Examining Mechanical Properties of Recycled Aggregate Concrete

Ali Alsalman[1], Jamal Khudair[2], Rahman S. Kareem[3*], Lateef Assi[4], Canh N Dang[5], José R. Martí-Vargas[6]
{alialsalman609@gmail.com[1], ali.mohamed@almaaqal.edu.iq [2], rahman.s.kareem@edu.stu.iq[3], lassi@email.sc.edu[4], dncanh86@gmail.com[5], jrmarti@cst.upv.es[6]}

Tatum-Smith-Welcher Engineers, Inc., 3100 S Market St., Rogers, AR 72758, USA[1]
College of Engineering, Civil Engineering Department, Al Maaqal University, Basra, Iraq[1]
College of Engineering, Civil Engineering Department, University of Basra, Basra, Iraq[2]
University of Arkansas, Department of Civil Engineering, 4190 Bell Engineering Center Fayetteville, AR 72701, USA[3]
Department of Structure, Shatrah Technical Institute, Southern Technical University, Shatrah, Dhi Qar, Iraq[3]
Department of Civil and Environmental Engineering, University of South Carolina, Columbia, USA[4]
Department for Management of Science and Technology Development, Ton Duc Thang University, Ho Chi Minh City, Vietnam[5]
Faculty of Civil Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam[5]
Institute of Concrete Science and Technology (ICITECH), Universitat Politecnica de Valencia, Valencia, Spain[6]

Abstract. Several mid-strength recycled aggregate concrete (RAC) combinations are developed in this study. Three groups are studied in the experimental section. Natural aggregate concrete (NAC) combinations, for example, employed 100 percent natural gravel aggregate. The second group (RAC-I) mixed natural gravel aggregate with recycled concrete aggregate (30 percent per total weight of coarse aggregates). The compressive strength of the parent concrete was 20-30 MPa. The third group (RAC-II) had a similar and larger percentage of recycled concrete aggregate replacement, ranging from 30% to 100%. The compressive strength of the reference concrete was 30-40 MPa. The results showed that using 30% recycled concrete aggregate had no effect on the workability and mechanical qualities of the concrete. At 112 days, the shrinkage of RAC-I combinations is 40 percent higher than that of NAC mixtures. Based on the results of the emissions analysis, RCA appears to be a viable alternative for reducing CO2 emissions.

Keywords: Sustainable Construction; Recycled Concrete Aggregate; Recycled Aggregate Concrete; Compressive Strength; Modulus Of Elasticity; Shrinkage; CO_2 Emission.

1 Introduction

Construction and demolition wastes account for a large portion of solid wastes. The generation of these wastes has been increasing rapidly worldwide. The annual amount of wastes produced from construction and demolition is about 859 million tons in the EU [1] and about 230-530 million tons in the USA [2]. The most conventional method of disposing of these

IMDC-IST 2021, September 07-09, Sakarya, Turkey

DOI 10.4108/eai.7-9-2021.2314894

wastes has been through its disposal in landfills [3], which is a key contributor to environmental pollution. Some countries have established laws to prohibit or applied specific taxes for generating waste areas [3]. For decades in the construction industry, concrete has been the most popular material and consequently generated a major portion of demolition wastes; the annual consumption of concrete globally is approximately 10 billion tons [4]. It is well known that a typical concrete mix consists of ordinary Portland cement (OPC), water, and aggregates. The primary aggregates that are used in the concrete industry are sand and gravel (crushed rocks can be used instead of gravel). The continuous use of such materials might yield irreversible influence on the natural resources and environment as well (e.g., agricultural losses and rainforest devastations); globally, the construction industry uses approximately 48.3 billion tons of aggregates annually [5]; this number is anticipated to double over the next two decades if the rate of consumption stays the same [6]. Thus, recycling of demolished concrete has been recognized as a promising solution, not only to preserve the natural resources but also to offer a cleaner and sustainable practice (e.g., reduce the CO_2 emission) for the construction industry [7].

Different kinds of solid wastes have been utilized as aggregates in concrete, such as recycled concrete aggregate (RCA), discarded tire rubber, and waste glass [8–10]. Among these materials, RCA gets a strong interest due to its readiness in a great amount, being available worldwide, and can partially or fully replace coarse and fine aggregates in new concrete [11–13]. RCA is processed from crushed, graded inorganic materials that are sourced from construction and demolition debris, such as buildings, roads, bridges, and sometimes even from catastrophes like wars or earthquakes [14, 15]. In terms of applications, RCA has been used in sub-base for road construction and permeable bases and concrete mixtures, such as sidewalks, curbs, bridge substructures, and building superstructures, concrete shoulders, and residential driveways [3, 16].

The utilization of RCA to develop recycled aggregate concrete (RAC) is locally oriented to fully reach its advantages. The aggregates are supposed to be collected, classified, and recycled within a small geographic region (e.g., a construction site, a city, or a town). This practice saves transportation costs, minimizes the burden on transportation infrastructures, and preserves energy. In this study, the researchers develop RAC mixtures from the demolition wastes of old buildings in the city of Basra. The wastes from the concrete account as the main source of construction and demolition wastes in Iraq due to the demolition from wars. The authors in this study aim to encourage design engineers in Basra to specify RAC in their design at least in non-structural concrete by presenting several tests to examine the performance of RAC. On the other hand, this study validates the applicability of existing design code equations for predicting mechanical properties.

2 Literature Review

In terms of concrete workability, several studies have been performed to examine the effect of RCA. It was reported that as the RCA content increased, the workability decreased [6]. When RCA was used as coarse aggregate, 5% mixing water was additionally needed for achieving workability similar to that of natural coarse aggregate. [17] stated that the concrete slump, which ranged from 50-100 mm, was achievable by using superplasticizers. [18], however, observed that the initial slump of RAC was slightly affected by the relatively high-water absorption of RCA. On the other hand, the rate of slump loss increased as the water absorption capacity of

RCA increased.

In terms of concrete mechanical properties, Younis and Mustafa [19] compared the mechanical properties of RAC to those of natural aggregate concrete (NAC). The investigated compressive strength ranged from 30.2 to 41 MPa at 28 days. The compressive strength of RAC was approximately 84% of the NAC. On the other hand, the splitting tensile strength was 93% of the NAC. Similar findings were reported by Ismail et al. [20] and Yaba et al. [21]. Zhou and Chen [22], nevertheless, informed that the compressive and flexural strengths of RAC were similar and even exceeded the strengths of NAC. The observation was attributed to the high water absorption capacity of RCA, which resulted in the improvement of the bond strength between aggregate and cement paste matrix [22].

The parent concrete of RCA is influential to the service performance and durability of concrete. [23] evaluated the long-term mechanical properties of RAC containing coarse RCA. RCA produced from high-strength parent concrete (the compressive strength of parent concrete equal to 110 MPa) could result in slightly higher strength in comparison to conventional high-strength concrete for the same water/binder ratio (*w/b*). However, the modulus of elasticity and splitting tensile strength of these high-strength RAC mixtures were similar to those of NAC at all ages. [24] pointed out that the utilization of RCA made from the parent concrete having a compressive strength of 50 MPa or greater did not affect the mechanical properties of RAC.

The shape of RCA is influential since it affects the bond between the cement paste matrix and coarse aggregate. The experimental results reported by [25] showed that the shape (i.e., angular or round shape) of RCA and replacement level up to 100% of natural aggregate had a minimal impact on the compressive strength of RAC. On the other hand, the authors concluded that the splitting tensile strength of RAC was influenced by the RCA properties (i.e., shape, surface texture, and crushing procedure) and replacement level.

The incorporation level of RCA influences the mechanical properties of RAC. [26] found that concrete compressive strength of 30-45 MPa was achievable with 25% of coarse RCA using the same amount of cement as in NAC. The modulus of elasticity of RAC was lower in comparison to that of NAC, and the tensile strength of RAC might be higher than that of NAC. [13] prepared RAC with different levels of replacement of natural coarse aggregate by RCA (20%, 40%, 60%, 80%, and 100%). The average reduction in compressive strength, splitting tensile strength, modulus of elasticity, and flexural strength were 10%, 14%, 11%, and 9%, respectively. Several studies stated that mechanical properties were not affected if RCA was incorporated by up to 30% of the natural coarse aggregate [11, 27–29]. On the other hand, the study conducted by [30] indicated that replacing all coarse aggregate with 100% of RCA had minimal influence on the performance. In terms of the correlation between compressive strength and other mechanical properties such as modulus of elasticity, flexural strength, and splitting tensile strength, several studies have reported the findings [22, 31, 32].

In terms of concrete deformation, several studies demonstrated that the incorporation of RCA increased concrete shrinkage. This increase was attributed to the high deformability of the attached mortar of RCA [25]. [33] reported that concrete mixtures prepared with RCA produced from high-strength parent concrete had lower drying shrinkage and higher resistance to chloride-ion penetration in comparison to the mixtures made with RCA produced from normal-strength parent concrete. The finding was confirmed by [34]. Also, [35] developed a drying shrinkage model for RAC containing both fine and coarse RCA. Test results showed that both fine and coarse RCA had a substantial influence on shrinkage, and the influence of fine RCA decreased with the content of coarse RCA increased. Moreover, [36] indicated that the internal curing effect of RCA delayed the development of free shrinkage at an early age.

3 Experimental Program

3.1 Materils Properties

The cementitious material was the ordinary type I Portland cement [37]. Fine aggregate was natural gradation sand and used for all concrete mixtures [38]. Two types of coarse aggregate were used: natural gravel aggregate with a maximum aggregate size of 20 mm and RCA, as shown in Fig 1. The RCA was divided into two types based on the reference concrete: Type I - obtained from a structural concrete source with 28-day compressive strength of 20-30 MPa, and Type II -obtained from a structural concrete source with 28-day compressive strength of 30-40 MPa. Both types of RCA were sourced from demolition wastes of concrete buildings. The demolition wastes were crushed, sieved, and stored in buckets for ready use. The gradation curves, along with specific gravity (bulk oven-dried, bulk saturated surface dry, and apparent), water absorption, and unit weight of natural sand, natural gravel aggregate, and RCA are presented in Fig 2 and Table 1, respectively [39–41].

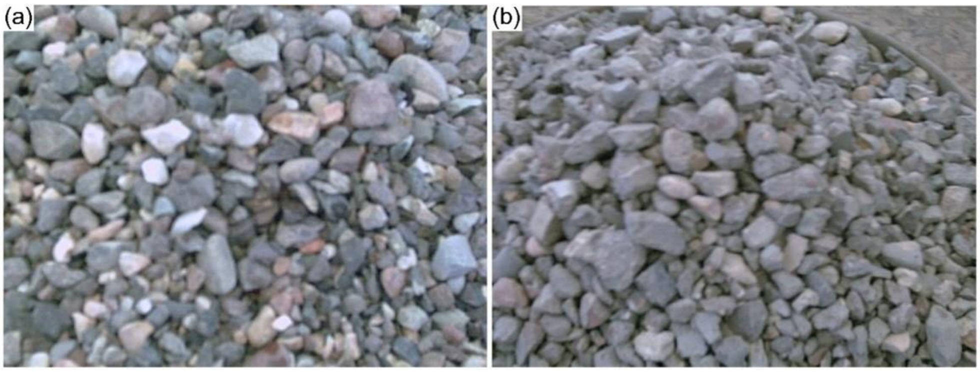

Fig 1. COARSE AGGREGATES: (A) NATURAL GRAVEL AGGREGATE (NGA) AND (B) RECYCLED CONCRETE AGGREGATE (RECYCLED CONCRETE AGGREGATE TYPE I)

The specific gravity of RCA was about 63% of the natural gravel aggregate on average. Previous studies indicated that the specific gravity of RCA ranges from 1.91 to 2.70 [42]. The average water absorption capacity of RCA was 3.9%, which is more than 4 times higher than that of natural gravel aggregate. Literature has reported values in the range of 0.5% to 14.75% [42]. On average, the unit weight of RCA was 84% of the natural gravel aggregate. The reduction in specific gravity and unit weight and the increase in water absorption capacity are attributed to the existence of loose paste in demolished construction wastes [11, 43].

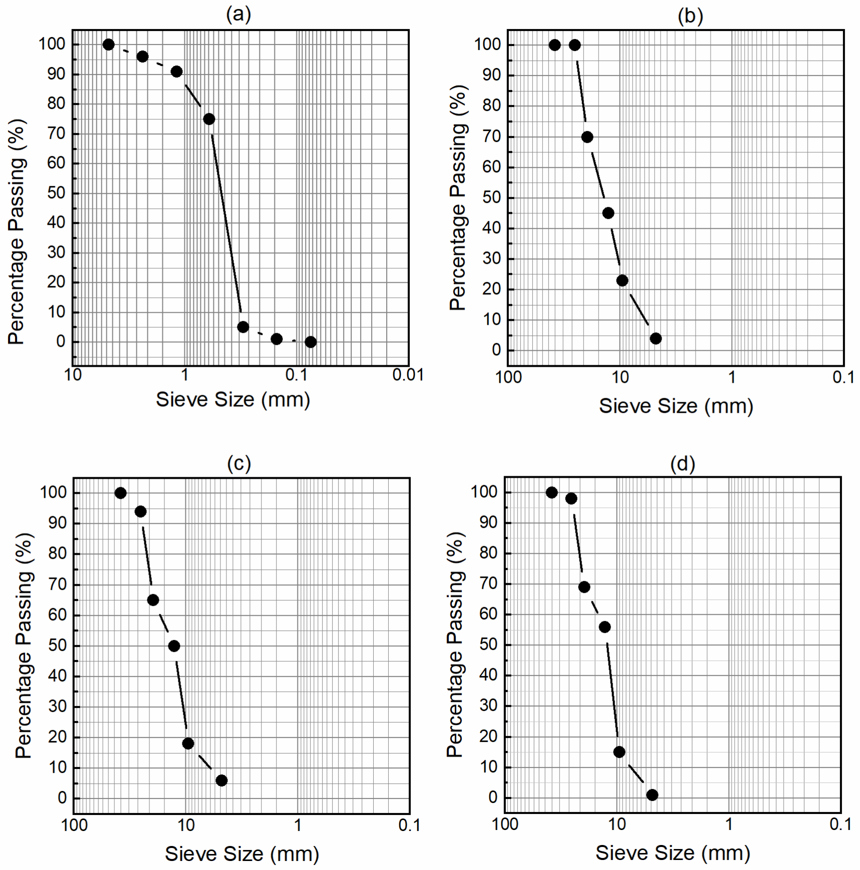

Fig 2. Gradation of aggregates: (a) natural sand, (b) natural gravel, (c) recycled concrete aggregate Type I, and (d) recycled concrete aggregate Type II.

Table 1. Properties of aggregates

Property	Natural Sand	Natural Coarse Aggregate	RCA Type I	RCA Type II
Specific gravity				
Bulk oven-dried	2.61	2.65	1.64	1.66
Bulk SSD	2.63	2.68	1.69	1.72
Apparent	2.68	2.70	1.70	1.75
Absorption (%)				
	1.29	0.90	3.83	3.90
Unit weight (kg/m^3)				
Loose	1400	1204	989	999
Compacted	1478	1266	1073	1092

3.2 Mixture Proportions

Table 2 summarizes the mixture proportions for three groups of concrete mixtures. For Group 1, mixtures NAC-1 to NAC-9 contained only natural aggregates (sand and natural gravel aggregates). Different *w/c* ratios and aggregate to cement (*Agg/C)* ratios were used to cover a wide range of strength and workability. For Group 2, mixtures RAC-1 to RAC-9 investigated the effect of RCA Type I, which was incorporated by 30% of the total weight of coarse aggregate. The replacement ratio was selected based on the recommendation of previous research studies [11, 27, 28, 43]. For Group 3, three subgroups were considered to investigate the effect of RCA Type II, as follows: (i) mixtures RAC-10, 13, and 16 examined the influence of the parent concrete grade on compressive strength (for the same replacement ratio in Group 2 -30%); (ii) mixtures RAC-11, 14 and 17 examined the effect of 50% replacement on concrete properties; and (iii) mixtures RAC-12, 15, and 18 examined the effect of 100% replacement on concrete properties. It should be noted that the content of cement is presented as an absolute amount, while the content of other concrete components is presented as a proportion to the cement content.

Table 2. Mixture proportions

Mixture	Cement kg/m^3	Weight Proportion					Ratio		
		Portland cement	Natural sand	Natural coarse aggregate	Recycled concrete aggregate		*w/c*	*Agg/C*	Recycle concrete aggregate / Total coarse aggregate
					Type I	Type II			
Group 1. NAC (mixtures including natural gravel aggregate)									
NAC-1	523	1	1	2	-	-	0.40	3	-
NAC-2	517	1	1	2	-	-	0.45	3	-
NAC-3	511	1	1	2	-	-	0.50	3	-
NAC-4	383	1	1.5	3	-	-	0.50	4.5	-
NAC-5	380	1	1.5	3	-	-	0.55	4.5	-
NAC-6	376	1	1.5	3	-	-	0.62	4.5	-
NAC-7	303	1	2	4	-	-	0.60	6	-
NAC-8	301	1	2	4	-	-	0.65	6	-
NAC-9	299	1	2	4	-	-	0.70	6	-
Group 2. RAC-I (mixtures including RCA Type I)									
RAC-1	523	1	1	1.4	0.6	-	0.40	3	0.3
RAC-2	517	1	1	1.4	0.6	-	0.45	3	0.3
RAC-3	511	1	1	1.4	0.6	-	0.50	3	0.3
RAC-4	383	1	1.5	2.1	0.9	-	0.50	4.5	0.3
RAC-5	380	1	1.5	2.1	0.9	-	0.55	4.5	0.3
RAC-6	376	1	1.5	2.1	0.9	-	0.62	4.5	0.3
RAC-7	303	1	2	2.8	1.2	-	0.60	6	0.3
RAC-8	301	1	2	2.8	1.2	-	0.65	6	0.3
RAC-9	299	1	2	2.8	1.2	-	0.70	6	0.3
Group 3. RAC-II (mixtures including RCA Type II)									

RAC-10	517	1	1	1.4	-	0.6	0.45	3	0.3
RAC-11	517	1	1	1	-	1	0.45	3	0.5
RAC-12	517	1	1	-	-	2	0.45	3	1
RAC-13	380	1	1.5	2.1	-	0.9	0.55	4.5	0.3
RAC-14	380	1	1.5	1.5	-	1.5	0.55	4.5	0.5
RAC-15	380	1	1.5	-	-	3	0.55	4.5	1
RAC-16	301	1	2	2.8	-	1.2	0.65	6	0.3
RAC-17	301	1	2	2	-	2	0.65	6	0.5
RAC-18	301	1	2	-	-	4	0.65	6	1

(Notes: NAC: Natural Aggregate Concrete; RAC: Recycled Aggregate Concrete; RCA: Recycled Concrete Aggregate; *Agg/C* = coarse aggregate to cement ratio; *w/c* = water to cement ratio).

3.3 Concrete Testing

The concrete was mixed using a tilting drum mixer. All dry materials were added and mixed for about one minute and then the water was added gradually to the mixer. The total mixing time was in a range of 3-5 minutes. The rheology of the concrete mixtures was evaluated by performing two tests: slump test and compacting factor test according to ASTM C143/C143M (2020) and [45], respectively. The slump test provides an approximate measurement of concrete consistency. In practice, the slump test is widely used as an indicator to evaluate consistency due to its simplification [46]. The compaction factor test, on the other hand, is more sensitive and accurate than the slump test and particularly beneficial for concrete mixtures with low workability and dry mixtures. The test can indicate significant differences in workability over a wide range since it is very sensitive and provides consistent results [47].

Cube specimens, 100 mm x 100 mm x 100 mm, were cast to determine the compressive strength. Prism specimens, 100 mm x 100 mm x 500 mm were cast to measure flexure strength and drying shrinkage. Cylindrical specimens, 150 mm x 300 mm, were cast to evaluate the splitting tensile strength and modulus of elasticity. The specimens were covered with damp canvas cloth and left in the laboratory for 24 hours. The specimens were then de-moulded and moist cured at 21ºC until the day of testing. Compressive strength was determined at 7 and 28 days of age according to EN B 2019 12390-3 [48], in which the 28-day compressive strength is the strength of interest in this study. Flexure strength, splitting tensile strength, and modulus of elasticity was determined at 28 days of age according to [49], [50], and [51], respectively.

Concrete shrinkage was investigated by measuring the linear change (swelling and shrinkage) according to [52]. Several concrete prisms (100 mm x 100 mm x 285 mm) were cast and moist cured at 21ºC for 14 days, then stored under laboratory general facilities conditions. Subsequent readings were recorded at intervals of 1 day, and at 3, 7, 10, and 14 days submerged in water, and after that at intervals of 3, 7, 14, 21, 28, 42, 56, 70, 84, and 98 days stored in air at a temperature ranging from 16 to 30ºC. The test was terminated after 112 days. It should be noted that all tests were conducted for NAC and RAC-I mixtures, while the only compressive test was conducted for RAC-II mixtures since recycled concrete aggregate Type II was difficult to obtain. Most of the old buildings utilized concrete with compressive strength ranging from 20-30 MPa.

4 Experimental Results and Discussions

4.1 Fresh Concrete Properties

The measured slump and compacting factor result for NAC and RAC-I mixtures are shown in Figure 3. It can be noted that for a given *w/c* and *Agg/C* ratio, the RAC-I mixtures experienced lower workability, both in the measured slump and compacting factor. This observation is associated with the higher water absorption capacity of RCA (refer to Table 1), which results in a reduction in the net water content effective to the concrete workability. A similar finding is indicated by [11, 43]. Furthermore, RCA particles have rougher surface texture and additionally contain old mortar attached to the particles in comparison to natural gravel aggregate indicated in Figure 1, thus more work is needed to overcome the increased internal friction [11].

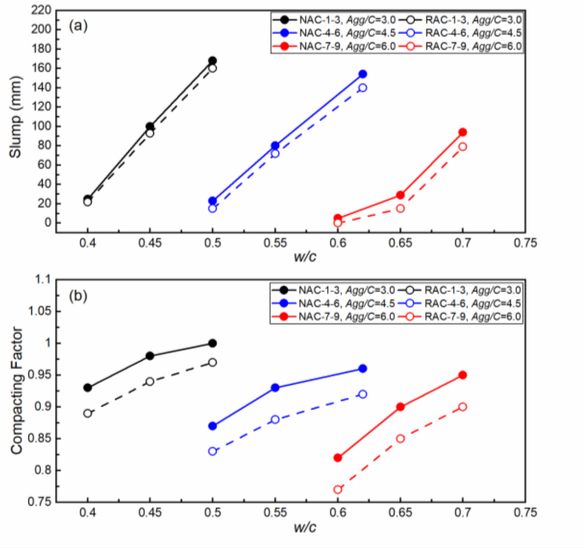

Fig 3. MEASURED (A) SLUMP AND (B) COMPACTING FACTOR

The effect of RCA types and replacement levels on the slump and compacting factor is indicated in Figure 4. For the same replacement level, the types of RCA have minimal influence on the slump and compacting factor, indicated by the results of the RAC-I and RAC-II mixture with 30% of RCA replacement. However, increasing the replacement level of RCA Type II from 30% to 50% reduced the slump and compacting factor by 22% and 3%, respectively. Replacing all coarse aggregate with RCA Type II decreased slump and compacting factor by 56% and 5%, respectively. This observation indicates that additional mixing and energy are needed for the concrete mixtures using 100% coarse RCA. Matias *et al.* [25] stated that the low workability mixtures contained RCA can be improved to be comparable to natural aggregate mixtures by using superplasticizers with dosage ranges from 0.42 to 0.5% by weight of the cement.

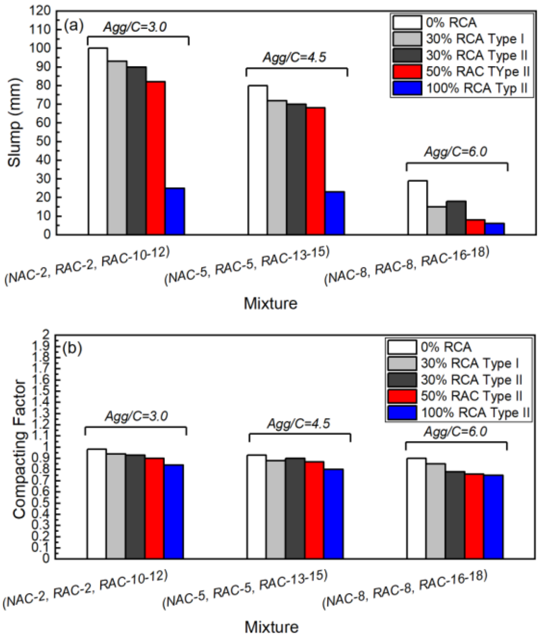

Fig 4. Effect of recycled concrete aggregate type and replacement level on (a) slump and (b) compacting factor.

4.2 Hardened concrete properties

4.2.1 Compressive strength

Aggregate in concrete represents the unit weight, modulus of elasticity, and dimensional stability of concrete (i.e., shrinkage and creep) [53]. The measured compressive strength at 28 days of the age of the NAC and RAC-I mixtures is presented in Figure 5. Overall, the NAC and RAC-I experienced a similar trend regarding the concrete strength reduction when the *w/c* ratio increased indicated by the dashed lines in the figure. This observation is apparent since the *w/c* ratio plays an important role in controlling the concrete compressive strength. The amount of coarse aggregate is another factor governing the concrete strength. As indicated in Figure 5, the compressive strength decreases as the *Agg/C* increases. In particular, the compressive strength of the concrete mixtures having *Agg/C* of 6.0 is nearly a half in comparison to the strength of the mixtures having *Agg/C* of 3.0. Figure 5 indicates the different effects of the RCA on the concrete compressive strength. For an *Agg/C* ratio of 3.0, the RAC-I mixtures had lower compressive strength than comparable NAC mixtures. The average reduction was 4%. This reduction may be attributed to the lower density and specific gravity of RCA as compared to natural gravel aggregate. A similar observation was found by [27, 28, 43]. As the aggregate content increased, RAC-I mixtures showed higher strength. The average increase was 12% and 20% for an *Agg/C* ratio of 4.5 and 6.0, respectively. The reason is related to the fact that RCA particles have an angular and rough surface texture and residual cementitious materials on the surface, which result in a better bond with cement paste matrix in comparison to natural gravel aggregate particles [24]. This observation is not in alignment with the one for *Agg/C* of 3.0.

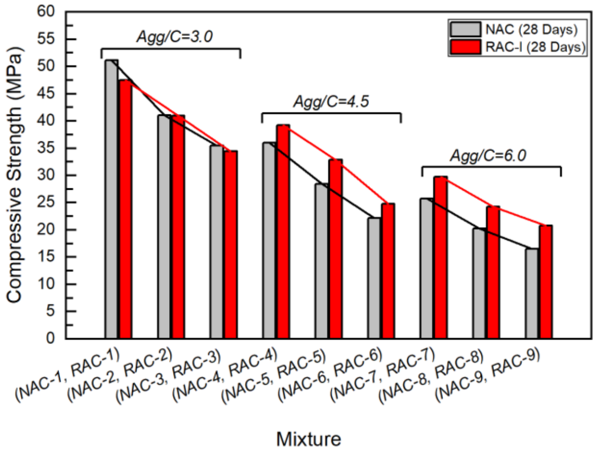

Fig 5. Measured 28-day compressive strength.

The effect of RCA type (Type I and Type II) and replacement level on compressive strength is presented in Figure 6. The RAC-II mixtures showed higher compressive strength than the comparable NAC and RAC-I mixtures. In comparison to the NAC mixtures, the increase was 20% on average. When the replacement of RCA Type II increased to 50% and 100%, strength increased by 33% and 27% in comparison to the NAC mixtures, respectively. In comparison to the RAC-I mixtures, the strength increase was 7%, 18%, and 14% for the replacement of 30%, 50%, and 100%, respectively. This finding is consistent with earlier research studies regarding the effect of parent concrete strength on the compressive strength of RAC [23, 26, 36, 54, 55]. The compressive strength of the parent concrete affects the quality of the RCA. This is the possible reason why RAC-II yielded higher compressive strength than RAC-I.

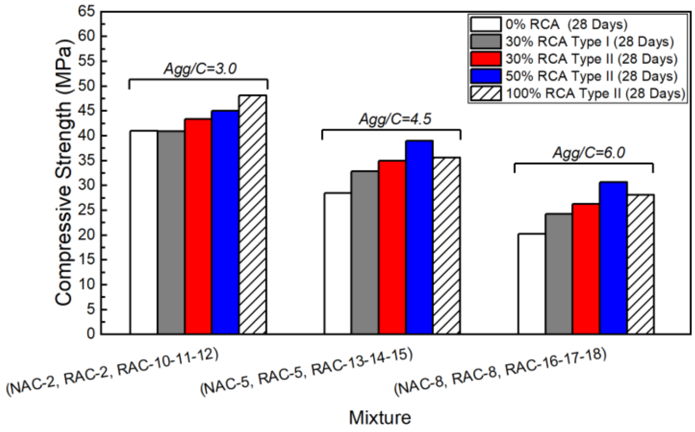

Fig 6. Effect of recycled concrete aggregate type and replacement level on compressive strength.

4.2.2 Modulus of Rupture (Flexural Strength)

Flexural strength depends on the aggregate type that affects the bond strength between cement paste matrix and coarse aggregate. The flexural strength results at 28-day of the age of the NAC and RAC-I mixtures are presented in Figure 7. For an *Agg/C* ratio of 3.0, the NAC and RAC-I had similar flexural strength. The difference was 2% on average. The flexural strength of RAC-I mixtures was 12% and 22% higher than that of the NAC mixtures when the *Agg/C* ratio increased to 4.5 and 6.0, respectively. These results are consistent with the findings by [26]. The high water absorption capacity of the adhered mortar that exists on the RCA surface can strengthen the bond between the coarse aggregate and cement paste matrix [24].

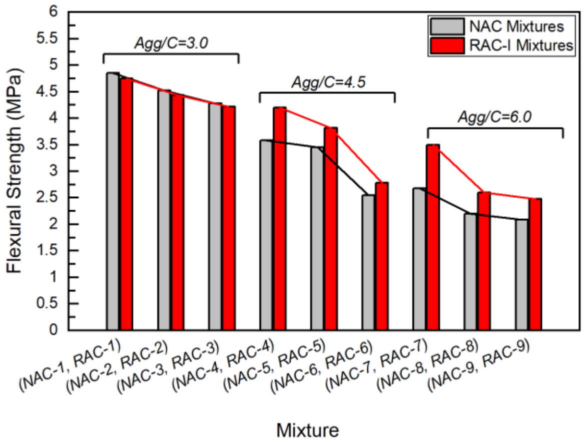

Fig 7. Flexural strength (Modulus of rupture)

The measured flexural strength of the NAC and RAC-I mixtures are compared to the predicted values by [56] as shown in Figure 8. Using the least-squares estimation method, the flexural strength of the NAC mixtures is represented by an equation $f_b = 0.19(f'c)^{0.84}$ with the coefficient of determination R^2 of 0.94. As shown, the ACI 318 equation provides a conservative prediction of flexural strength for the concrete mixture having compressive strength equal to or greater than 32.5 MPa, where 32.5 MPa as shown in Figure 8. For the mixtures having a compressive strength of less than 32.5 MPa, the ACI 318 equation overestimates the experimental values, which is unconservative in design. Similarly, the flexural strength of the RAC-I mixtures is represented by the equation $fb = 0.17(f'c)^{0.88}$ with the coefficient of determination R^2 of 0.95. The ACI 318 equation provides a conservative prediction for the mixtures.

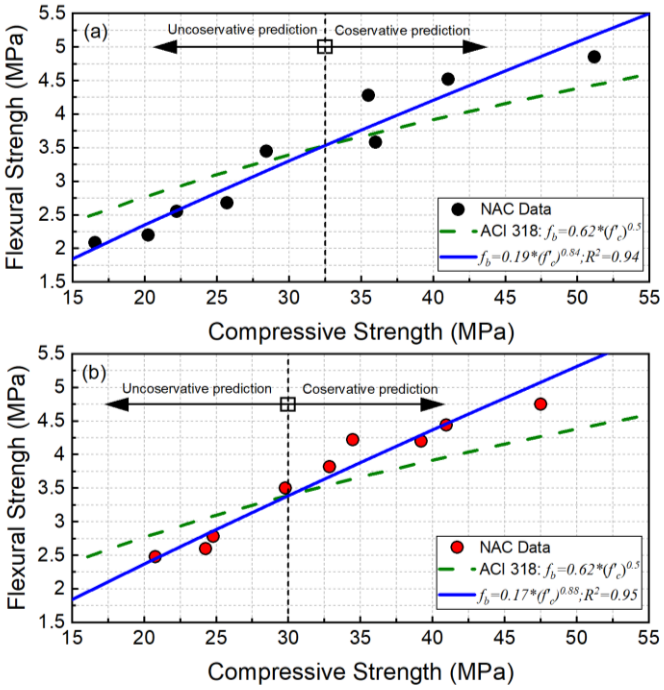

Fig 8. Flexural strength and compressive strength for (a) NAC and (b) RAC-I.

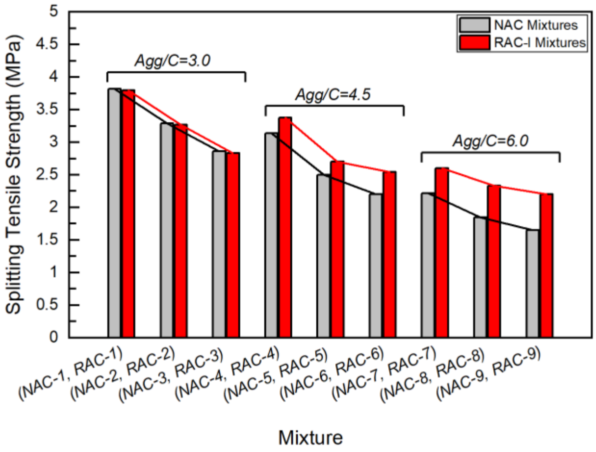

Fig 9. Splitting tensile strength.

4.2.3 Strength of Splitting Tensile

Like the flexural strength, the aggregate type can influence the tensile strength. The splitting tensile strength results at 28-day of the age of the NAC and RAC-I mixtures are presented in Figure 9. For an *Agg/C* ratio of 3.0, the RAC-I mixtures yielded approximately the same strength as the NAC mixtures. As the *Agg/C* ratio increased to 4.5 and 6.0, the RAC-I mixtures showed higher tensile strength by 10% and 25% in comparison to the NAC mixtures, respectively. The enhancement in the bond between the new cement matrix to the old one present on the surface of RCA particles is the source of the observation, which is like the one observed in the flexural strength results. The verification of the experimental values against the design code is presented in Figure 10. Using the least-squares estimation method, the experimental data of the NAC and RAC-I mixtures are represented by $f_t = 0.20(f'c)^{0.76}$ and $f_t = 0.31(f'c)^{0.64}$ with the coefficient of determination R^2 of 0.98 and 0.94, respectively. As shown in the figure, on average, the ACI 318 equation overestimates the tensile strength of all NAC and RAC-I mixtures.

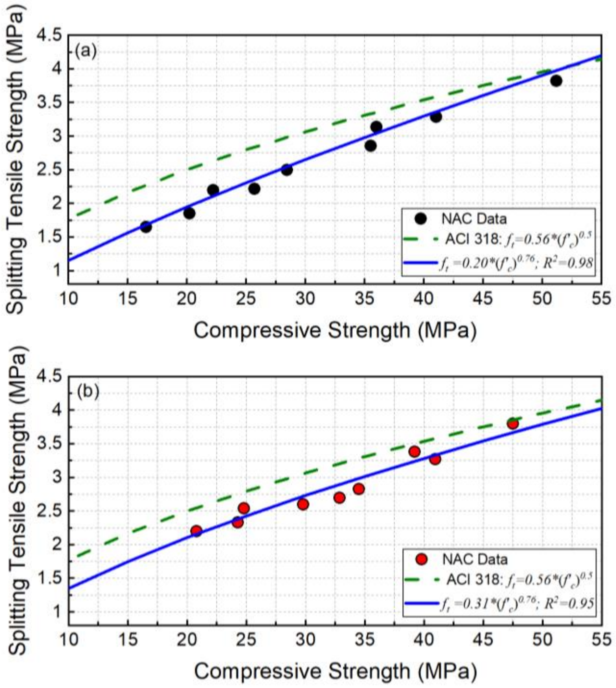

Fig 10. Relationship between splitting tensile strength and compressive strength (a) NAC and (b).

4.2.4 Modulus of Elasticity

The aggregate type is influencing the modulus of elasticity of concrete [53]. The modulus of elasticity test results of the NAC and RAC-I mixtures are presented in Figure 11. For an *Agg/C* ratio of 3.0, the RAC-I mixtures showed a lower modulus of elasticity in comparison to the NAC mixtures. The reduction was about 6%. The observed reduction is consistent with previous findings [11, 22]. Previous studies indicated that 30% incorporation of RCA by the total weight of coarse aggregate has minimal influence on the modulus of elasticity of RAC-I [11, 27–29, 43]. The minimal effect can be attributed to the fact that the modulus of elasticity. The concrete modulus of elasticity and concrete compressive strength is depicted in Figure 12. As can be observed, the ACI 318 equation captures the variation trend of the experimental data of the NAC and RAC-I mixtures. The experimental data of the NAC and RAC-I mixtures are represented by equation $Ec = 4520(f'_c)^{0.5}$ and $4520(f'_c)^{0.56}$ with the coefficient of determination R^2 of 0.99 and 0.97, respectively. On average, the ACI 318 equation overestimates the measured modulus of elasticity of the NAC and RAC-I mixtures by 5% and 14%, respectively. The lower density of RCA led to a reduction in stiffness. Furthermore, the natural gravel aggregate might participate in decreasing elasticity of concrete [28], at which the ACI 318 equation provides a fairly accurate prediction.

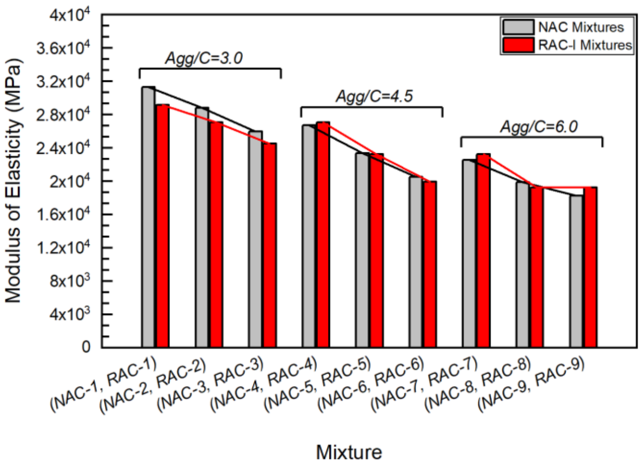

Fig 11. Modulus of elasticity.

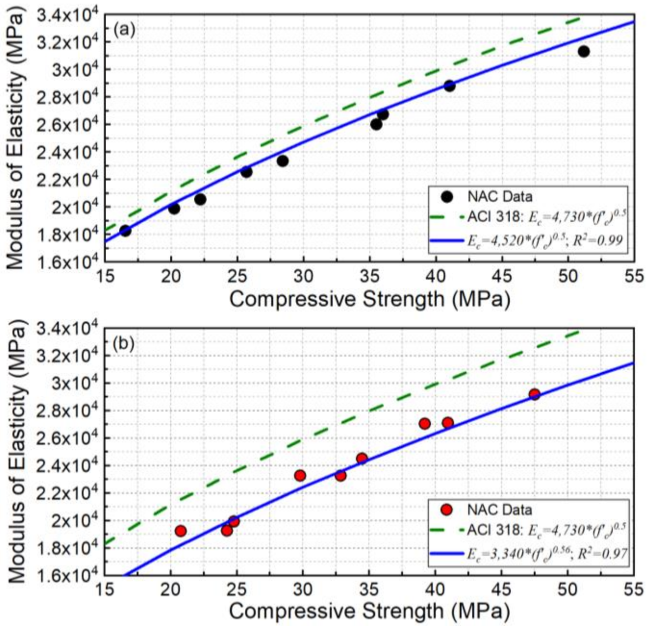

Fig 12. ELASTICITY AND COMPRESSIVE STRENGTH FOR (A) NAC AND (B) RAC-I.

4.2.5 Linear Change (Swelling and Shrinkage)

The error bars are based on a 95% confidence interval. On average, the expansion of the RAC-I mixtures at 3, 7, 10, and 14 days is 130%, 121%, 107%, and 116% higher than that of the NAC mixtures, respectively. The RAC-I mixtures exhibited higher shrinkage in comparison to the NAC mixtures regardless of *Agg/C* and *w/c* ratios. The difference in shrinkage between NAC and RAC-I mixtures tends to be consistent over time. The shrinkage of the RAC-I mixtures was 40% higher. This observation is accounted for the higher porosity and water absorption generated by the existing mortar present on the surface of RCA particles [25].

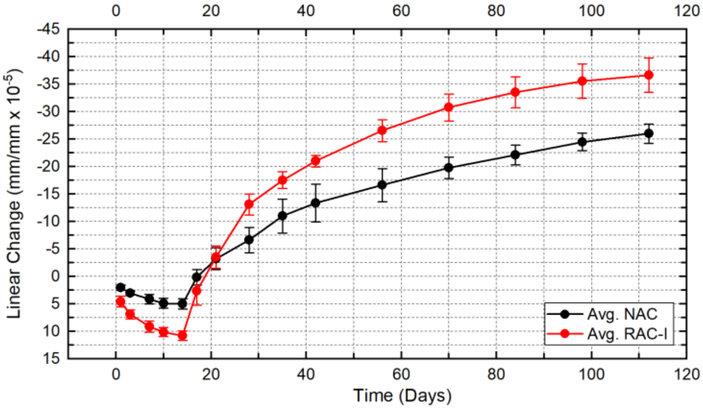

Fig 13. Average linear change: swelling and shrinkage for NAC and RAC-I.

4.2.6 CO_2 Emission of Concrete Mixtures

Because of the energy consumption during the process of manufacturing the raw materials of concrete, CO_2 is emitted into the atmosphere. Table 3 presents the resultant CO_2 emission of each component of the concrete.

Table 3. Emission factors of materials[1]

Material	kg-CO_2/kg	Reference
OPC	0.840	Sanjuán et al. [57]
Natural sand	0.0048	Hammond et al. [58]
Natural coarse aggregate	0.0048	Hammond et al. [58]
Recycled concrete aggregate (RCA-I & RCA-II)	0.0020	Alnahhal et al. [7] and García-Segura et al. [59]

[1] value of emission does not account for the emission resulted from transportation.

Table 3 summarizes the CO_2 emission for all concrete mixtures for one cubic meter of concrete as the functional unit. The highest CO_2 emission was observed with NAC-1 (447 kg-CO_2/m^3) and the lowest was RAC-18 (257 kg-CO_2/m^3). That OPC is the main contributor to the emission of all mixtures. On the other hand, the 100% replacement of natural coarse aggregate by RCA-II yielded an average reduction of the emission by 1.3%..

Table 4. Emission for one cubic of concrete.

Emission kg-CO_2/m^3						
Mixture	Cement	Sand	Gravel	RCA-I	RCA-II	Total
NAC-1	439	3	5	0	0	447
NAC-2	434	2	5	0	0	442
NAC-3	429	2	5	0	0	436
NAC-4	322	3	6	0	0	330
NAC-5	319	3	6	0	0	328
NAC-6	316	3	5	0	0	324
NAC-7	255	3	6	0	0	263
NAC-8	253	3	6	0	0	262

NAC-9	251	3	6	0	0	260
RAC-1	439	2	3	1	0	445
RAC-2	434	2	3	1	0	440
RAC-3	429	2	3	1	0	435
RAC-4	322	2	3	1	0	328
RAC-5	319	2	3	1	0	326
RAC-6	316	2	3	1	0	322
RAC-7	255	3	4	1	0	261
RAC-8	253	3	4	1	0	260
RAC-9	251	3	4	1	0	258
RAC-10	434	2	3	0	1	440
RAC-11	434	2	2	0	1	440
RAC-12	434	2	0	0	2	438
RAC-13	319	2	3	0	1	326
RAC-14	319	2	2	0	1	325
RAC-15	319	2	0	0	2	323
RAC-16	253	3	4	0	1	260
RAC-17	253	3	26	0	1	282
RAC-18	253	2	0	0	2	257

To examine the efficiency of each mixture, the ratio of the CO_2 emission to the compressive strength at the age of 28 days is considered as shown in Figure 14. It can be noticed that RAC-16 is the most efficient (5.4 kg-CO_2/MPa) which is 50% less compared to the corresponding with natural coarse aggregates (mixture NAC-8). In general, for medium-high strength concrete, mixtures with 30% of RCA-I showed less efficiency compared to NAC mixtures (NAC-1 and RAC-1, NAC-2 and RAC-2, NAC-3 and RAC-3). For medium and low strengths, RAC mixtures with 30% of RCA-I were more efficient; efficiency was 14% higher than NAC mixtures. Similarly, mixtures contained 50% and 100% of RCA-II showed higher efficiency with low strength concrete mixtures; the efficiency was 44% and 29%, respectively compared to NAC mixtures.

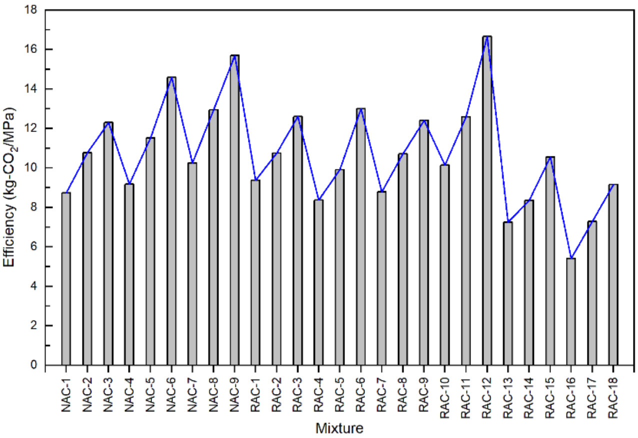

Fig 14. The eFFICIENCY OF CONCRETE MIXTURES.

5 Conclusion

The following list are the conclusions for the results:

1. RAC mixtures batched with 30% recycled concrete aggregate show lower workability than the NAC mixtures. The difference in workability between the two types of mixtures is more apparent as the *Agg/C* ratio increases.
2. For an *Agg/C* ratio of 3.0, the NAC mixtures show marginally higher compressive strength, flexural strength, splitting tensile strength, and modulus of elasticity as compared to those of the RAC mixtures. The average increase was 3%, 2%, 1%, and 7%, respectively.
3. For an *Agg/C* ratio of either 4.5 or 6.0, the NAC mixtures show lower compressive strength, flexural strength, and splitting tensile strength as compared to those of the RAC mixtures. The average reduction was 10%, 16%, and 17%, respectively. The modulus of elasticity, however, did not follow the same trend; both NAC and RAC mixtures show approximately the same values for an *Agg/C* ratio of 4.5 and 6.0.
4. Using RCA originated from a parent concrete with compressive strength of 30-40 MPa enhanced the RAC compressive strength by approximately 7% as compared to RCA originated from a parent concrete with compressive strength of 20-30 MPa at the same level of replacement. In comparison to NAC, the enhancement was 20% on average.
5. ACI 318 overestimates the measured splitting tensile strength and modulus of elasticity for all RAC and NAC mixtures. Regarding the flexural strength, ACI 318 overestimates the NAC and RAC mixtures having compressive strength less than 32.5 MPa and 30 MPa, respectively. Otherwise, the ACI 318 provides a conservative prediction.
6. The incorporation of 30% of recycled concrete aggregate increased swelling and shrinkage. The difference in shrinkage between the RAC and NAC mixtures tended to be consistent over time. At the age of 112 days, the difference was about 40%.
7. OPC is the main contributor to the CO2 emission of concrete, and it is responsible for approximately 97% of the total CO_2 emission.
8. The use of RCA can reduce the CO_2 emission generated from one cubic meter of concrete for low-strength concrete mixtures. As an average, mixtures contained 30%, 50, and 100% showed 14%, 44%, and 29%, respectively.

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