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Development and strength prediction of sustainable concrete having binary and ternary cementitious blends and incorporating recycled aggregates from demolished UAE buildings: Experimental and machine learning-based studies

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ABSTRACT

This study investigates the mechanical properties of concrete mixes containing recycled concrete aggregate (RCA) from demolished buildings in Abu Dhabi, aiming to promote sustainable construction practices. Ground granulated blast-furnace slag and fly ash were used as supplementary cementitious materials in 70 concrete mixes, incorporating varying RCA replacement levels (0%, 20%, 40%, 60%, and 100%). Uniaxial compressive and flexural tests were conducted, revealing that concrete with 20% RCA can be utilized in structural applications, as its strength exceeded 45 MPa. Most ternary blend mixes achieved the target design strength, excluding 100% RCA mixes. Analysis of variance evaluated the significance of strength differences across RCA levels, and accurate machine learning-based models were developed for predicting the compressive and flexural strengths of eco-friendly concrete containing RCA. The findings encourage wider adoption of RCA in structural applications, contributing to more sustainable concrete practices in the construction industry.

1. Introduction

The construction industry is resource and energy intensive and wasteful, thus, plays a pivotal role in climate change [1,2]. It is believed that the construction industry accounts for about 40% of the global energy demand as well as about 38% of global greenhouse gas emissions [1]. This data was supported and updated by the United Nations in 2019, attributing 39% of carbon dioxide emissions related to energy consumption to the building and construction sector [3]. It is worth noting that 11% of carbon dioxide emissions are directly related to the manufacturing of building materials [3]. Additionally, the industry consumes over 50% of raw materials [4]. In this context, concrete is the most widely used material in the construction industry. The ingredients required for its preparation mostly come from natural resources, where their extraction, transportation, and manufacturing adversely affect the environment [5–8]. Should the current rate of urbanization continue, it is estimated to cause 40 billion tons of carbon emissions annually worldwide [9]. Therefore, it is vital to implement sustainable construction practices to mitigate climate change and achieve the net-zero target outlined in the 2016 Paris Agreement [3].

Currently, major construction works are underway in the United Arab Emirates (UAE) for the new urban planning development. As a result, many existing structures of which the intended service life is close to elapsing or do not fit within the new urban improvements need to be demolished to accommodate new developments. However, the demolition of these structures generates a substantial amount of construction waste, which consists of demolished concrete, steel, concrete blocks, etc. Typically, these materials are disposed of in designated landfill areas [6,10]. As they are not biodegradable, they unnecessarily occupy valuable space in landfills for a longer period of time, causing environmental

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problems in soil, water, air, and the surrounding ecosystem [11]. For instance, in the case of the United States of America, reports showed that approximately 5% of the 348 million cubic meters of fresh concrete was sent back to the concrete plants, and then diverted to landfills [12]. It was reported that the slump dropped with the higher replacement of natural aggregates with recycled concrete aggregate (RCA), while the yield stress increased with the higher RCA replacement ratio [13]. Moreover, buildings in UAE are exposed to harsh environmental conditions, such as high humidity and temperature, especially in summer months. This exposure significantly increases the rate of building demolition in the country, especially for older structures that were not designed for extended service life under such conditions. About seventy percent of the total weight of solid wastes in the UAE comes from construction and demolition (C&D) wastes [14]. For instance, in Dubai alone, approximately 5,000 tonnes of construction waste is generated daily [15]. Therefore, the adoption of a circular economy has significant potential to mitigate the impact of such large-scale construction demolition on the environment.

The notion of circular economy has recently gained a major interest among practitioners, scholars, and policymakers to ensure a sustainable future. Kirchherr et al. [16] defined circular economy as "an economic system that replaces the 'end-of-use' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes." Accordingly, circular economy is mainly driven by the following three imperatives: reduce, reuse, and recycle [16], with the objectives of reducing the usage of virgin materials and achieving sustainable development. The construction industry has a high potential in successfully adopting circular economy practices compared to other sectors [17]. In an ideal case, the implementation of circular economy in the construction industry will result in a reduced waste generation and ensures sustainability in construction and reduction of carbon footprint. This can be achieved through recycling and reuse of aggregates generated from demolished structures or from rejected concrete that is returned from construction sites.

In addition to its reduced environmental impact, the use of RCA is more economical than natural aggregates, as it requires less transportation cost and energy consumption [18,19]. Among construction recycle materials, supplementary cementitious materials (SCMs), which are industrial by-products, have found to enhance the mechanical properties and durability of concrete [20,21]. It can in turn prolong concrete's service life and reduce the frequency of the structure's repair and maintenance. Therefore, SCMs can eventually help decrease the life-cycle cost of a structure and the long-term carbon dioxide emissions during its service life.

However, the construction industry in UAE is still reluctant to use waste materials from demolished buildings, primarily due to uncertainties about their performance [22]. The main concern of the use of RAC is its inferior mechanical properties, low density, and high water absorption [22]. As a result, the replacement level of normal aggregates with RCA is still limited by different legislations in multiple countries, with some countries prohibiting its use in structural concrete. For instance, the Spanish code on structural concrete and recent studies [23–24], limit the replacement level of RCA to 20%. However, the Canadian Standards Association (CSA) [25] permits its use in non-structural concrete, subject to quality control procedures to ensure that deleterious materials and other properties of RCA do not have adverse effects on quality. Despite these limitations, some researchers have proposed a higher replacement level of RCA, with upper limits of 50% and 60% suggested in studies [26–28]. Several studies investigated the effect of RCA on the quality of concrete. The following section provides a review on the previous studies conducted to investigate the effect of RCA on different mechanical properties of concrete.

2. Literature review

While previous studies have examined the impact of recycled aggregate on concrete properties for structural applications [13,18–20,22,26–40], recent research has specifically investigated the mechanical and durability characteristics of recycled aggregate concrete for structural use. For instance, Assaad et al. [29] evaluated the impact of recycled aggregate content on concrete mechanical performance, durability, and its bond to steel reinforcement. A drop in the mechanical performance of concrete was observed with an increase in the content of RCA [29]. Likewise, Tang et al. [30] investigated the effect of RCA replacement on the mechanical properties of self-consolidating concrete (SCC) based on the test results of five SCC mixes with various levels of RCA including 0% (control), 25%, 50%, 75%, and 100%. The SCC mixes incorporated fly ash and silica fume. The absorption of RCA was about 7 times higher than that of natural aggregates. Their results did not show any significant negative effect of RCA on the compressive strength of concrete when the replacement level of RCA was up to 50%. Al Martini et at. [31] investigated the effect of RCA on the bond strength development of two different types of reinforcement rebars: coated basalt fiber polymer bars (BFRP) and steel rebars and concrete at RCA replacement level of 40%. They observed that the bond strength of RAC and normal aggregate concrete (NAC) are very comparable, and concluded that concrete with 40% RCA can develop adequate bonding, that is comparable to that of NAC. The study by Ahmed et al. [32] demonstrated the potential of using RAC with a target compressive strength of 25 MPa for construction of concrete blocks and foundation systems using 20–30% RCA content. For construction of a sidewalk, a 32 MPa RCA concrete mix with 30–100% RCA content showed the highest compressive strength at 120 days, and RAC has a higher rate of compressive strength development compared to CC, especially for a 30% RCA substitution [32].

Butler et al. [33] studied the effect of RCA on the mechanical properties of concrete with recycled coarse aggregate and natural fine aggregate. Following several trial mixes, eight concrete mixes (two with NCA and six with RCA) were proportioned to achieve similar compressive strength (between 40 MPa and 60 MPa) and slump (between 75 and 125 mm) by adjusting w/c ratio, cement content, and water content. Some of the RAC mixtures required to incorporate water reducing admixtures to achieve the required strength as well as the desired slump. The recycled coarse aggregate was pre-soaked prior to batching to ensure adequate batch to batch repeatability. It was found that the splitting tensile strength for mixes with 60 MPa was not the same, while it was the same for the group of mixes with 40 MPa. In that research, only one replacement level (100%) of coarse aggregate was used, and no SCMs were incorporated.

Etxeberria et al. [34] investigated the effect of RCA content on compressive strength considering RCA replacement levels of 0% (reference), 25%, 50%, and 100%. The study found that the compressive strength of concrete with 25% RCA was comparable to the reference concrete (0% RCA). Additionally, it was reported that the compressive strength of concrete with 50% RCA was 25% lower than that of the reference mix with 0% RCA. Limbachiya et al. [35] recommended a 25% to 30% RCA replacement level to maintain adequate compressive strength of concrete.

Fakitsas et al. [36] investigated how the use of the high porosity RCA can provide internal curing, that may improve the mechanical properties of self-consolidating concrete containing RCA. The RCA was soaked for three days before being used in concrete. The recycled coarse aggregates were extracted from tested cylinders with compressive strength of 16 MPa. Both RAC and NAC incorporated the same mass of natural fine aggregate. An RCA replacement level of 50% was adopted, and no SCM was used in the mix. The compressive strength was measured at 28 days, 35 days, and 90 days. The results showed that the water absorbed in the recycled coarse aggregate played a positive role in the strength development of RAC by providing internal curing. Interestingly, they observed that the internally cured RAC had higher strength compared to NAC at all ages considered in the study.

Matar and Assaad [37] investigated the rheological property and resulting pressure of self-consolidating RAC on the formwork, intending to assess the integrity of casting structural elements in the presence of vertical steel reinforcements. They found that RAC exhibited lower initial pressure and faster pressure drop rates over time than control self-consolidating concrete. This is likely due to the high roughness of recycled aggregate resulting in an increase in internal friction. The suitability of RAC for use in high performance concrete (HPC) was investigated by Andreu and Miren [38]. Three replacement levels of RCA (20%, 50%, and 100%) obtained from crushed concrete of 100 MPa, 60 MPa, and 40 MPa were considered in the study [38]. Based on the test results, they concluded that RAC can achieve a strength of 60 MPa at 100% replacement level, while up to 50% replacement of RCA can achieve acceptable durability in HPC.

The flexural strength of RAC is another important mechanical property of concrete, as it plays a significant role in concrete structures, particularly, when considering serviceability such as deflection and crack mitigation. Additionally, it contributes significantly to shear capacity, crack control in prestressed concrete structures, and resistance to shrinkage and thermal stresses. Although concrete should have satisfactory tensile strength, it is rarely evaluated quality control on the construction site due to the tedious procedures and time consuming nature of such testing. As a result, engineers tend to rely on measuring the compressive strength to check the quality of concrete and use empirical equations to calculate the flexural tensile strength in terms of the compressive strength. Different models have been proposed to predict the tensile strength of RAC from its compressive strength [39]. However, these models are developed based on limited experimental results. Furthermore, the available models are primarily developed based on the experimental results of conventional concrete.

On the other hand, Rockson et al. [40] investigated the effect of rebar embedment lengths on the bond behavior of Recycled Aggregate Concrete (RAC) in comparison with Natural Aggregate Concrete (NAC). Despite a 36% reduction in compressive strength being recorded for concrete containing 100% recycled coarse and fine aggregate, no impact on the normalized bond strength was observed when using a bond length of 200 mm. Additionally, it was found that the bond strength increased by 18% when using a larger bond length of 300 mm [40].

Although numerous studies have examined the use of recycled aggregate in concrete, there is a significant knowledge gap regarding its impact on commonly used structural green concrete mixtures in the UAE. Therefore, this study aims to address this gap by conducting an in-depth investigation of the impact of recycled aggregates on commonly used structural green concrete mixtures in the UAE.

3. Research significance

Over the last few decades, there has been unprecedented growth and infrastructure development in the UAE, which is still continuing. However, to fight climate change and reduce carbon emissions from the construction sector, the government is looking for various alternative solutions. Since concrete is widely used, the use of RCA and SCMs could be an efficient way to offset the carbon footprint. However, there has not been any research in the past on the use of locally produced RCA in the UAE for structural concrete. Besides, there is no consensus on the replacement rate of RCA to obtain acceptable concrete strength due to differences in the source of RCA. Also, there is a significant knowledge gap regarding its impact on the commonly used structural green concrete mixtures in the UAE. Therefore, it is imperative to investigate the potential applications of RCA obtained from construction and demolition wastes in the UAE. Accordingly, this study investigated, for the first time, the application of RCA obtained from C & D wastes in the UAE, with the significance of addressing the knowledge gap regarding the impact of RCA on commonly used structural green concrete mixtures in the UAE. The effect of recycled aggregate replacement levels along with SCMs on the compressive strength and flexural strength of concrete is investigated at different concrete ages (3-day, 7-day, and 28-day). Moreover, machine learning-based predictive models are developed to predict the compressive and flexural strengths of RAC.

This investigation can play a crucial role in encouraging the UAE construction industry to adopt recycled aggregate in concrete. Currently, the industry is hesitant to use recycled aggregate due to insufficient information and studies on locally available materials, especially for structural concrete. In addition to addressing this knowledge gap, the current study provides recommendations for the optimal percentage of recycled aggregate in green concrete design. By promoting the use of recycled aggregate, the findings of this study can pave the way for a highly sustainable, circular economy-driven practice in the UAE construction industry.

4. Materials and methods

Ordinary Portland cement (ASTM Type 1) and SCMs were used in this investigation. The SCMs included GGBS and fly ash (FA). The SCMs were added to partially replace the ordinary Portland cement, but not coarse aggregates or fine sand. The primary objective of using SCMs in concrete mixtures was to increase the sustainability of concrete by using greener materials with significantly lower carbon dioxide footprints than Portland cement. The sustainability of concrete mixtures was further maximized by incorporating both RCA and SCMs. In addition to reducing the carbon footprint, SCM has other benefits such as reducing the heat of hydration during high temperature exposure. It is worth noting that the use of SCMs is mandatory in Dubai and most Abu Dhabi projects for structural elements. This requirement is in place to maintain a sustainable environment and achieve an extended service life for the structure with a minimum durability lifespan of 50 years. It is worth highlighting that while GGBS had a maximum of 20% particle sizes above 45 μm, the used fly ash had 8% of particles larger than 45 μm (retained on No. 325 sieve) only. A total of seventy (70) concrete mixtures were prepared with different RCA replacement levels and incorporating various SCMs. The first 35 concrete mixtures are tested under uniaxial compression test, while the remaining 35 mixtures are used to investigate the flexural strength of RAC. All mixes had the same w/c ratio of 0.38 and total cementitious materials of 400 kg/m^3, as listed in Table 1. Moreover, GGBS and fly ash were used as SCMs in binary and ternary blends. A low-range polycarboxylate-based admixture conforming to ASTM C494 as type G superplasticizer was used for all mixes in this study. Locally produced natural aggregates and recycled aggregates were used in the mixes. The natural aggregate was crushed limestone obtained from Ras Al-Khaimah, while RCA was supplied from a local recycled aggregate plant in Abu Dhabi. The total aggregate content in the reference mix with 0% RCA is 1880 kg/m^3. The plant recycles construction waste materials received from demolished concrete buildings in Abu Dhabi. Fig. 1 shows the gradation curves for the natural and recycled aggregates along with the BS 882 [41] specification limits; where the x-axis is in logarithmic scale. The nominal maximum size of the aggregates is 20 mm. The coarse fraction of recycled aggregate had an absorption capacity of 6.2%, while the fine fraction had 8.2% absorption capacity in accordance with BS 812–2 [42]. The absorption capacity for the coarse and fine fractions of natural aggregate were 0.5% and 0.90%, respectively. Thus, recycled aggregate used in this study can absorb around 10 times more water than that of the natural aggregate. Furthermore, the saturated surface dry specific gravity (referred also as "relative particle density") of the recycled aggregate as per BS 812–2 is 2.42, while it is about 2.70 for the natural limestone aggregate. Table 1 presents the details of the concrete mixtures used in this study. The absolute volume method (1 m^3) was used to design the concrete mixtures following BRE (Building Research Establishment) concrete mix design method [43]. As such, the total volume of cement and aggregates was kept constant for all mixes. Since the RCA had less saturated surface particle dry density, the mass of aggregates was modified for each mixture based on the replacement percentage of RCA. The saturated surface dry (SSD) condition was adopted in the mix design for all mixes

Table 1
Details of concrete mixtures used in this study.

RCA (%)	100% OPC	Supplementary Cementitious Materials					
		GGBS30%	GGBS50%	GGBS70%	FA20%	FA30%	FA20%+ GGBS30%
0	R0-F0-G0	R0-F20-G0	R0-F30-G0	R0-F0-G30	R0-F0-G50	R0-F0-G70	R0-F20-G30
20	R20-F0-G0	R20-F20-G0	R20-F30-G0	R20-F0-G30	R20-F0-G50	R20-F0-G70	R20-F20-G30
40	R40-F0-G0	R40-F20-G0	R40-F30-G0	R40-F0-G30	R40-F0-G50	R40-F0-G70	R40-F20-G30
60	R60-F0-G0	R60-F20-G0	R60-F30-G0	R60-F0-G30	R60-F0-G50	R60-F0-G70	R60-F20-G30
100	R100-F0-G0	R100-F20-G0	R100-F30-G0	R100-F0-G30	R100-F0-G50	R100-F0-G70	R100-F20-G30

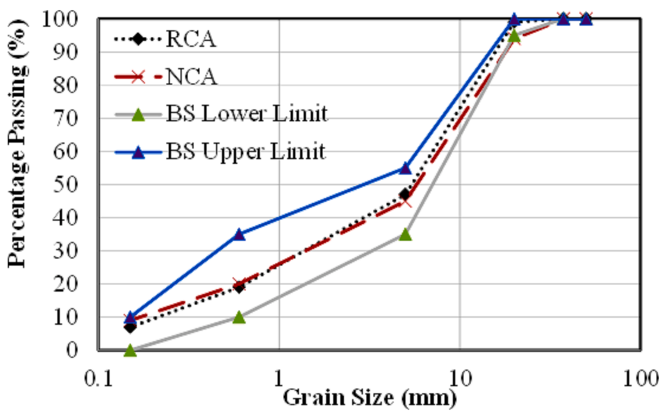


Fig. 1. Grading curves of natural and recycled aggregates against [41] envelope limits [41].

and, accordingly, the water content for each mixture was adjusted based on the absorption and moisture content of aggregates to maintain a constant w/c ratio of 0.38. The compressive strength of each concrete mix was measured at 3, 7, and 28 days, and flexural strength was taken at 28 days in accordance with BS 1881–116.

5. Results and discussion

5.1. Compression test results

The compressive strength of concrete (f_c) is an important parameter to evaluate the quality of concrete, which can be used to calculate various mechanical properties of concrete such as modulus of rupture and modulus of elasticity. It can also be correlated with other parameters such as porosity, durability, and thermal performance [44]. The compressive strength values of all the mixes at the ages of 3,7, and 28 days are shown in Fig. 2. As expected, the compressive strength generally increased with an increase in curing age (Fig. 2) owing to the increase in the formation of hydration products with time that densify concrete structure. As can be observed in Fig. 2, there is a clear effect of the RCA content on concrete compressive strength. In general, the

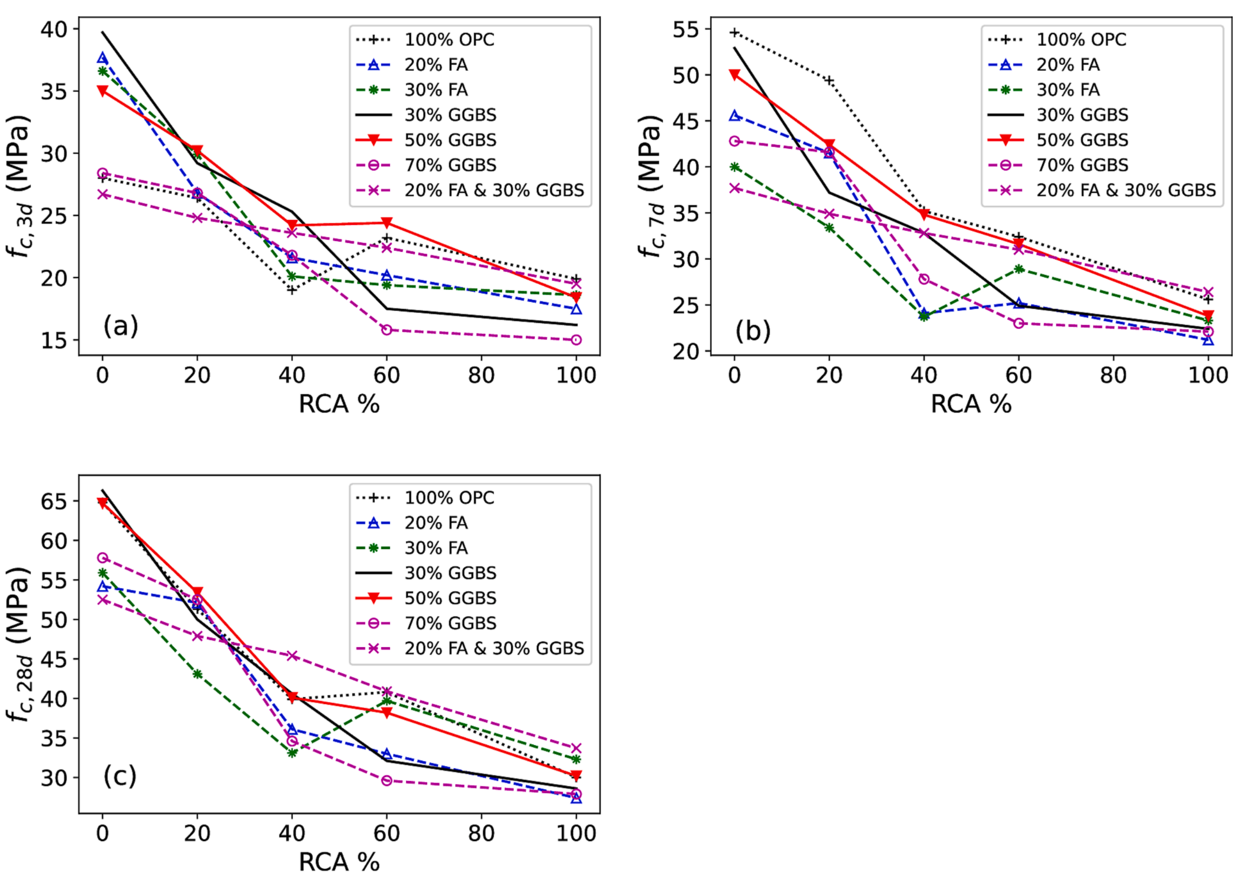


Fig. 2. The effect of RCA replacement level on (a) 3-day, (b) 7-day, and (c) 28-day compressive strengths.

higher the replacement level of RCA, the lower the compressive strength at all ages.

Considering the compressive strength at 3 days, for up to 40% RCA, the mixes with 100% OPC had lower compressive strength than the mixes incorporating SCMs, except for the ternary blends. However, for higher RCA replacement levels, an opposite trend was observed, where replacing OPC with SCMs reduced the concrete compressive strength at 3 days. This is likely due to the high porosity of RCA and its adhered mortar, which reduces the physical effect of SCMs on early strength. Additionally, at at the early age of hydration, the physical filling of SCMs has a larger effect on the compressive strength than the pozzolanic effects of SCMs.

As can observed in Fig. 2b and c, at later ages (7-day and 28-day), the 100% OPC mixes achieved higher strength than most mixes incorporating SCMs. The pozzolanic materials, SCMs, tend to slow down the hydration process, which could be the reason why the 100% OPC mix with 0% RCA had higher 7-day and 28-day strengths than the mixes incorporating SCMs. Thus, the effect of hydration becomes the dominant factor contributing to strength development at later ages.

As shown in Fig. 2, the drop in compressive strength was steep until 40% RCA for all mixes (except the mix with 20% FA & 30% GGBS), and it showed a slight reduction in compressive strength for higher RCA replacement levels. The reduction in compressive strength of concrete with 40% RCA mixtures ranged between 30% and 40%. For instance, as can be observed in Fig. 2, the compressive strength of 50% GGBS mixture with 40% RCA showed 31.0%, 30.0%, and 38.0% decrease in the compression strength at 3, 7, and 28 days, respectively, compared to the reference mix. While the drop of strength for the same mix (50% GGBS) incorporating 100% RCA was 47.0%, 52.0%, and 53.0% at 3, 7, and 28 days, respectively, which is about only 15% drop in compressive strength compared to the same mix with 40% RCA. The ternary blend mix showed superior performance over the other mixes, as RAC incorporating ternary blends had 28-day compressive strength of over 40 MPa for up to 60% RCA replacement. It can be observed that at the age of 3 days, the mix with 30% FA experienced a sharp drop in the compressive strength up to 40% before reaching a plateau at and beyond 40% RCA.

For the 7-day compressive strength, generally, a similar trend to that of the 3-day compressive strength was observed, in which the compressive strength dropped with an increase in the RCA replacement level, as shown in Fig. 2b. Unlike the 3-day compressive strength, the concrete mixes with RCA and incorporating 100% OPC had higher values than the binary and ternary blend mixes. The difference in the strength between 100% OPC and SCMs mixes became less noticeable when the replacement level of RCA was high (see Fig. 2b). Looking at the compressive strength curve for 30% FA, it can be noticed that this mix had similar behavior to its 3-day compressive strength, as it dropped sharply for up to 40% RCA, but the strength of this mix sharply increased after 40% RCA and decreased after 60% replacement.

As shown in Fig. 2c, all mixes with 0% RCA had a 28-day compressive strength higher than the design compressive strength of 40 MPa. Moreover, some of the concrete mixes with RCA achieved 28-day compressive strength values that exceeded the design target strength of 40 MPa, as can be seen in Fig. 2. It can be observed that the 28-day compressive strength for concrete mixes with 0% RCA and incorporating binary blends of GGBS (30% and 50%) were higher than the strength of the remaining four mixes. This can be attributed to the noticeably slower rate of hydration in the remaining mixtures of the same group of 0% recycled aggregate, especially when fly ash or GGBS at a higher percentage (such as above 50%) of the total cement content was incorporated. The aforementioned mixes had a delay in strength gain due to the late reaction of slag with generated calcium-hydroxide to produce further calcium-silicate-hydrate. The lowest values of 28-day compressive strength were observed for mixtures with 100% RCA at all ages. It can be observed that high content of FA (30%) was beneficial for mixes with high replacement of RCA (60% and 100%), as the 28-day compressive strength of these mixes was higher than the other mixes (except for the ternary blend mix). The reason for the increased compressive strength of concrete mix incorporating 30% FA with increased RCA replacement ratio unlike other mixes that showed reduced compressive strength with increased RCA percentage, may be attributed to the higher fineness of FA compared with GGBS and cement. It should be noted that the fineness of the used FA was 855 m^2/kg, while it was 407 m^2/kg and 343 m^2/kg for GGBS and cement, respectively.

All the concrete mixes with 20% RCA had 28-day compressive strength of over 45 MPa which is higher than the design strength of 40 MPa. The percentage drop in the compressive strength of the RAC related to the reference mixture ranged between 6% and 26%. Thus, concrete with 20% RCA can still be acceptable to be used for structural applications. The lowest 28-day compressive strength (27.4 MPa) is reported for 20% FA with 100% RCA. However, this strength is still acceptable to be used for nonstructural and infrastructure applications. The RCA mixtures incorporating FA experienced an average reduction in 28-day compressive strength of 15% and 50% for 20% RCA and 100% RCA, respectively. On the other hand, the ternary blend mixtures (FA + GGBS) had the lowest percentage drop in 28-day compressive strength for both 20% and 100% RCA that ranged between 7.8% (20% RCA) and 30.9% (for 100% RCA). It can be argued that RCA may have a slightly positive influence on the strength, due likely to the adhered mortar and rough surfaces.

Taking the above into consideration, while a previous study by Tang et al. [30] reported an insignificant reduction in strength with an increase in recycled aggregate content, and a similar study by Ahmed et al. [32] reported no effect on concrete designed for concrete block and sidewalk construction with strengths of 25 MPa and 32 MPa, respectively, the results obtained in this study were more comparable to the findings of Etxeberria et al. [34] where a noticeable compressive strength drop of 25% was recorded starting from 50% recycled aggregate level of content in the mixture.

To further investigate the effect of RCA on compressive strength, the percentage reduction in the compressive strength relative to the reference mix (100% OPC and 0% RCA) was calculated at each of the three testing ages using Eq. (1), and the results are plotted in Fig. 3.

$$Reduction f_c(\%) = \frac{f_c - f_{c(ref)}}{f_{c(ref)}} \times 100 \quad (1)$$

where $f_{c(ref)}$ is the compressive strength value for 0% RCA (reference mix) at each testing age.

As shown in Fig. 3, the difference between the compressive strength of RAC and the reference mix gradually increased with the increase in the RCA content. The rate of the reduction of the 3-day compressive strength ranges between 2.8% and 20% with the lowest reduction corresponding to the mix with 100% OPC and 20% RCA, and the largest reduction corresponding to the mix with 30% GGBS and 100% RCA, as shown in Fig. 3. The reduction rate for the 7-day compressive strength ranged between 5.3% (for the mix with 30% FA and 20% RCA) and 30% (for the mix with 30% GGBS and 100% RCA). For the 28-day compressive strength, the rate of reduction was between 5% and 38%, which corresponds to the ternary blend mix with 20% RCA and the mix with 30% GGBS and 100% RCA, respectively. Based on the results in Fig. 2, the mixes incorporating 30% GGBS showed the highest rate of reduction in compressive strength at all three testing ages. The compressive strength of RAC experienced the highest rate of reduction at the 28-day strength followed by 7-day strength and 3-day strength. Thus, the difference in the strength between the reference and the RCA mixes gradually increased with curing age. This may suggest that the strength of the weak particles in the adhered mortar is the main factor that influences the strength development in RAC. In the later stages of hydration, more of the adhered mortar will hydrate causing larger difference in the strength between the reference concrete mix and the RAC that increases with higher RCA content.

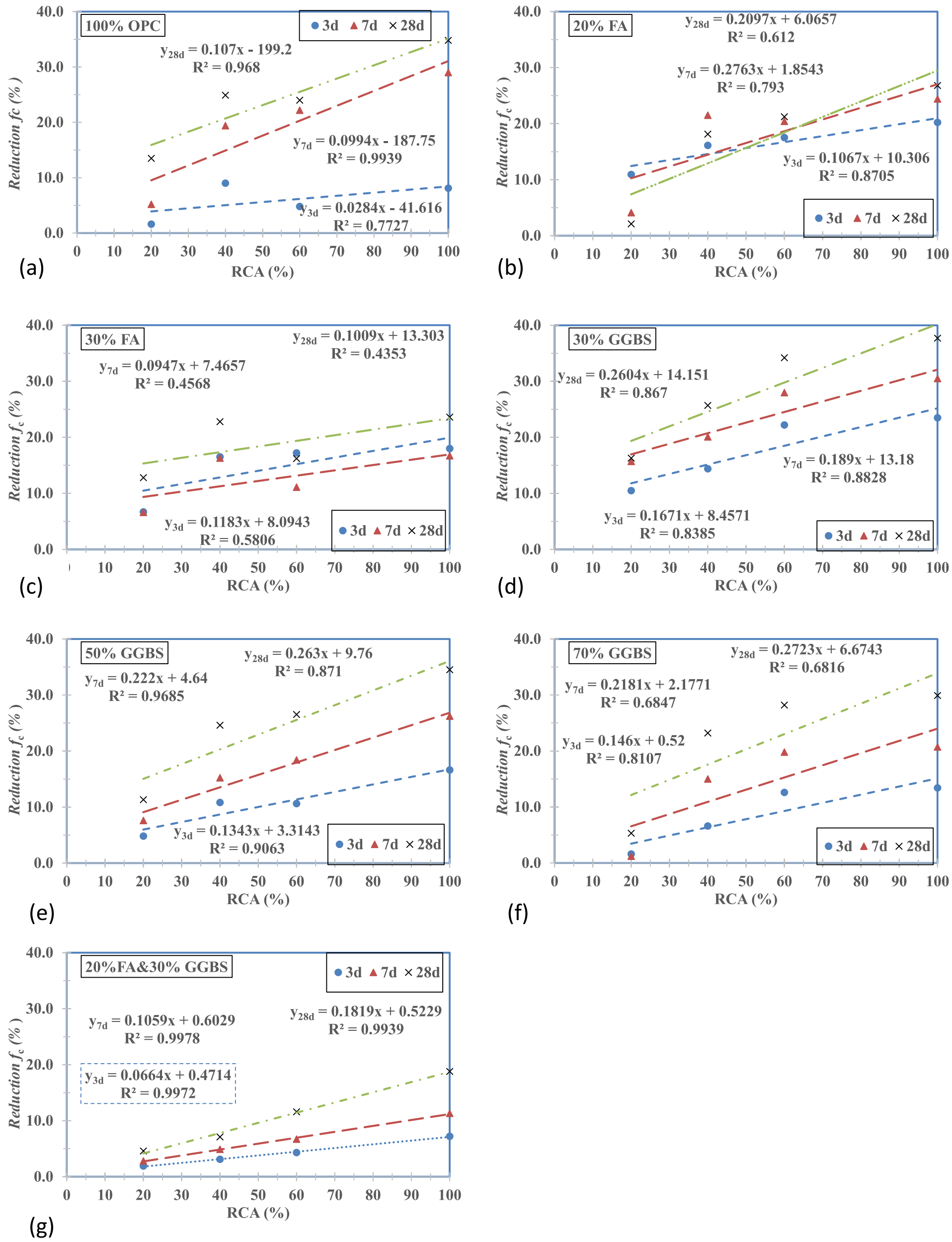


Fig. 3. Reduction rate of compressive strength of RCA mixtures relative to that of the reference concrete mix.

5.2. Flexural test results

The flexural test results demonstrated the influence of both RCA and SCMs contents on the flexural strength of concrete. Similar to compressive strength, the flexural strength decreased with an increase in the content of RCA, as can be observed in Fig. 4 which shows the effect of RCA content on the 28-day flexural strength of tested concrete mixtures. For instance, the flexural strength of the mixtures with 100% RCA dropped by about 48% from similar mixtures without RCA (Fig. 4). Similar results have been reported in the previous study conducted by Yang et al. [27]. This behavior can be attributed to the bond between paste and aggregate in RAC, which is inferior to those of NCA. As reported in the literature, coarse aggregates are usually oriented with the longitudinal direction of the beam (the bending axis) [45]. This indicates that the interfacial bond between the cement paste and aggregate surface is more effective along the length of the specimen [45]. Thus, the lower flexural strength of RCA mixtures compared to NCA mixtures could be attributed to the better orientation of NCA compared

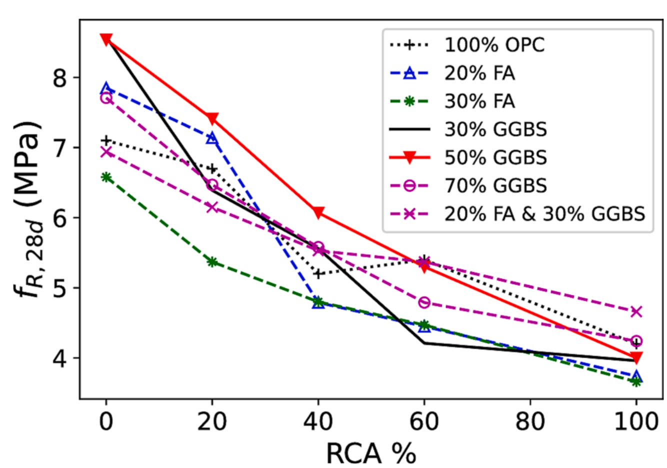


Fig. 4. Effect of recycled aggregate content on concrete's flexural strength.

to RCA which resulted in a better bond between NCA and cement paste. In general, the drop of the flexural strength was sharp up to 40% RCA, and then it became smaller afterwards. The highest drop in flexural strength of 48.45% was noted for the 30% FA with 100% RCA. The highest flexural strength for mixes with zero recycled aggregates can be observed for the mixture with 30% GGBS and it was 8.58 MPa. It can be argued that this dosage of GGBS is beneficial for the flexural strength of RAC. The flexural results of the ternary blend mixes had the highest flexural strength when the content of RCA is high (60% and 100% RCA). The mixture with 30% FA and incorporating 100% RCA achieved 3.67 MPa which is recognized as the lowest achieved flexural strength.

Despite the aforementioned findings generally aligning with the overall conclusions of several previous studies, where a higher replacement of NCA by RCA leads to a greater drop in flexural strength, Elansary et al. [46] reported that incorporating RCA at 30% and 50% replacement levels from the coarse fraction does not reduce the mechanical properties of concrete including its flexural strength. Another investigation showed that replacing NCA with a maximum of 30% of RCA had a negligible impact on the flexural strength of concrete by having a minimal reduction of 3.5% only [47].

5.3. Statistical analysis

In this section, the one-way analysis of variance (ANOVA) was performed to investigate the significance of the effect of RCA replacement level on the compressive strength at each of the three tested ages (3-day, 7-day, and 28-day) as well as the flexural strength of the mixes. The test of the hypothesis is given by:

Null hypothesis: H_0: There is no significant difference between the strength (compressive strength or flexural strength) of the mixes with different RCA replacement levels for a given age.

Alternative hypothesis: H1: There is some remarkable difference between the strength (compressive strength or flexural strength) of the mixes with different RCA replacement levels for a given age.

The analysis was performed at a significance level (α) of 0.05, which corresponds to a 95% (two-way) confidence level.

5.3.1. Results of statistical analysis for compressive strength

The ANOVA results are shown in Table 2 for all testing ages. The results of the analysis showed that the P-value for all testing ages was less than the chosen significance level of 0.05 which gives enough evidence to reject the null hypothesis and conclude that the change in RCA replacement level has a statistically significant effect on the compressive strength. This conclusion can also be drawn when comparing the F values presented in Table 2 with the corresponding F critical values as all F values are larger than the F critical values, which will result in the rejection of the null hypothesis.

To check which of the samples, in terms of compressive strength results, represent two different populations, the post hoc test was performed for each of the available pair options of the results at each test age. The p-values from the post hoc tests for all three test ages and all pairs were smaller than 0.05 indicating that they have significant variation from each other except for the pair of RCA40% and RCA60% for all ages that showed a p-value larger than 0.05. To calculate how much proportion of the variability in the compressive strength results are due to the difference in the RCA replacement level, the Eta Squared (η^2) was calculated and results are presented in Table 3. The results of η^2 in Table 3 indicated that 77%, 78%, and 88% of the difference between the compressive results at 3-day, 7-day and 28-day test age, respectively, are due to the difference in the RCA replacement level. This indicates that the RCA has a higher impact on the results of long-term compressive strength than short-term compressive strength.

Fig. 5 shows the boxplots for the five groups of concrete mixtures to investigate the distribution of compressive strength due to the variation of SCMs for each RCA replacement. The medians and mean of the results for the five groups are shown in the figure as the middle straight line and the X in the boxplot, respectively. They both in general decrease with the increase of the replacement level of RCA. This is consistent with previous results discussed earlier. The results shown in the boxplot and the variance values for each of the RCA replacement level shown in Table 4 indicates that the variability of the compressive strength results due to SCMs for all ages is the highest for the group with zero RCA replacement and is the smallest for the group with 100% RCA replacement. This gives an indication that the variation in the SCMs has the largest and least effect on the compressive strength results at all ages in the case of zero RCA and 100% RCA replacement levels, respectively.

The factorial effect of RCA on compressive strength was studied and the results are shown as box plots in Fig. 6. Each group in the presented box plots represents a mixture with specific cementitious materials. For example, the group named F0-G30 is for the binary blend mixture with zero fly ash and 30% GGBS, while group F20-G30 is for the ternary blend mixture with 20% FA and 30% GGBS. It can be observed that the compressive strength of the ternary blend mixture was less affected by the variation of RCA replacement level among the other groups, as it showed the least variability (least variance) in the compressive strength considering the factor of RCA replacement level. This was more evident for 3-day and 7-day testing ages (Fig. 6).

Table 3
The η^2 results from ANOVA for compressive strength of the mixes with different RCA replacement levels at different testing ages.

Test Age	η^2
3-day	0.777
7-day	0.780
28-day	0.878

Table 2
ANOVA results for compressive strength of the mixes with different RCA replacement levels at different testing ages.

Test Age	Source of Variation	SS	df	MS	F	p-value	F crit
3-day	Between Groups	1056.427	4	264.1069	26.18302	2.08E-09	2.689628
	Within Groups	302.6086	30	10.08695			
	Total	1359.036	34				
7-day	Between Groups	2406.971	4	601.7429	26.56545	1.76E-09	2.689628
	Within Groups	679.54	30	22.65133			
	Total	3086.511	34				
28-day	Between Groups	3873.567	4	968.3919	53.89793	2.85E-13	2.689628
	Within Groups	539.0143	30	17.96714			
	Total	4412.582	34				

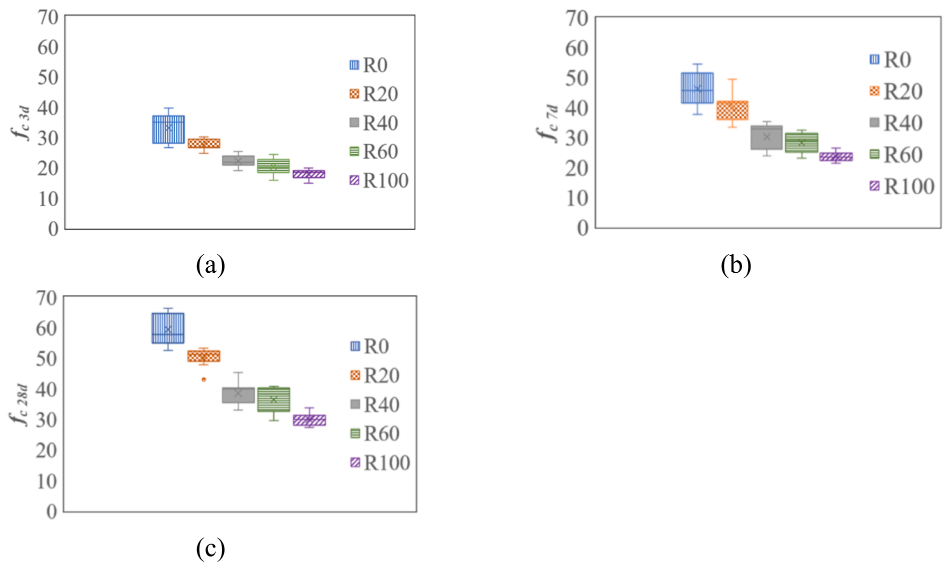


Fig. 5. Boxplots of compressive strength with different replacement of RCA and variation of SCMs.

Table 4
The variance of the compressive strength at each testing age for each RCA replacement level.

Groups	Variance		
	f_{c3d}	f_{c7d}	f_{c28d}
R0	28.26952	42.08238	32.38286
R20	4.175714	29.38619	12.65286
R40	5.122381	24.14905	17.77619
R60	9.741429	14.07286	21.66571
R100	3.125714	3.56619	5.358095

5.3.2. *Results of statistical analysis for flexural strength*

The ANOVA results for flexural strength are presented in Table 5. The analysis results showed that the p-value for all testing ages was less than the chosen significance level of 0.05, which gives enough evidence to reject the null hypothesis and conclude that the effect of the change in the RCA replacement level on the flexural tensile strength is statistically significant. This conclusion can also be drawn when comparing the F values shown in the table with the corresponding F critical values, as all F values are larger than the F critical values, which will result in the rejection of the null hypothesis.

Furthermore, the p-value from the post hoc tests for all pairs was smaller than 0.05 indicating that they have significant variation from each other, as listed in Table 6. The η^2 was also calculated for the flexural strength and was found to be equal to 0.848 which indicates that more than 84% of the variability in the flexural strength results is due to the difference in the RCA replacement levels.

Fig. 7 shows the effect of the two investigated factors i.e., RCA and SCMs on the flexural strength of concrete. The medians and mean of each group in Fig. 7a decreased with the increase in RCA replacement level. It can be also observed that the group with 100% RCA had the lowest variability (least variance as shown in Table 6) for the flexural strength, indicating that concrete with 100% RCA is least affected by the factor of SCMs replacement and combinations. Furthermore, the mixture with ternary blend had slightly lower variability (as indicated also by the variance values) than the other groups, and it indicates that is marginally less affected by the RCA variation if compared with other

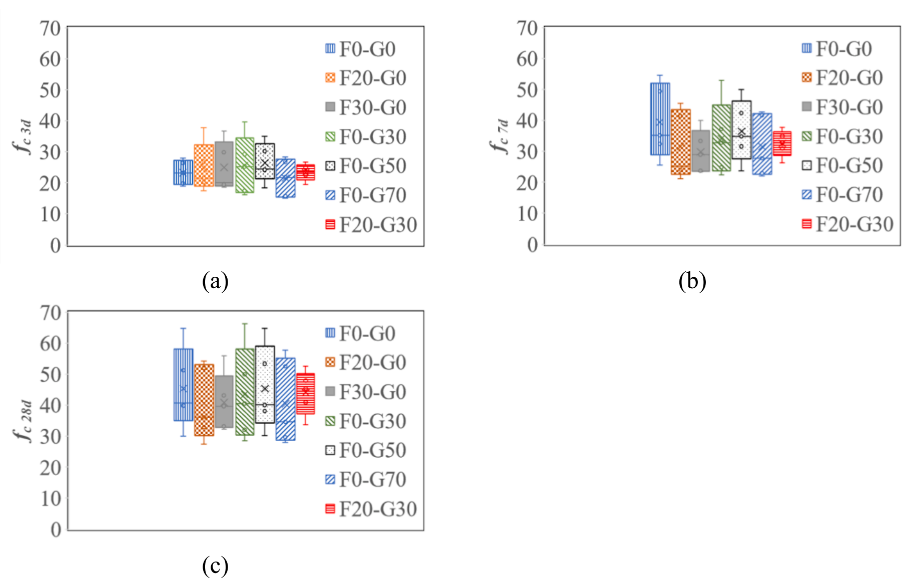


Fig. 6. Box Plots of compressive strength with different replacement of SCMs and variation of RCA replacement level.

Table 5
ANOVA results for flexural tensile strength of the mixes with different RCA replacement levels at different testing ages.

Source of Variation	SS	df	MS	F	p-value	F critical
Between Groups	54.82027	4	13.70507	41.96762	7.05733E-12	2.689628
Within Groups	9.796886	30	0.326563			
Total	64.61715	34				

Table 6
The variance of flexural strength at each testing age for each RCA replacement level.

Groups	R0	R20	R40	R60	R100
Variance	0.6072	0.44795	0.21425	0.2488	0.11463

groups.

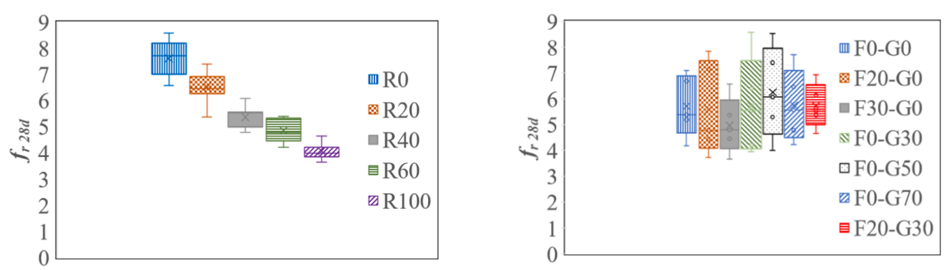
5.4. Relationship between early age and 28-day compressive strength of RAC

The compressive strength results were plotted in Fig. 8 to come up with a general equation by correlating the 28-day compressive strength to the 3-day and 7-day compressive strengths using a power regression function. The following equations express the relationship between 28-day strength and early age (3-day and 7-day) strength with good correlation, which seems a promising equation to predict the 28-day compressive strength at an early stage for concrete mixes incorporating different RCA replacement levels:

$$f_{c,28d} = 2.0763\left(f_{c,3d}\right)^{0.948} \tag{2a}$$

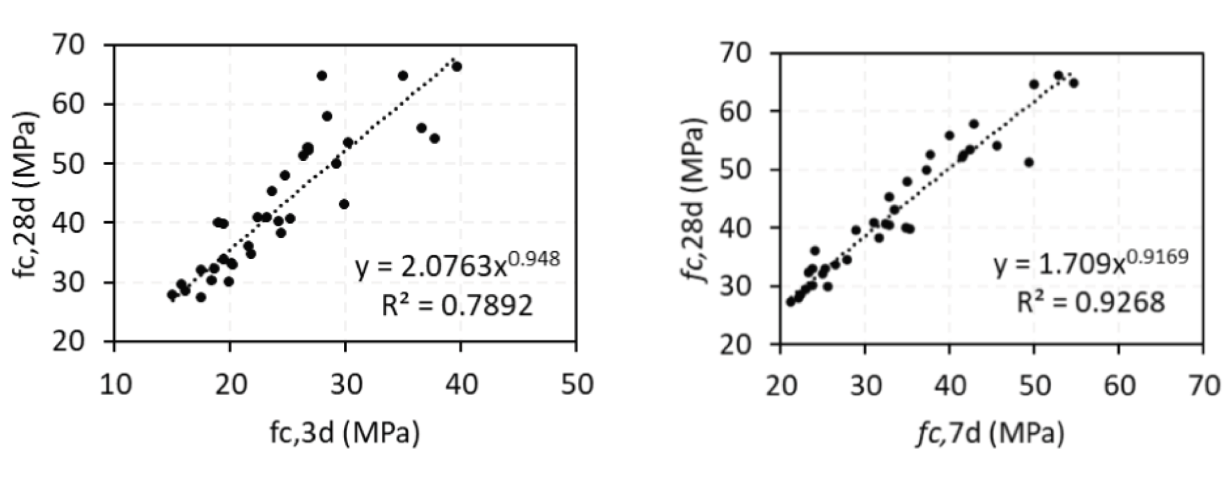
$$f_{c,28d} = 1.709\left(f_{c,7d}\right)^{0.917} \tag{2b}$$

Eq. (2) above is useful for quality control that can save the time of waiting for 28-day of curing required to know the 28-day strength. However, further research should be conducted considering more experimental test results and additional parameters. Moreover, it is vital to develop a more fundamental predictive model for the compressive strength of RAC based on its constituent materials, and independent of the early age strength. Similarly, although there are several models for predicting the flexural strength of concrete from its compressive strength, these models were developed for conventional concrete. As such, there is a need to develop an accurate predictive model that is valid for RAC. Thus, in the following section tree-based machine learning models are used to accurately model the compressive strength and flexural strength of RAC.



(a) (b)

Fig. 7. Box Plots of modulus of rupture (a) with different replacement of RCA and variation of SCMs and (b) with different replacement of SCMs and variation of RCA.



(a) (b)

Fig. 8. Relationship between early age and 28-day compressive strengths.

6. Machine learning-based strength predictive models

In this section, different machine learning models are used to predict the 28-day compressive strength and flexural strength of recycled aggregate concrete. A database of RAC compiled by Ahmad et al. [48], in addition to those tested in this study, is used to develop the compressive strength model. Following data pre-processing and cleaning of outliers, the final database for the compressive strength prediction comprised 323 data points. Data pre-processing for this study involved identifying the input vector, cleaning outliers, normalizing the data, and splitting the database into training and test datasets. The outliers were identified using the widely-used Grubb's test in Python [49], and the database was then normalized to a range between 0 and 1 using the following equation:

$$x_n = \frac{x_{orig} - x_{min}}{x_{max} - x_{min}} \quad (3)$$

where x_{orig} is the original value of the variable, x_n represents the normalized value of the same variable, x_{min} and x_{max} are the minimum and maximum values of x_{orig}, respectively.

The input vector comprised nine parameters, namely, the content of water (W), cement (C), FA, NCA, RCA replacement level, and superplasticizer (SP), maximum aggregate size (S_{agg}), density (ρ_{agg}), and water absorption (ω_{agg}) of RCA. Fig. 9 shows the statistical distributions of all input variables along with the Pearson correlation coefficient between each pair of input parameters.

In existing models for NAC, the flexural strength is expressed as a function of its 28-day compressive strength. However, previous studies showed that water absorption of RCA also influences its flexural strength, in addition to its compressive strength [50]. Accordingly, this study proposed machine learning-based model for accurate prediction of the flexural strength of RAC using the 28-day compressive strength of RAC and its water absorption as input features. In addition to the test results in this study, flexural strength test results compiled by Yuan et al. [50] were utilized to train the ML models. The final database for flexural strength prediction comprised a total of 96 data points. Fig. 10 shows the statistical distribution of the two input parameters for the flexural strength prediction models.

6.1. Overview of machine learning models

In this study, different decision tree (DT) based ML models are used. The decision trees algorithm is a supervised machine learning model that bears a resemblance to a flowchart in which the top (root) node represents the most relevant feature, while the test on the attribute is specified in the internal nodes [51]. Despite its simplicity and ease to

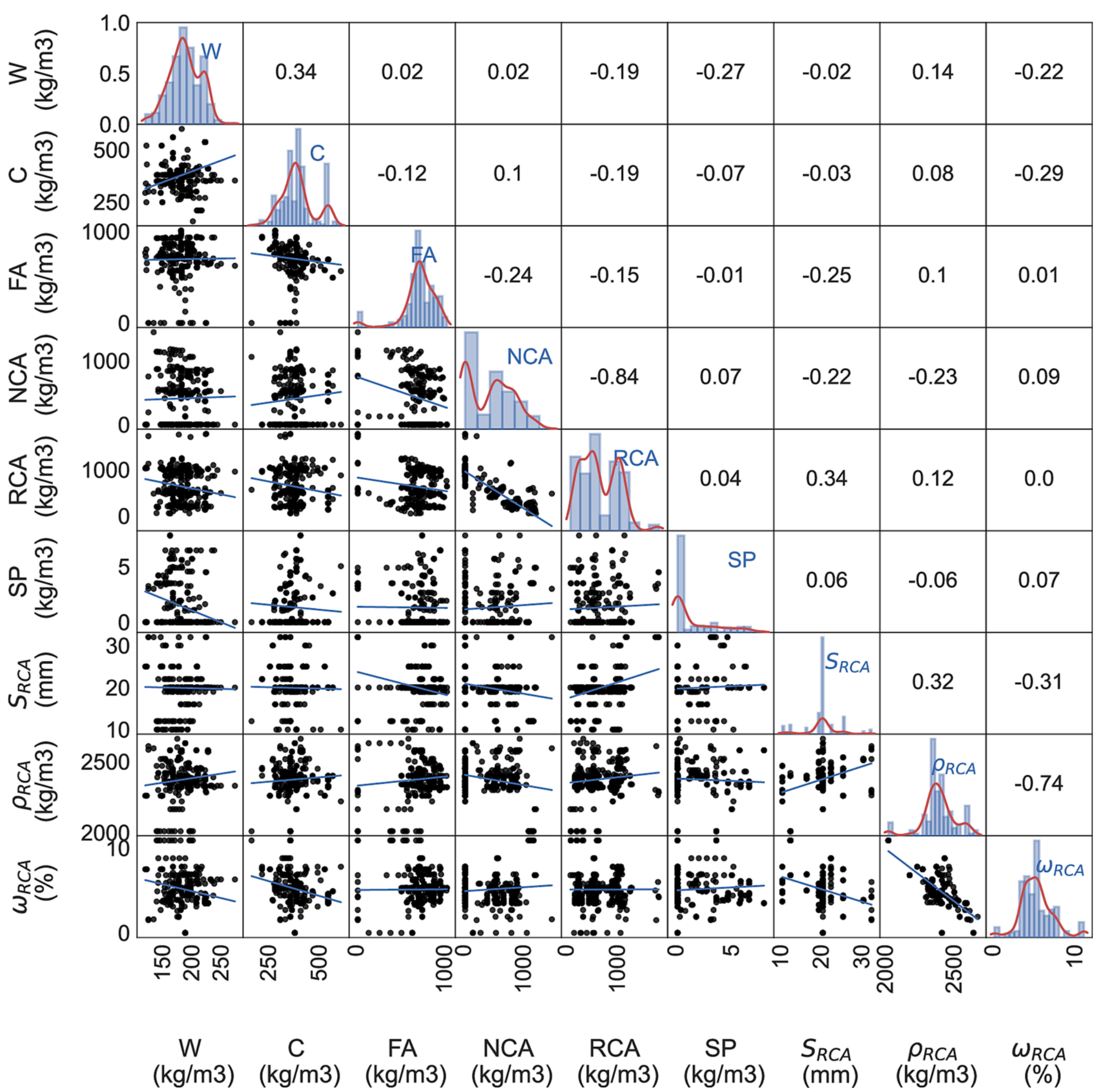


Fig. 9. Distribution of compressive strength database used in this study.

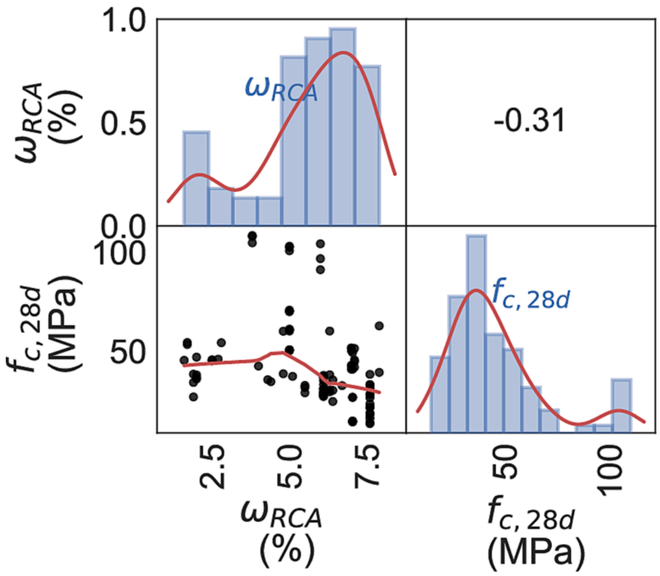


Fig. 10. Distribution of flexural strength database used in this study.

understand and interpret, the DT algorithm suffers from high bias, high variance, and low generalization ability. However, numerous DT models can be integrated into an ensemble model to improve the generalization ability of the model and produce a strong model. Boosting ensemble models are one of the most widely used and powerful ensemble models in which the base learners (usually DTs) are combined sequentially to produce a strong model. Adaptive boosting (AdaBoost), gradient boosting machine (GBM), and extreme gradient boosting (XGB) are the three most powerful boosting algorithms. In AdaBoost, the first base learner is trained on the training examples by assigning an equal weight of $\{w_{1,i} = 1/N, \forall i\}$ to each observation [52]. In the following iterations, a new learner is added by increasing the weight of wrongly predicted observations. Similar to AdaBoost, GBM aggregates multiple base learners to form a strong learner; however, it uses a gradient descent method to improve the shortcomings of the previous model (s) unlike the AdaBoost model that improves the model efficiency by increasing the weight of wrongly predicted observations. Extreme gradient boosting is a variant of boosting algorithm developed as an efficient implementation of GBM [53]. It adds a regularization term in the objective function In order to overcome overfitting and reduce model complexity [53]. The hyperparameters of each model are optimized using grid search combined with a standard K-fold cross-validation technique (K = 10 in this study). Moreover, the predictive performance of the models is assessed using the following statistical performance indices including mean absolute percentage error (MAPE), root mean squared error (RMSE), and coefficient of determination (R^2):

- Mean absolute error (MAE):

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|Y_i - \widehat{Y}_i| \tag{4}$$

- Mean absolute percentage error (MAPE):

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{Y_i - \widehat{Y}_i}{Y_i}\right| \tag{5}$$

- Root mean squared error (RMSE):

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Y_i - \widehat{Y}_i)^2} \tag{6}$$

- Coefficient of determination (R^2):

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(Y_i - \widehat{Y}_i)^2}{\sum_{i=1}^{N}(Y_i - \overline{Y})^2} \tag{7}$$

where $\widehat{Y}_i$ is the ith predicted response value, and $\overline{Y}$ is the mean of the response value Y.

A comprehensive review of the machine learning models and the hyperparameter optimization procedures can be referred elsewhere [54].

6.2. Predictive performance of the ML models

Fig. 11 shows the scatter plots of the experimental 28-day compressive strength ($f_{c,exp}$) versus the corresponding predicted values ($f_{c,pred}$) based on DT, AdaBoost, GBM, and XGB, respectively. As can be observed in these figures, the scatter points are located very close to the ideal y = x equity line for all models apart from DT, which demonstrates the predictive performance of the proposed boosting ensemble models. It is evident from Fig. 11a that the DT is generally not capable of achieving accurate predictions for the compressive strength, as a significant portion of the samples is either highly overpredicted or highly underpredicted. In contrast, the tree-based boosting ensemble models; namely, AdaBoost, GBM, and XGB showed remarkable improvement in the prediction performance compared to the DT model, as shown in Fig. 11a – d.

Like the compressive strength, the flexural strength of RAC is best predicted using the XGB, as can be observed in Fig. 12 which shows the scatter plots of the experimental versus predicted flexural strength based on the four ML models. Generally, all models including the DT model showed good predictive performance on both the training and test datasets (with $R^2 \geq 93.6$).

The performance of the models is further evaluated through the four indices, i.e., R^2, MAE, RMSE, and MAPE, and results are plotted in Fig. 13 and Fig. 14 for the compressive strength and flexural strength predictions, respectively. The results of the performance indicators in Fig. 13 confirmed that the XGB model is the most accurate model with the highest R^2 = 96.5% and lowest MAE, MAPE, and RMSE values of 2.36 MPa, 6.04%, and 3.31 MPa, respectively, on the test dataset. Similarly, as can be observed in Fig. 14, the XGB model showed the highest predictive performance on both the training and test datasets. This is a clear indication that the proposed XGB model can be considered the best model for predicting the compressive strength and flexural strength of RAC.

7. Conclusions

This study investigated potential applications of concrete incorporating recycled aggregates from locally demolished buildings in UAE based on experimental, analytical, and machine learning-based studies, to encourage and promote the implementation of a circular economy through recycling and reuse of concrete in structural applications. This will be in line with the efforts undertaken in UAE to promote sustainability and circular economy in the construction industry, to preserve natural resources, and to attenuate the construction wastes disposed in landfill sites and their harmful impacts on the environment. The RCA used in this study was obtained from a recycling plant near Abu Dhabi, UAE which recycles the construction wastes collected from demolished buildings in Abu Dhabi. A total of seventy (70) concrete mixes were designed and tested to investigate the compressive strength and flexural

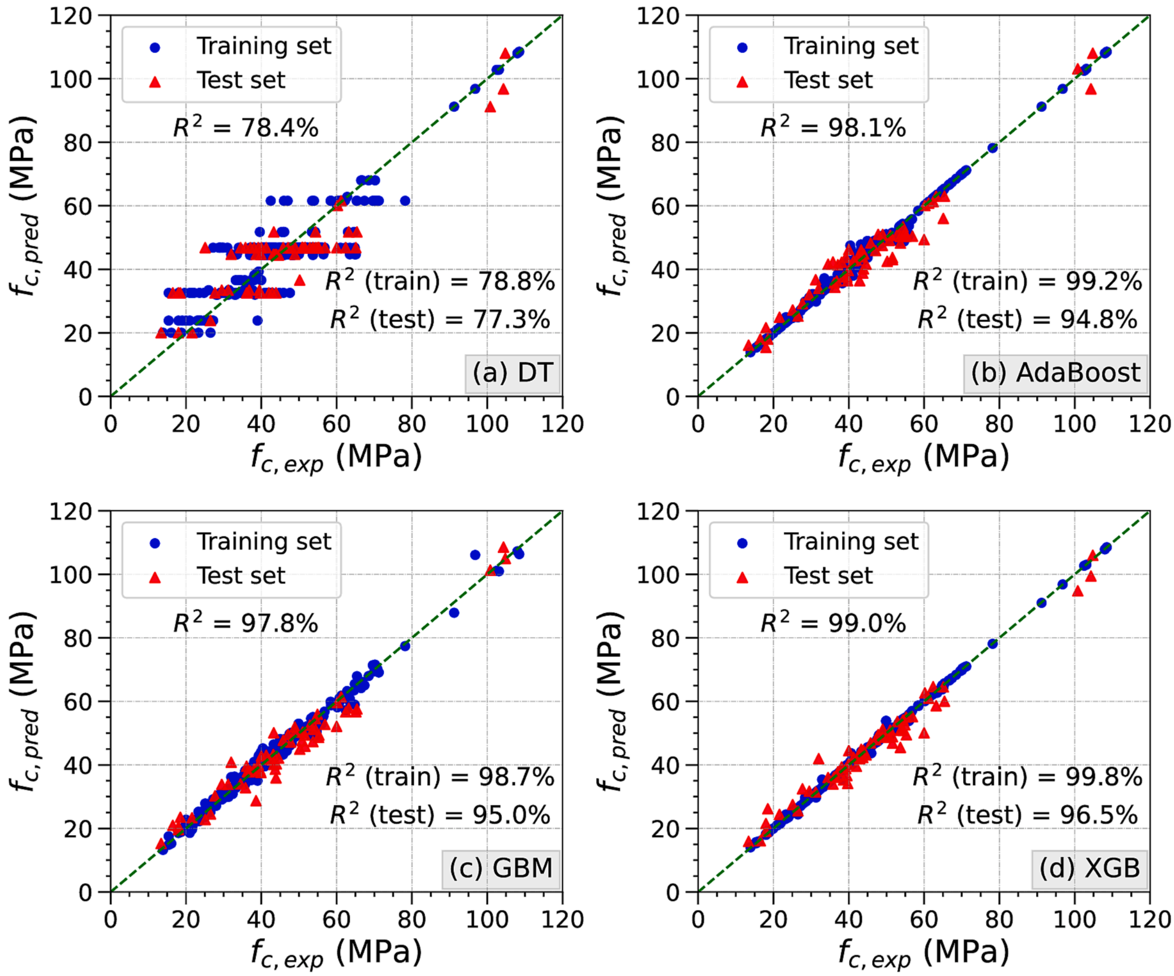


Fig. 11. Scatter plots of experimental versus predicted 28-day compressive strength.

strength of the RAC at three different periods (3-day, 7-day, and 28-day). Moreover, machine learning-based accurate models are proposed to predict the 28-day compressive strength as well as the flexural strength of RAC. The following conclusions can be drawn from this study:

1. The increase in the percentage replacement of NCA with RCA adversely affected the strength of concrete, and higher replacement of RCA produced weaker concrete in terms of compressive strength and flexural strength.
2. Generally, the mixes incorporating 30% GGBS showed the highest rate of reduction in compressive strength (compared to the reference mix) at all the tested ages (3-day, 7-day, and 28-day).
3. At the early concrete age (3-day), generally, the mixes with 100% OPC showed lower compressive strength compared to the mixes that incorporate SCMs (except for the ternary blends).
4. A high FA replacement level (30%) is recommended to be used in mixes with high content of RCA (60%, 100%), as the 28-day compressive strength of these mixes was higher than the other mixes (except the ternary blend mix).
5. Concrete incorporating 20% RCA showed acceptable 28-day compressive strength that exceeded the design strength and can be proposed to be used for structural applications.
6. The incorporation of ternary blends was beneficial to the strength of RAC, as all ternary blend mixes (except the 100% RCA) had 28-day compressive strength that exceeded the structural design strength. Similarly, the flexural results of the ternary blend mixes were superior, as they achieved the highest modulus of rupture for high contents of RCA (60% and 100% RCA). Thus, they can be proposed for structural use.
7. RCA with up to 60% replacement level can be used in producing sustainable concrete with acceptable hardened properties. This will encourage the sustainable development of concrete in the UAE.
8. The Eta Squared ($^{\eta 2}$) calculated for the compressive strength in the statistical analysis showed values larger than 77%, indicating that more than 77% of the difference between compressive strength results of each age is due to RCA. The results also indicated that the RCA replacement level has a higher contribution to the variability of the compressive strength results for the long term versus short term, as the results of $^{\eta 2}$ for 28-day was 0.88 (the highest). For the flexural strength, the calculated $^{\eta 2}$ was 0.848 indicating that more than 84% of the variability in the flexural strength results is due to the difference in the RCA replacement levels.
9. The results of the statistical analysis showed that the effect of SCMs on the variation of compressive strength diminishes when RCA is incorporated, i.e., the variability of the results was the highest for 0% RCA mixes and the lowest for 100% RCA mixes.
10. The factorial study showed that the ternary blend mix is the least influenced mix by the variation of RCA replacement level, as the compressive strengths for that mix had the minimum variations as a function of RCA content.
11. The proposed predictive equation in this study for the 28-day compressive strength from its 3-day compressive strength was acceptable with R^2 >0.80. Moreover, the proposed equation to

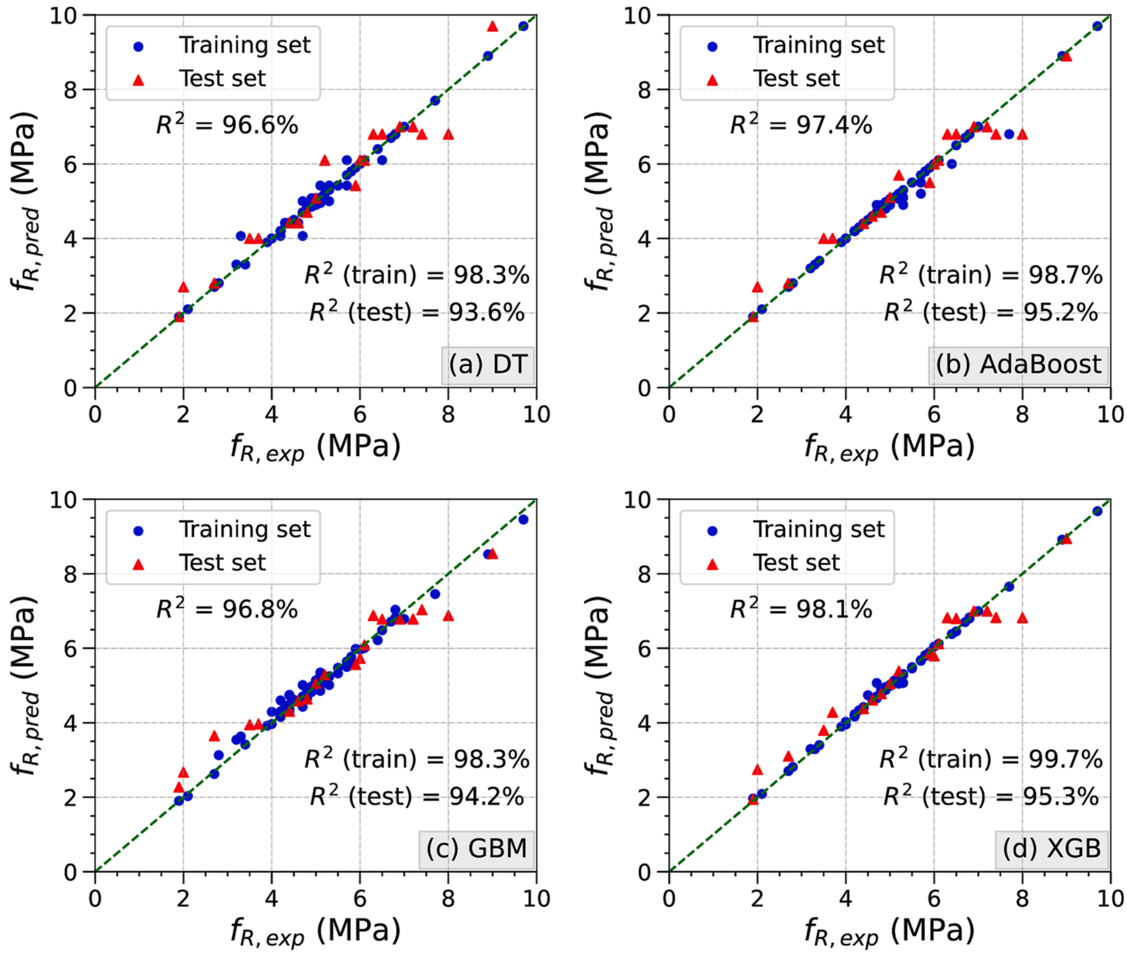


Fig. 12. Scatter plots of experimental versus predicted flexural strength.

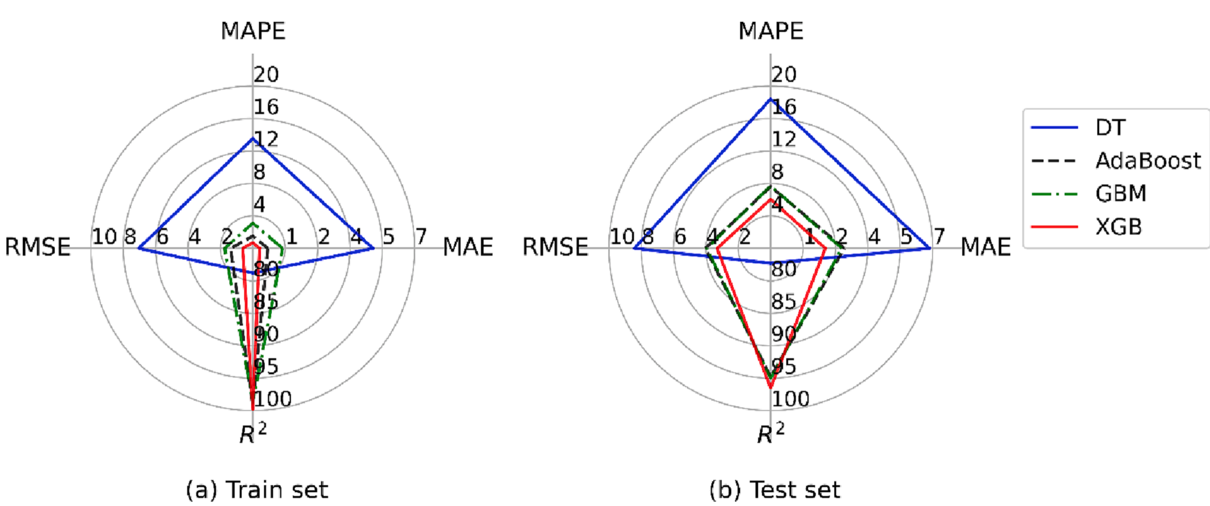


Fig. 13. Performance of the ML models in predicting the 28-day compressive strength of RAC.

predict 28-day compressive strength from its 7-day compressive strength proved to be satisfactory R^2 >0.90. However, this model requires experimental results of early age concrete strength, which limits its application.

12. Tree- and boosting ensemble-based machine learning models are developed for predicting the compressive strength and flexural strength of RAC based on its constituent materials, and independent of its early age strength. Generally, the developed models are capable of predicting the compressive strength and flexural strength of mixes containing recycled concrete aggregate with reasonable accuracy. Among the considered ML models, DT showed the least predictive accuracy, while the extreme gradient boosting ensemble model showed the highest predictive performance.

Future studies will investigate the long-term performance of

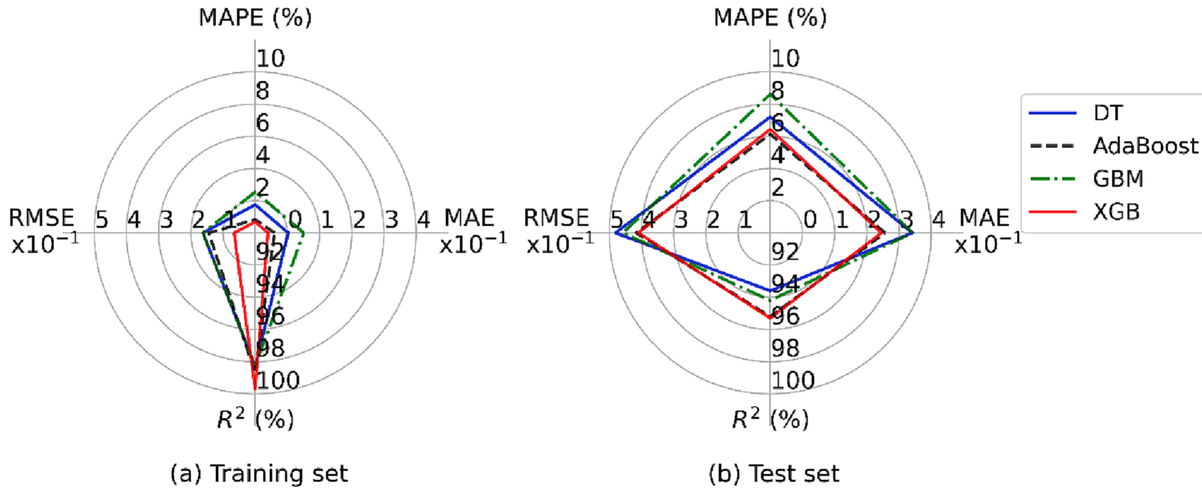


Fig. 14. Performance of the ML models in predicting the flexural strength of RAC.

concretes containing recycled concrete aggregate obtained from C&D waste in the UAE to further affirm its application in structural components. Moreover, the performance of structural concrete elements made with RCA by incorporating locally obtained construction and demolition wastes in the UAE should be investigated under various loading conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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