, flower-shaped structures represent CSH gel, and needle-like structures indicate ettringite. The test findings show that surface-modified RCA improves concrete microstructure by forming a thick cement paste that increases paste-aggregate binding. Thicker and stronger interfacial transition zones (ITZs) result from this increase. SEM studies show that removing linked mortar from RCA via abrasion treatment and surface coating with cement slurry improves recycled aggregate concrete's microstructure, quality, and strength. These findings match earlier findings [56,57]. SEM study shows that surface modification improves recycled aggregate concrete microstructure and strength.

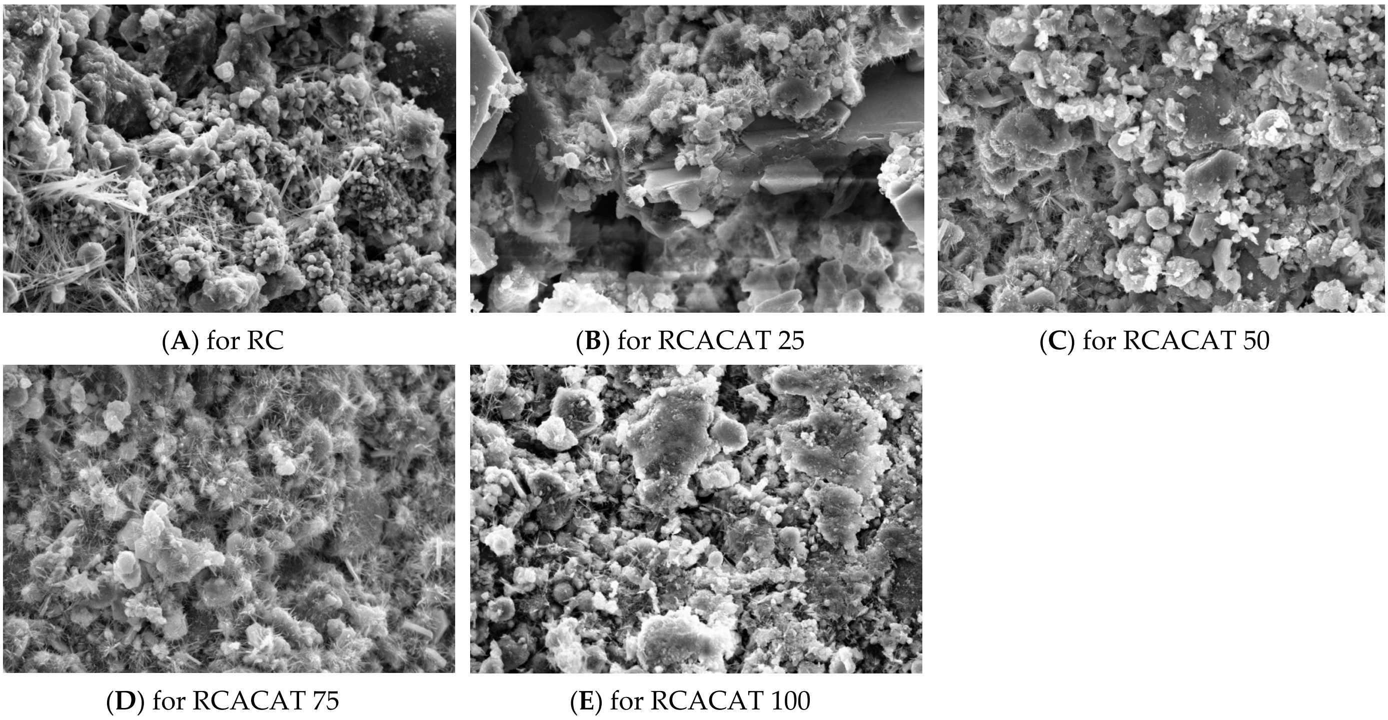
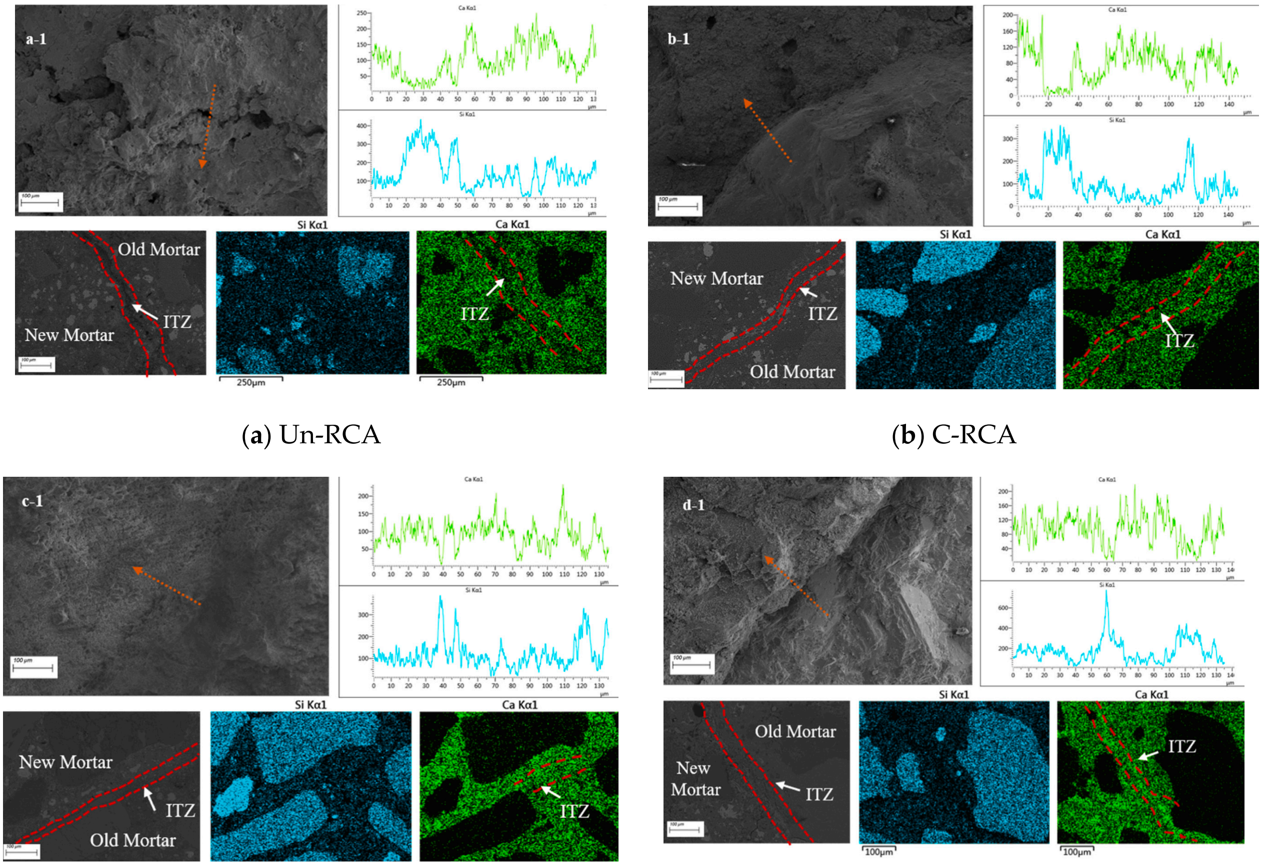


Figure 8. Microstructure of RAC and TRAC.

H. Katkhuda, N. Shatarat [174] evaluated different techniques for enhancing recycled concrete aggregates using chemical treatment, biological modification and synergistic reinforcement. The effect of reinforcement treatment on the micro-morphology of RCA was further investigated by taking the attached mortar on the surface of the RCA for SEM testing. After adding RCA to concrete, two ITZs form: A-N ITZ between connected mortar and fresh mortar and G-N ITZ between aggregate and fresh mortar. In Figure 9a, SEM images indicate a loose structure of A-N ITZ and G-N ITZ with unreinforced RCA in the RAC, with evident 80 µm gaps. A-N and G-N ITZ transition bands are seen in the BSE picture. EDS shows that Si and Ca element density at ITZ decreased. The chemical strengthening of RCA improves the ITZ structure (Figure 9b). SEM pictures reveal a tight RCA-fresh mortar bond with a narrow ITZ. BSE and EDS pictures demonstrate that the G-N ITZ is much smaller and that the Si and Ca components no longer have substantial voids, suggesting better porosity. The cement slurry covering RCA creates a distinct and vivid elemental Ca band at the A-N ITZ location. Cement paste connected old and new mortar in ITZ, improving its morphology. Figure 9c illustrates that biological alteration enhances ITZ morphology, although not as much as chemical strengthening. In the SEM and BSE photos, the two ITZs were narrower, but the RCA and new mortar bonded poorly, leaving gaps. According to EDS, the biological modification treatment reduced the Ca elemental transition zone void frequency at the ITZ of the RAC sandstone and its size. There was still a severe Ca elemental shortage. Figure 9d reveals that synergistic reinforcement enhances ITZ morphology more. ITZ was thick and strongly linked between new mortar and RCA at the A-N and G-N positions. G-N ITZ has a consistent Ca element distribution according to EDS. Using the Ca element distribution to locate the ITZ is almost hard. The dense Ca element distribution of A-N ITZ forms a Ca element distribution band. RAC ITZ micromorphology has improved dramatically.



(**a**) Un-RCA (**b**) C-RCA

(**c**) M-RCA (**d**) CM-RCA

Figure 9. Micro-morphology and distribution of characteristic elements in the ITZ of untreated and treated RCA.

4. Structural Behavior of RAC and TRAC Beams

Several studies on the behavior of TRCA concentrate on the curing process [16,173–175]. S.B. Desai [176] examined the shear strength of frames made from various materials. He used limestone filler as the third ingredient and pulverized fuel ash and Portland cement (PC) as the first two. (PL). The author observed that as compressive concrete strength increased, the shear capacity of the beam increased, and shear failure occurred soon after oblique fractures first appeared. N.K.Bui et al. [133] suggested an RAC treatment using a sodium silicate solution and silica fume. It was stated that the hardened characteristics of the concrete were enhanced because of the RAC treatment. The increment percentages for compressive strength, modulus of elasticity, and tensile splitting strength were discovered to be between 30% and 50%, 15.5% and 42.5%, and 33% and 41%, respectively. Kathkuda et al. [174] made experimental and analytical observations of the shear response of reinforced concrete supports. They saw people hauling loads. The capacity of treated RAC beams was greater than that of untreated and naturally strengthened control beams. They also noticed that the shear span-to-depth(a/d) ratio significantly affected the shear strength and load-carrying capacity during four-point bending tests at various a/d ratios, i.e., a/d = 2.0 and 3.0.

4.1. Flexural Behavior of RAC Beams

In this part, the flexural behavior of RAC beams is covered. Multiple investigations studies used a four-point bending setup to conduct experimental experiments on simply supported beams while varying the beams' dimensions and the properties of the mixtures of RAC [148,177–181]. The effects of (1) the ratio of RA replacement (r) and (2) the main reinforcement ratio (ρL) on flexural behavior are described in the sections that follow. The amount of RACs to the overall total coarse aggregates is expressed as the RAC replacement ratio, or r, which measures the substitution of RACs. The percentage of longitudinal steel reinforcement is:

$$\rho L = \frac{As}{b * d} \tag{2}$$

where b is the cross-section width, d is the cross-section effective depth, and As is the main reinforcement ratio.

Mass or volume can be used to represent the RAC replacement ratio. The research mentioned has variations in the definition of the percentage of RAC [135,178,179,182,183] that adopted the mass ratio. Because RAC has a lower mass density than NA, there is a difference in volume and mass. Due to the difference in density, a mixed design is created using a greater proportion of RAC and the mass ratio replacement rather than the replacement ratio of volume in every study mentioned in this article, RACs were employed for both NAs and continuous grading. The pre-soaking in water process is used to treat RACs [180,183]. This technique was used to make up for the low fresh properties issue with RAC concrete by lowering the water absorption of RAC. RAC concrete. Fathifazl et al. [177] used the replacement technique known as equivalent mortar volume (EMV). The EMV approach considers that both new and residual mortar comprises the entire mortar volume in concrete produced using RAC. The mix design for the EMV method ensures that the total mortar volume (including remaining and new) in concrete created using RAC is equal to that in the corresponding NAC [184].

It is depicted that the RC beam's crack patterns at failure load. It is observed that the following phenomena are associated with the fracture growth as the load is applied: (1) vertical cracks begin at the maximum bending area, (2) cracks spread towards the compression area before becoming angled the cracks of flexural shear, and (3) crushing of concrete in the compression area with tensile beam failure [165]. Ignjatovic et al. [183] observed that an increase in the percentage of RAC increased cracks and damaged concrete in the compression zone. The inadequate ITZ and the micro-cracks of RACs are responsible for the larger concrete crushing, concrete crushing in the compression area, and flexural cracks in the tension zone increase as the percentage of RAC increases [183,184].

Figure 10 depicts the impact of the percentage of RAC on cracking load at different limit states. The description of the figure reports the w/c and the main reinforcement ratio (ρL) of the various investigations. It is observed from Figure 10 that the cracking load of RAC mixed reduced as the RAC replacement level increased, proving the harmful impact of raising RAC [16]. These decreases in the cracking load might be due to the poor binding between the RAC and cement mortar, micro-cracks in AM on the RAC, and increasing water absorption of the RAC compared to the NCA [16,52,72,185]. Including AM in the RAC leads to the design mixes water consumption, which is important for cement hydration [16].

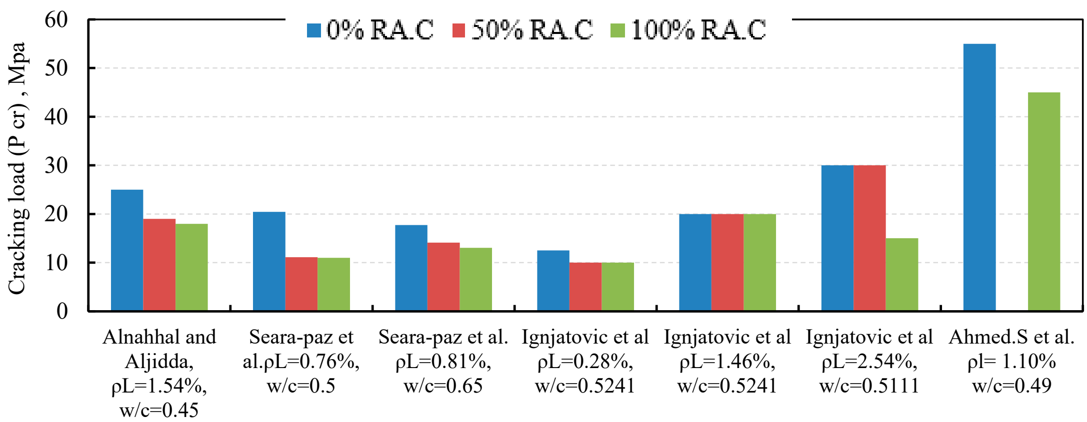


Figure 10. Effect of the RAC replacement ratio on the cracking load [132,180,181,183].

The influence of the replacement ratio of the RAC on the ultimate load (P Ult) of RAC mixes is illustrated in Figure 11. It is shown in Figure 11 that the ultimate load of RAC beams increased as the ρL and w/c ratio increased. However, the replacement level of NCA by RAC reduced the ultimate load. The main reason was the weak bond between RAC and concrete mortar and the microstructure change for the mixes containing RAC [128,174,176]. However, when the load increases, the tension-shattering concrete cracks and the longitudinal steel reinforcement carries the majority of the moment forces. Therefore, independent of the replacement of NCA by RAC, beams with a higher longitudinal reinforcement ratio (ρL) have stronger flexural resistance than those with a lower ratio.

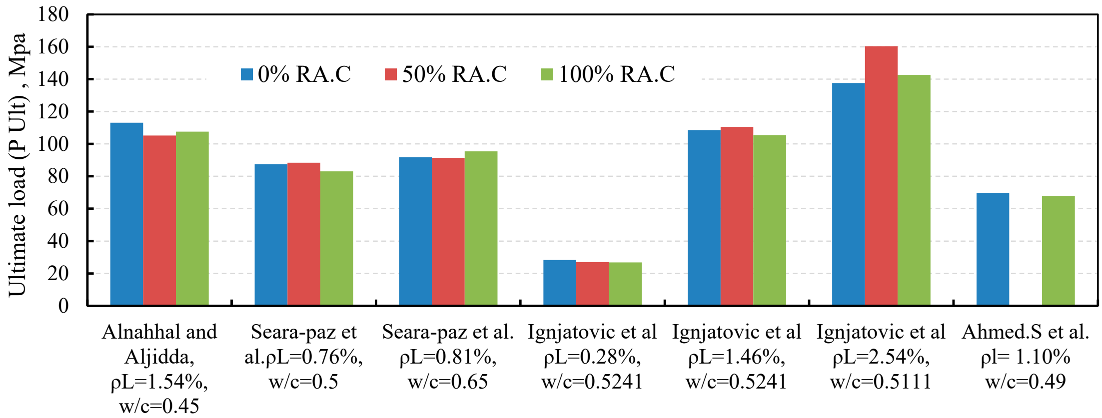


Figure 11. Impact of the RAC replacement level on the ultimate load [132,180,181,183].

Figure 12 shows the relation between the RAC replacement ratio and mid-span deflection at failure load. It is observed from Figure 12 that the deflection at mid-span with various RAC levels is more than 0% RAC beam [16,135,178,180]. This is due to RAC's weaker ITZ than NCA [56]. The ultimate mid-span deflection affected several parameters such as w/c ratio, replacement ratio of RAC, and ρL. The ultimate mid-span deflection ratio decreases as ρL increases but only slightly increases by increasing the RAC replacement ratio. Confirming previous investigations, Ignjatovic et al. [183] measured the concrete compressed depth, finding that this increases when increasing the reinforcement ratio regardless of the RAC ratio.

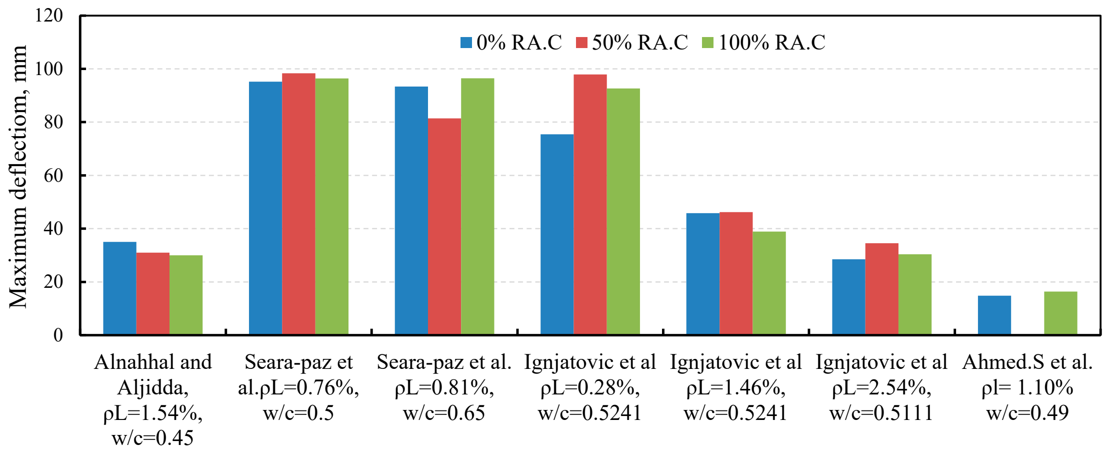


Figure 12. Impact of the RAC replacement level on the mid-span deflection at failure load [132,180,181,183].

4.2. Shear Response of RAC Beams

Due to its brittle properties, transverse steel primarily controls shear failure, which is frequently regarded as more dangerous than flexural failure [184]. When considering beams without transverse steel, the shear forces are primarily countered by the following four mechanisms: coarse aggregate interlocking in the crack, concrete shear stress under compression, and dowel impact submitted by the main reinforcement [184].

The effects of the influencing variables, the percentage of RAC replacement (r), and transverse shear reinforcement percentage (ρw), (ρL), and (a/d) on the shear capacity and failure mechanisms, are examined in the experiments that follow.

$$\rho w = \frac{Asw}{b \times s \times \sin(\alpha)} \quad (3)$$

where α is the angle between the beam's longitudinal axis and shear reinforcement, Asw is the shear reinforcement area measured along the beam axis, and b is the width of the cross-section area. The ratio of the beam's effective sectional depth (d) to its shear span (α) is known as the shear a/d.

4.3. Shear Behavior of RAC and TRAC Beams

H. Katkhuda N. Shatarat [174] treated the RAC. The original recycled aggregates were pre-soaked in hydrochloric acid (HCl) for 24 h to remove adhering mortars. Their surfaces were then coated for an hour with sodium metasilicate pentahydrate solution. B. Ordo et al. [186] used the application to structural concrete beams without shear stirrups, which will be guided by the pozzolanic preparation with slurry-containing cement and RHA for the ideal coarse RAC size. This work also suggests a surface treatment mechanism for RACs use a targeted strategy to improve the physical and mechanical characteristics of the aggregate to enhance aggregate performance in beams. G. Fathifazl et al. [187] used the so-called Equivalent Mortar Volume (EMV) method to balance the concrete mixtures for the RRC beams. Recycled concrete aggregate (RAC), a composite material, is the basis for the technique. Consisting of natural aggregate and mortar, and when proportioning concrete mixes incorporating RAC, each phase's volumetric content and characteristics must be considered quantitatively.

Previous investigations studied crack patterns of treated and untreated beams at shear failure. H. Katkhuda N. Shatarat [174] proved that the first flexural cracks developed at the midpoint of the beams, where the largest moment was present. New flexural cracks formed as the applied load grew and spread out in the space between the applied load and the supports of the beam. As they developed, lateral, flexural shear cracks began to tilt toward the beams' neutral axis. After that, the beams' shear zones at both ends started to exhibit symptoms of breaking. Flexural shear cracks widen and spread upward in the direction of the applied load as the applied force rises. Therefore, it is possible to conclude that the tested beams broke in shear because of a significant transverse shear fracture, concrete fibers cracking under tension, and local bond failure of the bottom reinforcement close to the supports. The failure process is substantially the same for all tested beams, and the crack patterns are all considered identical. These studies support the effectiveness of employing untreated and treated RAC.

4.3.1. Effect of RAC Replacement Ratio on Shear Behavior of RAC Beams

Several investigations by Choi et al. [188], Knaak and Kumra [182], Ignjatovic et al. [189], H. Katkhuda, N. Shatarat [174], Pradhan et al. [190], and Rahal and Alrefaei [191] studied the shear response of RAC beams. All the researchers' failure patterns revealed that RAC beams and the companion NCA exhibited comparable behavior. The failure phenomena often manifest as vertical bending-related cracks that proceed to inclined cracks that travel horizontally along the beam and upward on the compression side. All the researchers above' failure patterns revealed that RC. Beams exhibited behavior comparable to that of the companion NCA ones regarding crack pattern and propagation. The failure phenomena typically manifest with the phenomenology described below; vertical bending-related cracks start to show up, followed by inclined cracks that move horizontally along the beam and upward on the compression side.

Figure 13 shows the ultimate shear force with different treated and untreated RCA. The caption of the figure reports the a/d ratio and the main steel ratio (ρL) of the various tests. The shear capacity generally decreases with an increase in the replacement ratio of RCA because of the reduced hardened performances of RAC [172,192]. Fathifazl et al. [187] utilized the EMV replacement approach, which improves or equalizes the performance of the RAC mix with the corresponding NAC mixture by enhancing aggregate interlock effectiveness in the ITZ's cracked faces. In addition, Katkhuda, N. Shatarat [174] confirmed that the RCA beams with RAC acid treatment displayed an increase in shear capacity compared to NAC beams. In contrast, the untreated RCA beams demonstrated a reduction in shear capacity, proving the findings of other investigations [182,188–191,193].

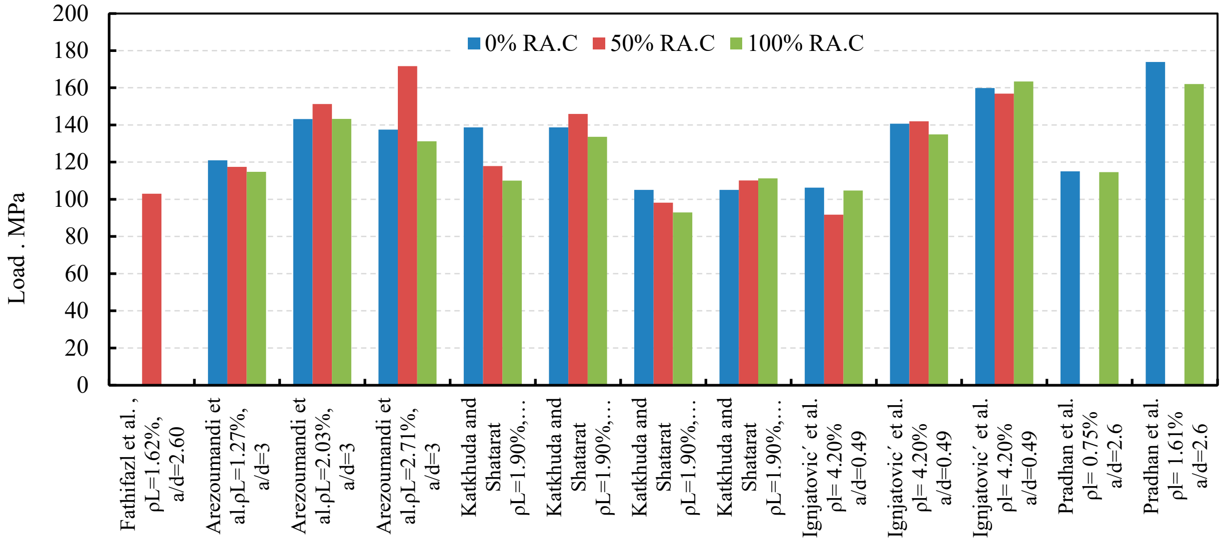


Figure 13. Influence of RAC replacement ratio on the ultimate shear force: [17,187,189,190,193].

4.3.2. Effect of the Shear-to-Span Ratio (a/d) on the Shear Response of RAC Beams

The a/d ratio significantly influences the shear response of RAC beams. For example, the shear span-to-depth ratio is one of the key characteristics used by the CEBFIP Model Code to forecast the shear capacity of RC beams [3]. The shear strength of RC beams is demonstrated using a/d for both the RAC and NAC situations, showing how much the beam action and arch action mechanisms contribute [194].

Researchers Katkhuda, N. Shatarat [174], Fathifazl et al. [187], and Choi et al. [188] all carried out experimental studies on the shear response of RAC beams with changing the a/d. In particular, Choi et al. [188] investigated alternative a/d values, i.e., 1.5, 2.5, and 3.25; Fathifazl et al. [187] studied four different a/d, i.e., 1.5, 2, 2.7, and 4; and Katkhuda, N. Shatarat [174] took into account two different a/d, i.e., 2.0 and 3.0. By changing the a/d, there was no observable difference in the failure mode. Flexural cracks start at the maximum moment area between the applied load point and the supports under modest loads. Once the load is increased, flexure-shear fractures develop into inclined shear cracks that spread toward the loading points and eventually cause a global shear failure.

5. Conclusions and Proposed Research

Using RA in the concrete industry protects the environment and conserves natural aggregate, which is considered a non-renewable resource. However, the cement mortar's adhesion makes RA less dense and more porous than the natural aggregate (NA). As a result, RAC is less durable than NAC. Therefore, several methods have been used to treat recycled aggregates. According to the literature evaluation of the paper conducted on RAC, the following considerations can be outlined:

1. Concrete made of RA has low workability compared to concrete with natural aggregates, requiring more water to achieve the same workability. This is because of the mortar attached to the recycled aggregate, which has high porosity and a high thirst for water absorption.
2. The mechanical properties (cube compressive strength, splitting tensile strength, and flexural strength) of RAC mixtures decreased as the RAC replacement ratio increased, proving the adverse effect of adding RAC.
3. Compared to NCA concrete, the concrete mixes made of untreated RAC are porous concrete with a higher tendency for chloride migration, high water absorption, double water permeability, and increased carbonation depth.
4. As a treated method, SCMs and nanomaterials are used to increase the mechanical and durability properties of RAC.
5. Flexural behavior: NAC and RAC beams display similar crack patterns and propagation. The cracking load and average ultimate load capacity decreased with RCA increasing. Mid-span deflection increased with the increase of RAC at the same ρL.
6. Shear behavior: RAC beams' crack patterns, propagation, and failure mode of RAC beams are comparable to those of NAC beams. RAC beams have a somewhat lower shear capacity than NAC beams for the same ρL and a/d.

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