



Fresh and hardened properties of concrete made with recycled brick aggregate

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Abstract

To understand the prospect of recycling recycled brick aggregate (RBA), concrete samples were collected from 50 demolished building sites over a period of 20 years. After investigation of the properties of RBA, concrete specimens (RBAC) were fabricated using recycled brick aggregate (RBA). The variables were W/C (0.55, 0.45, 0.40 and 0.35) and cement content (340, 400, 450 and 500 kg/m³). As control case, virgin brick aggregate (BA) and concrete made with brick aggregate (BAC) were also investigated. For fresh concrete, slump was measured. For hardened concrete, compressive strength, stress–strain curves, Young’s modulus, tensile strength, ultrasonic pulse velocity (UPV) were evaluated. Moreover, by using a scanning electron microscope (SEM), interfacial transition zones (ITZs) in and around RBA were evaluated. RBA shows lower water absorption and lower abrasion compared to the virgin BA. Based on the abrasion value of RBA; the RBA was classified as excellent, good, and poor. RBA can be used to produce concrete of different grades from 21 to 34 MPa. A statistical regression model was developed considering compressive strength as dependent variable and W/C, cement content, age, and abrasion of RBA as independent variables.

Keywords Recycling · Brick aggregate · Concrete · ITZ · Sustainability

Introduction

Globally, concrete is the second most consumed material after water. The volume of production of concrete has been estimated from the data of global cement production. The amount of cement production in the world in 2019 was 4.08 billion tons [1]. Considering average cement consumption per cubic meter of concrete is 300 kg/m³; the amount of concrete production can be estimated to be 33 billion tons. This estimation exactly matched with ISO/TC 071 [2]. Considering the population of the world is 7.8 billion [3], the rate of global consumption of concrete per person per day is

estimated at 11 kg. Aggregate occupies 75% of mass of concrete, therefore it can be estimated that 24.5 billion tons of aggregate (almost 8.6 kg/person/day) is necessary to produce 33 billion tons of concrete. The amount of aggregate can be further divided; 10 billion tons as fine aggregate and 15 billion tons as coarse aggregate. Generally, rocks are collected from hard rock quarries and then crushed into appropriate grading for utilization in concrete as coarse aggregate [4]. Fine aggregate is collected from pits or river deposits. Considering sustainability of construction materials as well as relevant environmental issues associated with virgin aggregate production, it is necessary to reduce the rate of consumption of virgin aggregates.

In opposition, the amount of construction and demolition wastes (CDW) was assessed at 3 billion tons in 2012 and it was also projected that the rate of production will be increased gradually [5]. In the next 10 years, it was also predicted that the volume of recycled concrete will be amplified to 12.5 billion tons [6]. It is clearly understood that the amount of CDW is approaching the required quantity of virgin aggregate for construction works. Considering the limited available natural resources as virgin aggregate, recycling of demolished concrete is necessary for making structural concrete. With this

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objective, European countries have introduced the concept of circular economy [7]. The basic concept in circular economy is that the raw materials that will be used for construction works will not be considered as waste after the life-cycle of the structures but will be used again efficiently and smartly for making new construction works. The member states of European Unions have also been taken initiatives for utilization of 70% of the total non-hazardous CDW [8]. National level guidelines for recycling of concrete were formulated for recycling of brick masonry as well as recycling of concrete made with stone aggregate in many countries, such as Australia, China, Hong Kong, Japan, Belgium, Italy, Netherland, Norway, Portugal, Switzerland, UK, and USA as structural and non-structure applications [9]. Again, the UN has imposed seventeen Sustainable Development Goals (SDGs) with 169 targets [10]. To support SDGs, we need to understand the design of green buildings that will eventually help in several SDGs. Researchers are producing tremendous amount of research results for utilizing recycled aggregate; specifically, to understand the properties of aggregate and concrete mixed with recycled aggregate, durability performance and life cycle cost of structures made with recycled aggregate, etc. [11–20]. Considering the outputs of the research findings; guidelines for utilization of recycled aggregate have been approved in many countries as mentioned earlier. However, these guidelines show very strict limitations due to the uncertainty of performance of the recycled aggregate. More studies considering the wide range of data related to the recycled aggregate are still necessary to waive the strict limitations on application of recycled aggregate in new constructions.

Bangladesh is the largest delta in the world. Clay burnt BA is commonly used in construction works to avoid dependency on import of stone aggregate from abroad. In most demolished building sites, BA was found as coarse aggregate. Therefore, a study for recycling of RBA was planned in 2004. An interim report covering the data related to 33 demolished building sites was published in 2015 [21]. Further study was continued covering 17 newly demolished building sites. In all these demolished buildings, brick aggregate was used as coarse aggregate. In this report, data related to 50 different demolished building sites are summarized covering the properties of RBA, properties of RBAC, ultrasonic pulse velocity (UPV) through RBAC, interfacial transition zone (ITZ) in and around RBA, multi-variable linear regression analysis for the forecasting the compressive strength of RBAC, and carbon-dioxide emission due to the use of RBA in new construction.

Research significance

Considering environmental concerns as well as sustainability, utilization of demolished concrete in new construction works as aggregate is specified in ACI 318-19 [22]. In

some countries, a significant portion of recycled aggregate is utilized for making new concrete as the quality of recycled aggregate is improved by detaching the adhered mortar from the recycled aggregate [23, 24]. To utilize the recycled aggregate without detaching the adhered mortar, investigations based on a large sample size is still necessary. The research data will give confidence to the engineers for wider utilization of recycled aggregate globally. Therefore, a study on fresh and hardened properties of RBA was planned over a period of 20 years from 2004. It was also planned to collect RBA samples from 50 individual demolished buildings in Bangladesh over the period of this study. The experimental results of this study on RBA and fresh and hardened properties of concrete made with RBA (RBAC) are summarized in this report. The results will be very helpful to understand the properties of RBA as well as fresh and hardened properties of RBAC. Moreover, based on the results of this study over a large sample size of RBA, a guideline for utilization of RBA for structural concrete can be developed.

Experimental methods

Materials

Demolished concrete samples were collected from 50 demolished buildings. The ages of the buildings varied from 1 to 60 years. The demolished concrete was crushed manually to produce recycled brick aggregate (RBA). A photograph of demolished concrete sample as well as RBA is presented in Fig. 1. The grading of the RBA was controlled by satisfying ASTM C33 [4]. Specific gravity, absorption capacity, unit weight, and abrasion of aggregate were measured as per ASTM C128, ASTM C128, ASTM C29, and ASTM C131, respectively. As a control case, good quality virgin brick aggregate (BA) was investigated. It can be noted that brick aggregate is used in many constructions in Bangladesh. The saturated surface dry (SSD) unit weight, specific gravity, wear, and absorption capacity of BA (control aggregate) were 1321 kg/m³, 2.2, 47.8%, and 21.1%, respectively. Natural river sand as fine aggregate (FA) was used. The grading of the sand satisfied ACTM C33. The fineness modulus (FM), absorption capacity, and specific gravity of sand were 2.64, 3.9% and 2.61, respectively. The moisture state of all aggregates (RBA and BA; and natural sand) was in saturated surface dry (SSD) state. CEM Type II BM (as per BDS EN 197-1:2010), maximum amount of mineral content = 35% cement was used as binder. Tap water was used as mixing water. To improve slump of concrete, naphthalene-based water reducing chemical admixture (dosing as 8 ml per kg of cement) was used for the cases with water to cement ratio of 0.45 or less.

Fig. 1 Demolished concrete sample and RBA

Specimens

For the first 33 demolished building sites, the specimen's size was 150 mm (diameter) by 300 mm (height) and for the remaining 17 cases; it was 100 mm (diameter) by 200 mm (height). In the beginning of this study in 2004, the larger sized cylindrical specimens (150 mm by 300 mm) were commonly used to test for compressive strength of concrete; however, after some time the smaller size of specimens became familiar to test for compressive strength of concrete. Concrete specimens were tested for compressive strength at the ages of 7, 14, and 28 days. All strengths data related to the previous 33 cases were converted to the equivalent smaller size specimen by a conversion factor. The compressive strength of large cylinder data was multiplied 1.03 to convert to the compressive strength of smaller size cylindrical specimens [25–27].

Mixture proportions and curing

Key parameters related to concrete mixture proportions are listed in Table 1. Based on these design parameters, the unit contents (coarse aggregate, fine aggregate, water, chemical admixture for $W/C \leq 0.45$) of materials for making one cubic meter of fresh concrete were determined by varying specific gravities of recycled brick aggregates and control aggregate. Detailed mixture proportions of these cases can be obtained from other reports [21, 28, 29]. Utilizing the aggregates collected from the 50 different sites and control cases, 102 cases were investigated as listed in Table 1 for BAC, and RBAC. In RBAC and BAC specimens, cement content was 340 kg/m^3 , W/C s were 0.55 and 0.45, and sand to total aggregate volume ratio was 0.44. For RBAC, six special cases were also investigated by lowering W/C as 0.40 and 0.35 and increasing the amount of cement to 400, 450 and 500 kg/m^3 to understand the likelihood of improving strength of RBAC. The specimens were removed from the mold after one day of pouring concrete.

Table 1 Key mix design parameters

Mix design parameters	Values for general cases	Comments
Maximum size – coarse aggregate	20 mm	For all cases
W/C	0.45 and 0.55	Some special cases were investigated for low W/C , such as 0.30, 0.40
s/a	0.44	For all cases
Cement content	340 kg/m^3	Some special cases were investigated for higher amount of cement, such as 400, 450, and 500 kg/m^3
Dosage of chemical admixture	8 ml/kg	For $W/C \leq 0.45$

Number of cases investigated:

Brick Aggregate Concrete as Control Cases (BAC) – 2 Cases (denoted as BAC-55 and BAC-45); BAC-45 indicates the case of concrete made with brick aggregate (BAC) and $W/C=0.45$

Recycled Brick Aggregate Concrete (RBAC) – 50 cases with W/C of 0.45 (denoted as RBAC-45); 44 cases with W/C of 0.55 (denoted as RBAC-55); RBAC – 45 indicates the case of recycled brick aggregate concrete (RBAC) made with $W/C=0.45$

Special RBAC – 6 cases ($W/C=0.40$ and 0.35 and cement = 400, 450, and 500 kg/m^3)

The cases are denoted as RBAC-Y48-CC500-WC40, RBAC-Y48-CC450-WC35, RBAC-Y38b-CC400-WC45, RBAC-Y38b-CC400-WC40, RBAC-Y25-CC400-WC40, RBAC-Y25-CC450-WC40. The case RBAC-Y48-CC400-WC40 indicates the concrete made with 48 years old RBA with cement content of 400 kg/m^3 and W/C of 0.40

Total Number of Specimens Investigated – 1122 specimens

Then the specimens were kept in a closed container with high humidity and temperature of 20 ± 5 °C before the time of testing.

Test items

Immediately after discharging from the mixture, slump was measured as per ASTM C143. The specimens were tested at different ages (7, 14, and 28 days) to evaluate compressive strength of RBAC and BAC. From the stress–strain graph, the modulus of concrete was calculated. Two dial gauges were used to monitor deformation of the specimens as presented in Fig. 2. Modulus of elasticity was determined as per ASTM C469. Fractured surfaces of concrete were observed carefully. The total number of investigated cases was 102 with a total number of specimens of 1122.

The splitting test was conducted at 28 days to determine the tensile strength of concrete. After splitting test, the fractured surfaces were examined visually. Before destructive testing of cylinders, UPV was measured by a Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) as presented in Fig. 3 (as per ASTM C597). A transducer was used for generating a pulse of 54 kHz. The transit time of pulse from transducer to receiver was measured. From the transit path, UPV was calculated. Microstructures of concrete (new mortar and old mortar adhered with RBA) and interfaces in and around recycled brick aggregate (old interface in RBA between old mortar and old aggregate, old mortar and new mortar, old aggregate and new mortar) were investigated by using a scanning electron microscope (SEM). For SEM investigation, the freshly fractured small pieces of the concrete samples were coated by sputtering gold and a VEGA3 TESCAN was used for taking images.



Fig. 2 Measurement of deformation under compression load



Fig. 3 Measurement of UPV

Experimental results

Properties of RBA

The distribution of ages of demolished buildings is shown in Table 2. The number of buildings for age of 1–30 years, 30–50 years, and 50–60 years were 15, 30, and 5, respectively. It is found that the age of the buildings is within 30–50 years for 60% of the buildings investigated. Unit weight, specific gravity, wear, and absorption capacity of RBA with the variation of ages are shown in Fig. 4. The age of the building has no correlation with the investigated parameters of RBA, such as unit weight, specific gravity, wear, and absorption capacity. It is understood that the quality of concrete during construction of the buildings will play a significant role to control the overall quality of RBA. The statistical variations of the investigated parameters of RBA are summarized in Table 3. Absorption capacity of RBA (coefficient of variation = 0.22) is varied significantly compared to the unit weight (COV = 0.05), wear (coefficient of variation = 0.08), and specific gravity (COV = 0.05). Compared to the control BA, most of the RBA has lower unit weight, lower specific gravity, lower absorption capacity, and lower wear value. Only 10% of RBA shows wear over

Table 2 Ages of demolished buildings investigated

Age of demolished buildings (years)	Number
1–10	3
10–20	5
20–30	7
30–40	19
40–50	11
50–60	5
Total	50

Fig. 4 Variation of properties of RBA with respect to age of demolished buildings

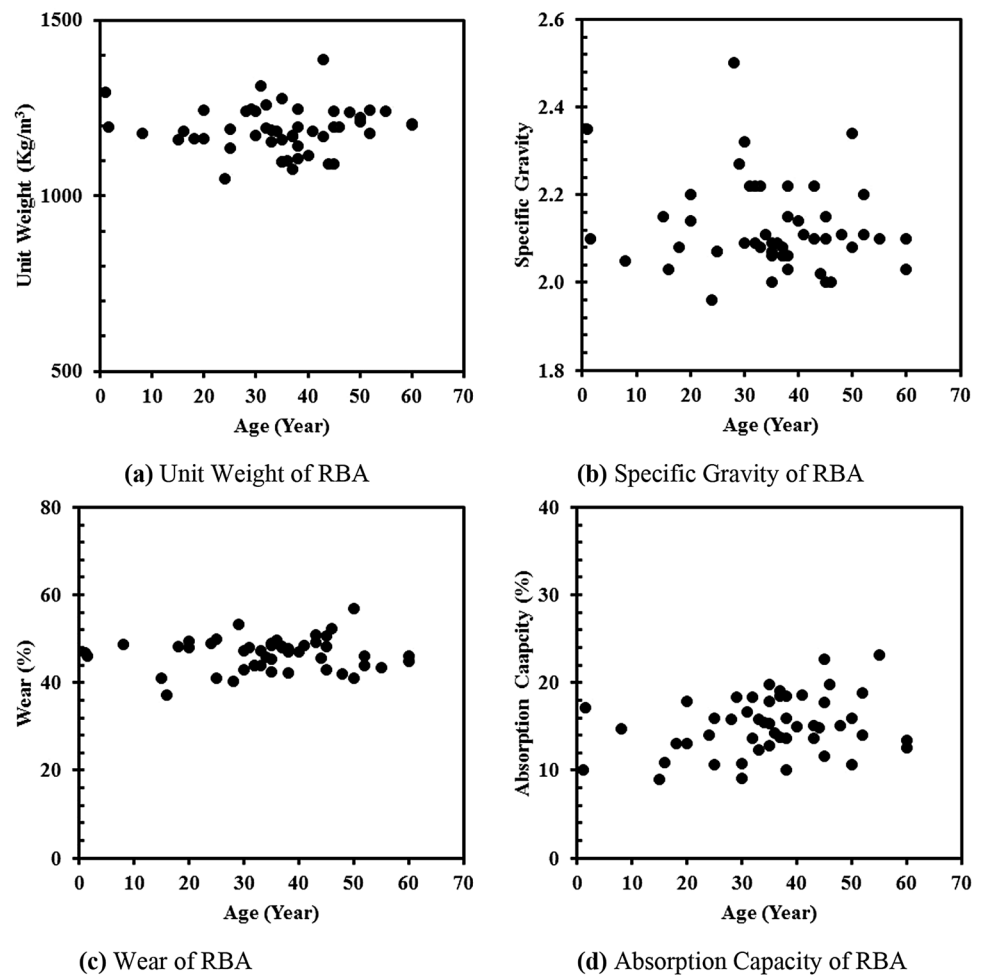


Table 3 Statistical parameters of RBA

Statistical parameters	Unit weight (kg/m ³)	Specific gravity (SSD)	Absorption (%)	Wear (%)
Data points	50	50	50	50
Maximum	1388.50	2.50	23.15	57.00
Minimum	1049.44	1.96	9.03	37.17
Average	1188.24	2.12	15.11	46.53
Percentile -10%	1097.07	2.02	10.65	41.10
Percentile -90%	1257.92	2.27	19.07	50.51
Standard deviation	65.09	0.10	3.31	3.64
Coefficient of variation	0.05	0.05	0.22	0.08

50%, the maximum limit specified in ASTM C33 for coarse aggregate [4]. The cross variation of wear and absorption capacity of RBA is shown in Fig. 5. No correlation is found between absorption capacity and unit weight of RBA. However, it is seen that there is a tendency of higher absorption capacity for RBA having higher value of wear. It is because the voids in aggregate will increase with the increase of absorption capacity of aggregate, and it will eventually reduce the strength of aggregate against abrasion.

Slump of fresh concrete

Figure 6 presents the variation of slump of fresh RBAC for W/C = 0.55 and 0.45 with the variation of absorption capacity of RBA. The slumps of concrete made with BA were 10 mm and 80 mm for W/C = 0.45 and 0.55, respectively. As expected, relatively more slump was found for W/C = 0.55 compared to W/C = 0.45. No good correlation was found between absorption capacity of aggregate and

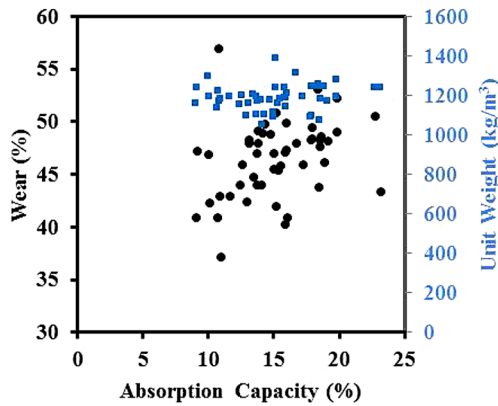


Fig. 5 Wear, absorption capacity, and unit weight of RBA

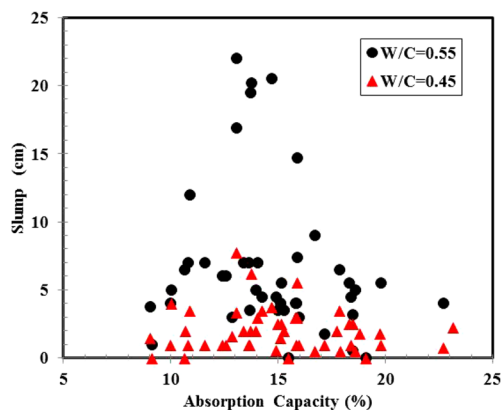


Fig. 6 Workability of concrete made with RBA

slump of RBAC. A tendency of reduction of slump of RBAC is found for RBA having absorption capacity over 15%. It can be noted that to increase slump for W/C of 0.45 or less, water reducing chemical admixture (8 ml per kg of cement) was used.

Compressive strength

The compressive strength of RBAC was normalized by the compressive strength of BAC (control case). The variations of the normalized strength of RBAC with the variation of wear, absorption capacity, and age of RBA are given in Fig. 7. For W/C=0.55, RBAC gives a lower level of strength compared to the BAC. Contrary, for W/C=0.45, the average strength for RBAC becomes very close to the strength of BAC. Correlations were not found between compressive strength of RBAC and the age or the absorption capacity of RBA. However, a tendency of reduction in compressive strength of RBAC with the increase of wear of RBA is found. A larger value of wear designates a relatively soft aggregate, and it eventually causes reduction in compressive

strength of RBAC. The statistical data related to compressive strength of RBAC for W/C=0.45 and W/C=0.55 are summarized in Tables 4 and 5. The average strength of RBAC was found at 25 MPa and 21 MPa for W/C=0.45, and 0.55, respectively. As per ACI 318–19, the lower level of strength of structural concrete is quantified to be 21 MPa [22]. Therefore, RBA can be utilized for producing structural concrete as per ACI 318–19. The coefficient of variations for the data related to compressive strength of RBAC were 0.16 and 0.14 for W/C=0.45 and 0.55, respectively.

The average compressive strength of RBAC and BAC (control case made with BA) is presented in Fig. 8. It can be observed that for W/C=0.55, the compressive strength of RBAC is 15% lower than BAC. Contrary, comparable results were obtained between RBAC and BAC for W/C=0.45. It indicates that for recycling of concrete in an efficient way, W/C of RBAC is to be reduced. For further increase of strength of RBAC, some special cases were investigated with lower W/C and higher cement content. The results are shown in Fig. 9. For RBA with a lower level of wear value (such as 42%), the compressive strength of RBAC became 34 MPa. For RBA with a higher level of wear, a slight increase of strength of RBAC is also found. Due to the soft nature of RBA, crushing of aggregate plays a major role for RBAC made with a low W/C and higher cement content. It is also understood that for further increase of strength of RBAC, it is necessary to improve the properties of RBA. Studies related to improvement of wear value of aggregate as well as reduction of water absorption of aggregate are necessary.

Tensile strength of concrete

The average tensile strength of RBAC and BAC are shown in Fig. 10 for W/C=0.45 and 0.55. Same as compressive strength of RBAC, for W/C=0.55 about 15% reduction in tensile strength of RBAC is found compared to BAC. However, when W/C=0.45, the tensile strength of RBAC becomes comparable to BAC. These results matched well with the results of compressive strength explained earlier. The statistical data for tensile strength of RBAC are summarized in Tables 4 and 5 for W/C=0.45 and 0.55, respectively. The coefficients of variation related to tensile strength of RBAC are 0.14 and 0.12 for W/C=0.45 and 0.55, respectively.

Modulus of elasticity of concrete

The variations of normalized modulus of elasticity of RBAC with variation of age of RBA, wear of RBA, and absorption capacity of RBA are shown in Fig. 11. No correlations between elastic modulus and the investigated parameters of RBA, such as age, wear, and absorption

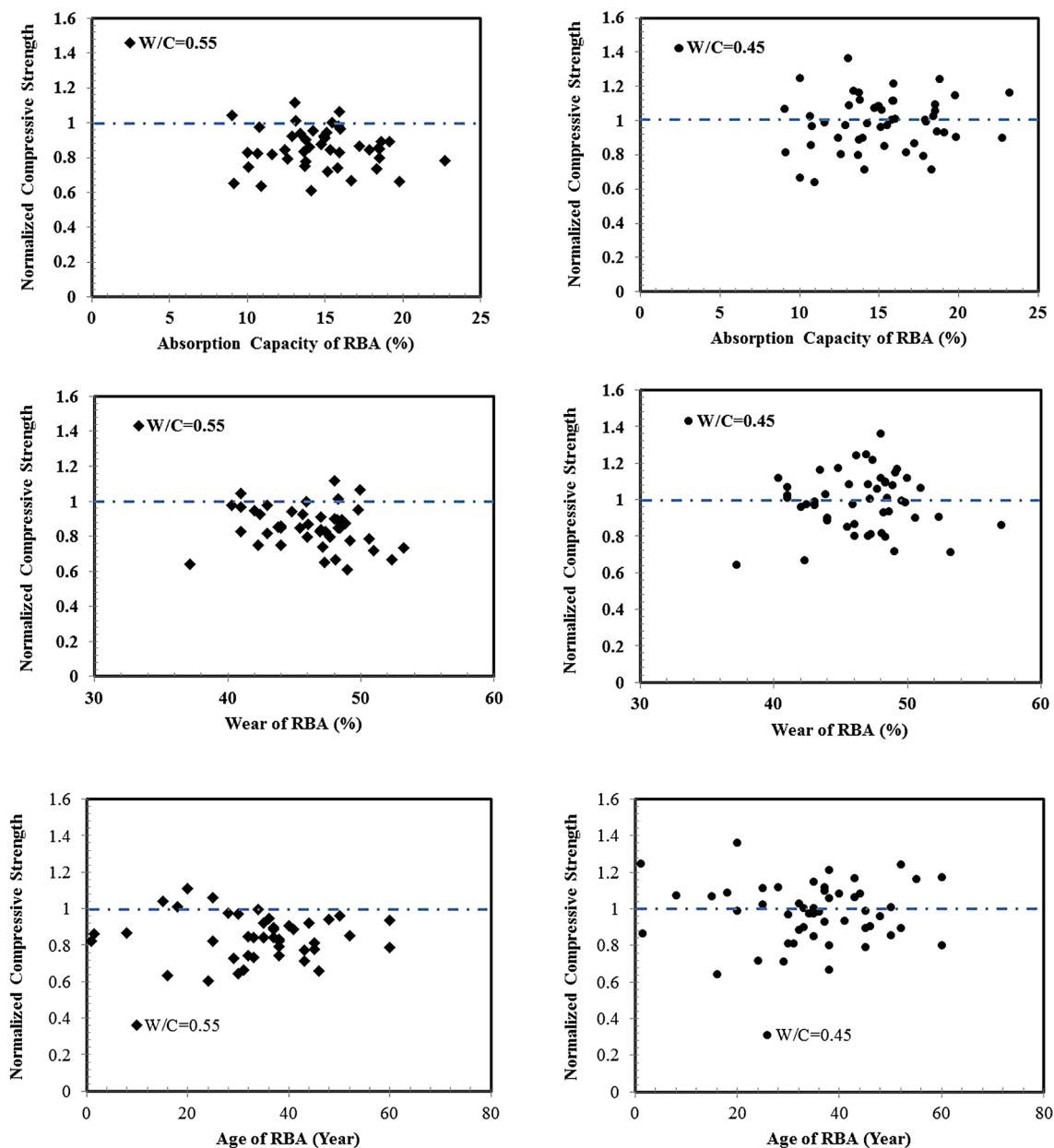


Fig. 7 Normalized compressive strength of RBAC versus age, wear, and absorption capacity of RBA

capacity are found. The statistical parameters associated with the elastic modulus of concrete made with RBA are summarized in Tables 4 and 5 for W/C = 0.45 and 0.55. The average elastic modulus was found at 16,798 MPa and 16,080 MPa for W/C = 0.45 and 0.55, respectively. The coefficients of variation related to modulus of elasticity of RBAC are 0.16 and 0.13 for W/C of 0.45 and 0.55, respectively. Figure 12 shows the average values of elastic modulus of RBAC and BAC. Compared to the BAC, no significant drop in average elastic modulus of concrete is found irrespective of W/C.

Stress–strain relationship

The variation of normalized stress and strain of RBAC is shown in Fig. 13. Based on the experimental data, the following non-linear constitutive relationship is formulated for RBAC:

$$\frac{f_c}{f'_c} = \frac{1.68\varepsilon}{0.0014 + \varepsilon}, R^2 = 0.81 \quad 0 \leq \varepsilon \leq 0.0025 \quad (1)$$

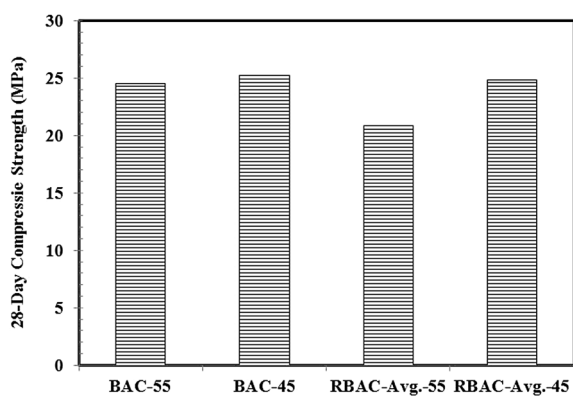
where f_c is stress in concrete, f'_c is compressive strength and ε is strain of RBAC. For a specified grade of RBAC, the

Table 4 Statistical parameters related to compressive strength, W/C=0.45

Statistical parameters	Related to compressive strength	Related to tensile strength	Related to elastic modulus
<i>W/C = 0.45</i>			
Data Points	50	49	49
Maximum (MPa)	34.3	3.2	24,341
Minimum (MPa)	16.2	1.8	11,670
Average (MPa)	24.8	2.4	16,797
Percentile -10% (MPa)	20.2	2.0	13,112
Percentile-90% (MPa)	29.4	2.9	20,205
Standard deviation (MPa)	3.9	0.3	2721
Coefficient of variation	0.16	0.14	0.16

Table 5 Statistical parameters related to compressive strength, W/C=0.55

Statistical parameters	Related to compressive strength	Related to tensile strength	Related to elastic modulus
<i>W/C = 0.55</i>			
Data Points	44	44	44
Maximum (MPa)	27.3	2.6	21,195
Minimum (MPa)	14.9	1.3	8796
Average (MPa)	20.8	2.2	16,080
Percentile -10% (MPa)	16.7	1.7	11,396
Percentile-90% (MPa)	24.3	2.5	17,961
Standard deviation (MPa)	2.9	0.3	2012
Coefficient of variation	0.14	0.12	0.13

**Fig. 8** Compressive strength of RBAC and BAC

stress–strain curve can be formulated from this equation and can be applied for non-linear analysis of concrete structural elements made with RBAC.

Relationships between mechanical properties of concrete

The variations of tensile strength of RBAC with the compressive strength of RBAC are presented in Fig. 14. Based on these data, the following relationship between tensile and compressive strength of RBAC is proposed:

$$f_t = 0.48\sqrt{f'_c}, \quad R^2 = 0.31 \quad (2)$$

where f_t = tensile strength (MPa) and f'_c = compressive strength of RBAC (MPa). In ACI 318–19, the following equation is proposed to correlate tensile strength and compressive strength of concrete:

$$f_t = 0.62\lambda\sqrt{f'_c} \quad (3)$$

The factor λ is associated with lightweight concrete. As the average unit weight of RBAC is 135 lb/ft³, therefore the value of λ can be considered as 1.0. Comparing Eqs. 2 and 3, it is found that a new factor related to RBA, β (=0.77) is to be introduced in the above-mentioned equation to take into account of RBA:

$$f_t = 0.62\beta\sqrt{f'_c} \quad (4)$$

The variation of elastic modulus and compressive strength of RBAC is presented in Fig. 15. Based on the data of Fig. 15, the following relationship between elastic modulus and compressive strength of RBAC is proposed:

$$E_c = 3383\sqrt{f'_c} \quad (5)$$

where E_c = elastic modulus (MPa), and f'_c = compressive strength of RBAC (MPa). As per ACI 318-10, the following relationship can be used for calculation of elastic modulus (in psi) of concrete from compressive strength (in psi) and unit weight (in lb/ft³) of concrete:

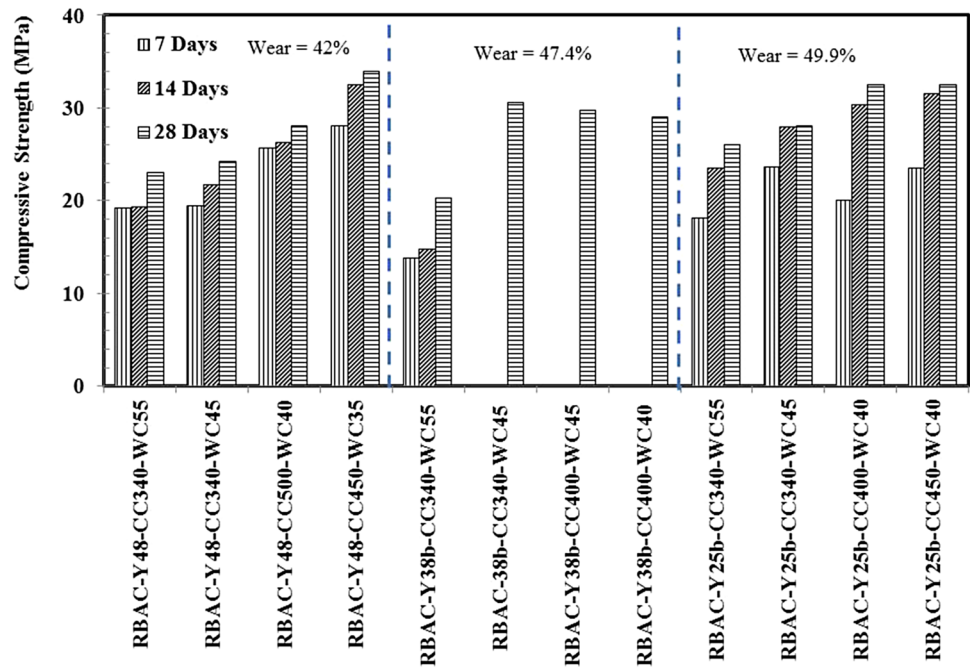
$$E_c = 33W_c^{1.5}\sqrt{f'_c} \quad (6)$$

Using the average value of unit weight of RBAC (135 lb/ft³), the equation can be converted into the following form:

$$E_c = 4295\sqrt{f'_c} \quad (7)$$

Comparing Eqs. 5 and 7, it is found that a factor associated with RBA, γ (=0.8) is to be incorporated in the Eq. 8 as below:

Fig. 9 Strength of RBAC for special cases



Relationships between compressive strength and elastic modulus with UPV

The variation of compressive strength of RBAC with respect to UPV through RBAC is presented in Fig. 17. Based on these data, the following relationship between compressive strength of RBAC and UPV through RBAC is proposed:

$$f'_c = 0.6924e^{0.0009 \text{ UPV}}, \quad R^2 = 0.45 \tag{9}$$

where f'_c = compressive strength (MPa) and UPV = ultrasonic velocity through RBAC (m/s). The results were also compared with the relationships found in another study on brick aggregate [28]. It is found that compared to the virgin BA, RBA shows less compressive strength for the same UPV. The proposed relationship can be used to predict the compressive strength of RBAC from UPV.

The variation of compressive strength (in MPa) of RBAC with UPV is presented in Fig. 18. Based on the data, the following relationship is proposed between elastic modulus and UPV through RBAC:

$$E_c = 2841.7e^{0.1111 \text{ UPV}^2}, \quad R^2 = 0.56 \tag{10}$$

where E_c = elastic modulus (MPa) and UPV = ultrasonic pulse velocity through RBAC (km/s). The results of RBAC are also compared with the results of BA [30]. For the same UPV through concrete, a lower level of elastic modulus is found for RBAC compared to the virgin BA.

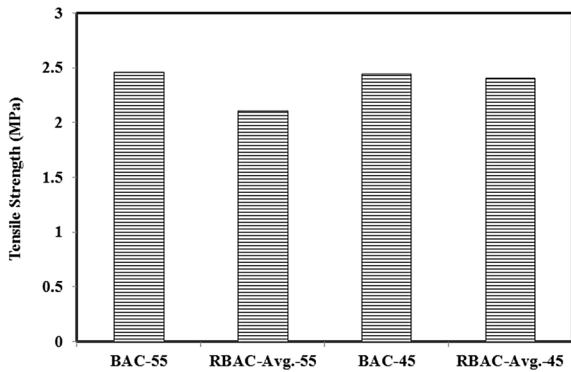


Fig. 10 Tensile strength of BAC and RBAC

$$E_c = 33\gamma W_c^{1.5} \sqrt{f'_c} \tag{8}$$

The variation of compressive strength of RBAC with the wear of RBA is presented in Fig. 16. It is observed that with the increase of wear of RBA, the strength of RBAC is reduced both for $W/C=0.55$ and 0.45 . From the relationships proposed in Fig. 16, it is possible to predict the compressive strength of RBAC from the value of wear of RBA. Based on these results, it is possible to classify the quality of RBA as Excellent, Good, and Poor for wear value less than 45%, 45–50%, and more than 50%, respectively.

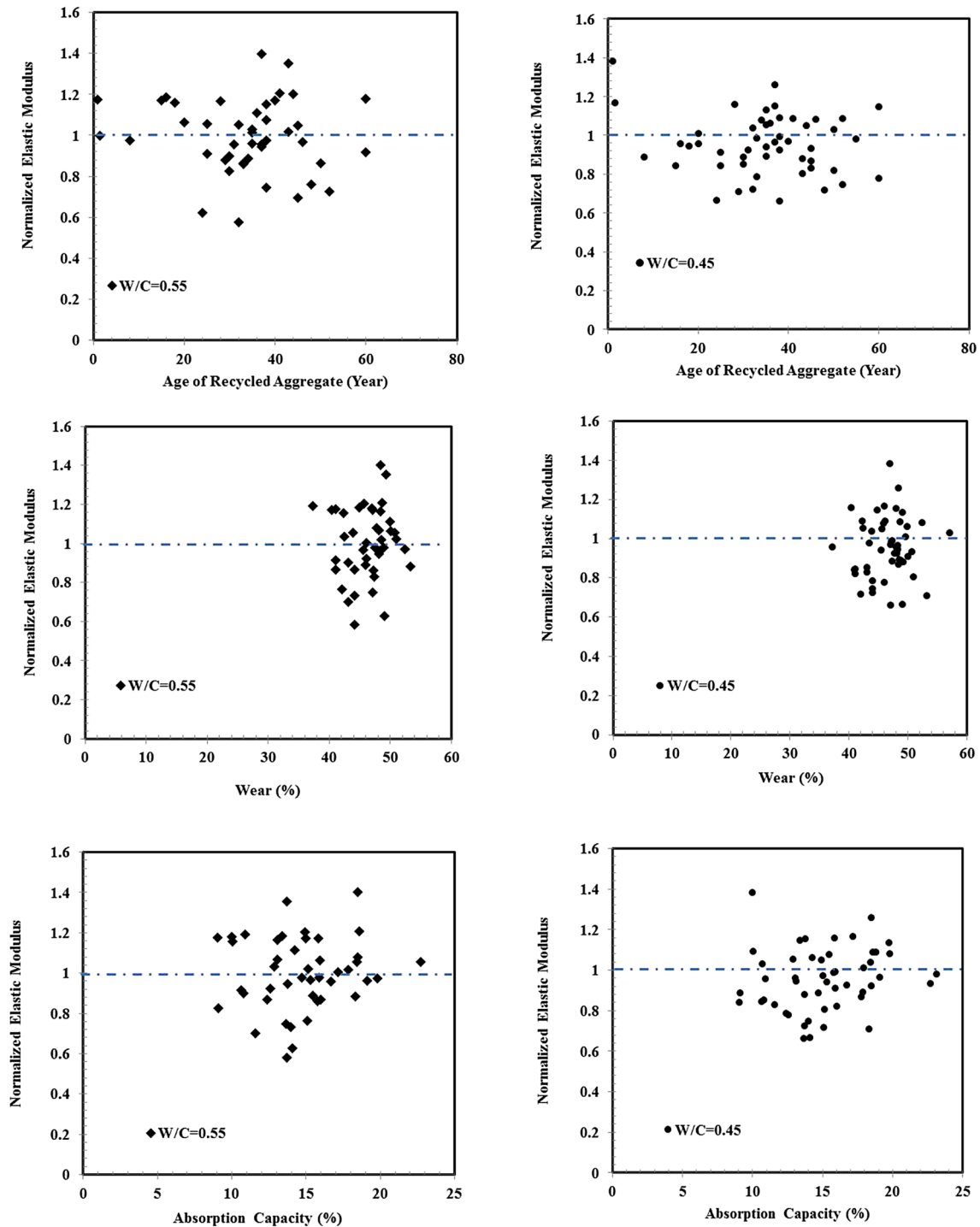


Fig. 11 Normalized elastic modulus of RBAC with the variation of age, wear, and absorption capacity of RBA

Standard multiple linear regression to calculate compressive strength from W/C, cement content, age, and abrasion of RBA

Multiple linear regression was utilized to evaluate compressive strength (MPa) for RBAC from the data of W/C,

abrasion (%), cement content (kg/m^3) and age (days). At first analyses were conducted to confirm that no violation of the assumptions related to normality, linearity, multi-collinearity, and homoscedasticity had occurred. Though the response variable is not normally distributed, enough data ($N=208$) has been considered for obtaining a more precise

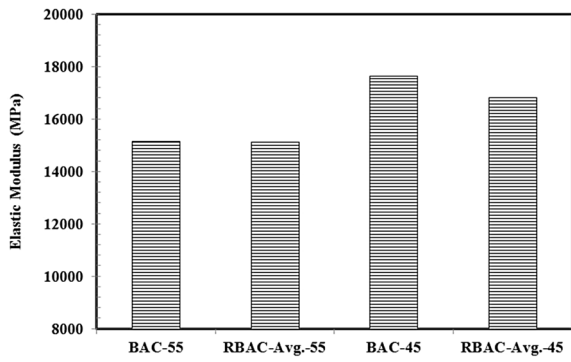


Fig. 12 Elastic modulus of BAC and RBAC

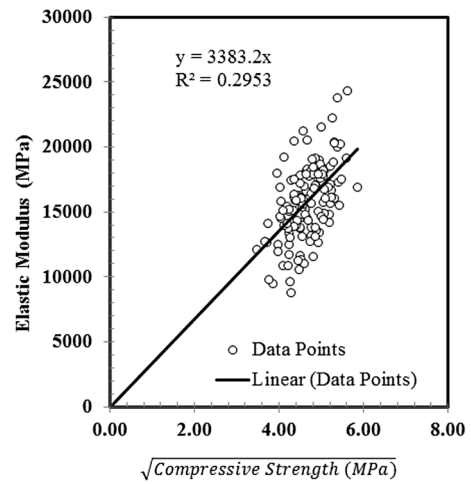


Fig. 15 Variation of elastic modulus with compressive strength of RBAC

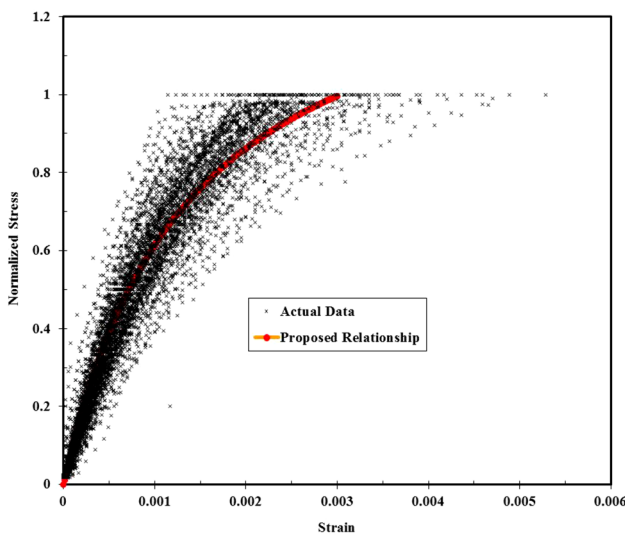


Fig. 13 Stress–strain curve of RBAC

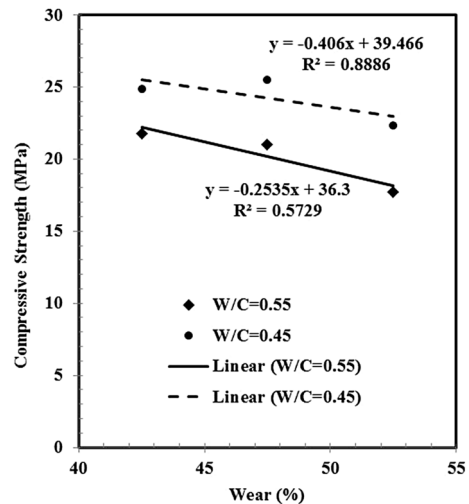


Fig. 16 Compressive strength of RBAC versus wear of RBA

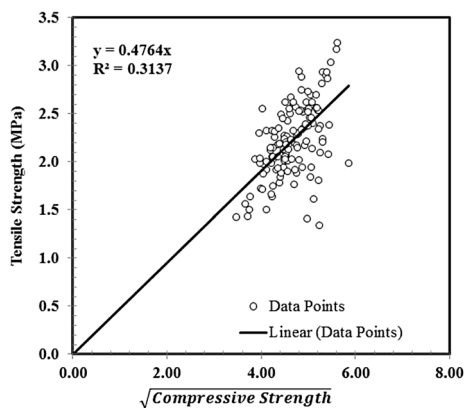


Fig. 14 Variation of tensile strength and compressive strength of RBAC

relationship. The following model is developed to evaluate compressive strength (as dependent variable) of RBAC (f'_c) from W/C, cement content, age, and abrasion of RBA as independent variables:

$$f'_c = 27.002 - 37.654 \times \frac{W}{C} + 0.032 \times \text{Cement Content} \left(\frac{\text{kg}}{\text{m}^3} \right) + 0.247 \times \text{Age(in days)} - 0.066 \times \text{Abrasion}(\%) \quad (11)$$

Even though, $R^2 = 0.544$ and adjusted $R^2 = 0.535$; the other statistical parameters indicate the model is statistically significant. All the explanatory variables satisfy the significance in accordance with a confidence interval of 95% except abrasion. It dictates that abrasion is relatively statistically insignificant. However, the data of abrasion has

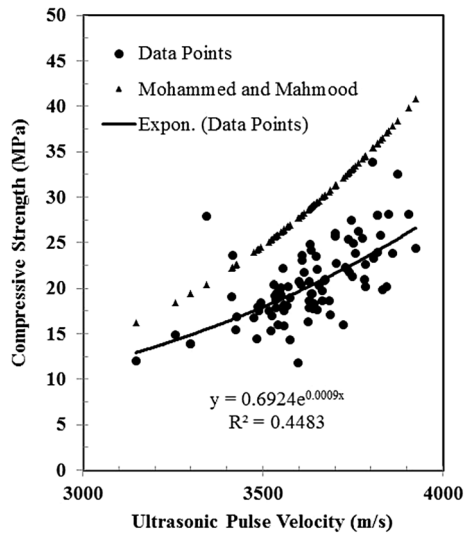


Fig. 17 Compressive strength versus UPV

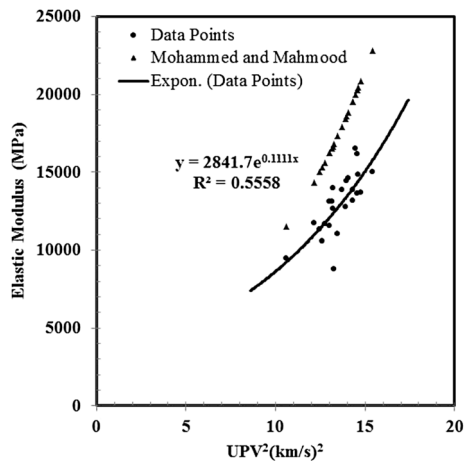


Fig. 18 Elastic modulus versus UPV

been incorporated in the model to consider the variability of aggregate to evaluate the compressive of RBAC. The evaluated strength and experimental data are shown in Fig. 19. It is confirmed that the model can reasonably evaluate compressive strength of RBAC from W/C, cement content, age of RBAC, and abrasion of RBA.

Interfaces in and around RBA

Recycled aggregate is different than the fresh aggregate because of the presence of adhered old mortar with the old aggregate as shown in Fig. 20. Three different interfacial transition zones (ITZs) can be formed in and around an RBA, such as ITZ between old mortar and new mortar (marked as A), ITZ between old brick and old mortar

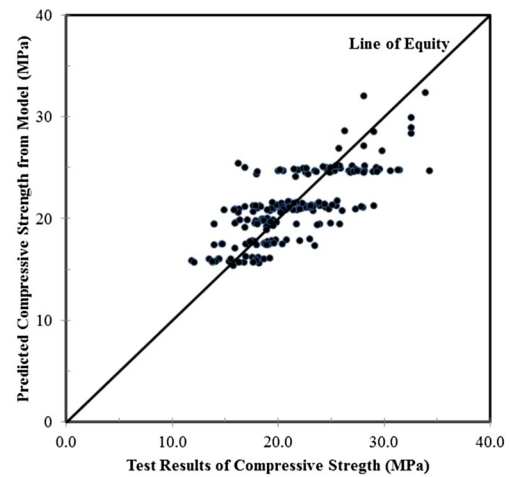
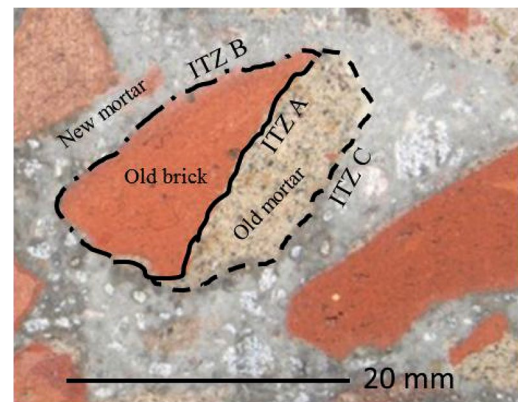


Fig. 19 Experimental data and predicted compressive strength of RBAC



ITZ A – Interfacial Transition Zone : Old brick and old mortar
ITZ B – Interfacial Transition Zone : Old brick and new mortar
ITZ C – Interfacial Transition Zone : Old mortar and new mortar

Fig. 20 ITZs in RBAC comprises of old brick and old mortar

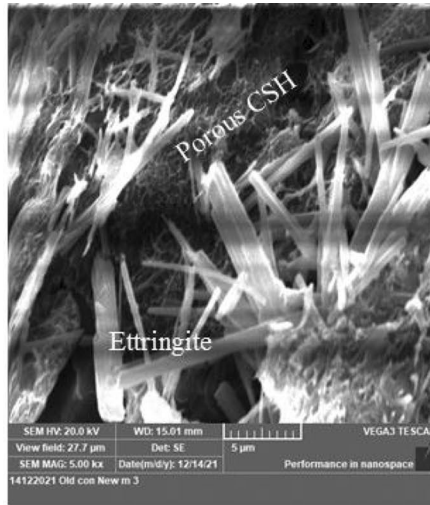
(marked as B), and ITZ between old brick and new mortar (marked as C).

SEM micrographs of ITZ in and around RBA are shown in Fig. 21. In the interfacial transition zones, the presence of cracks, deposit of $\text{Ca}(\text{OH})_2$, porous layers of CSH, and needle-shaped structure of ettringite were found. The interfaces were found as weak zones in concrete as in virgin aggregate.

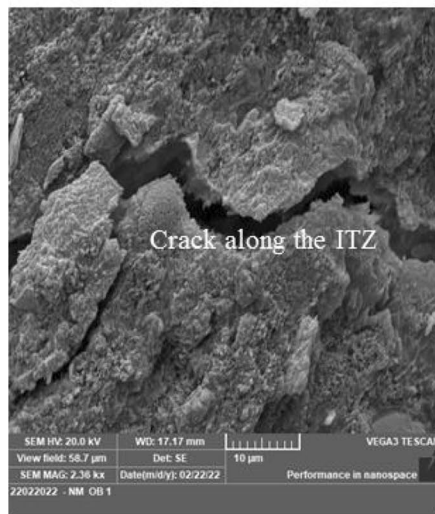
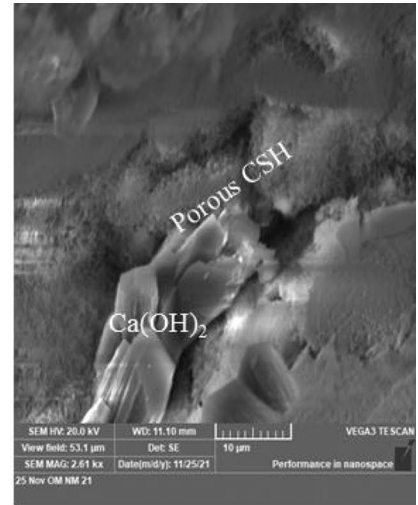
CO₂ footprint, cost comparison, and other environmental implications

Approximate CO₂ footprints and materials costs per cubic meter of RBAC and BAC are presented in Figs. 22 and 23, respectively. In cost estimation, the cost of cement, brick aggregate, sand, and water were considered based on the local market prices in Bangladesh. Due to the absence of

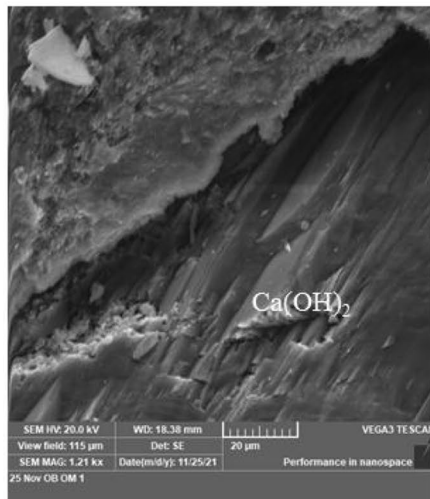
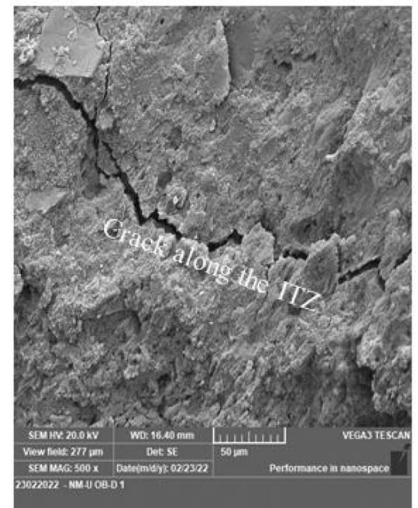
Fig. 21 Interfacial transition zones (ITZ)



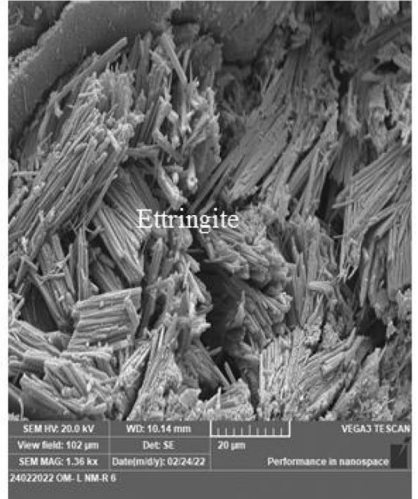
ITZ A : Old brick and old mortar



ITZ B : Old brick and new mortar



ITZ C – Old mortar and new mortar



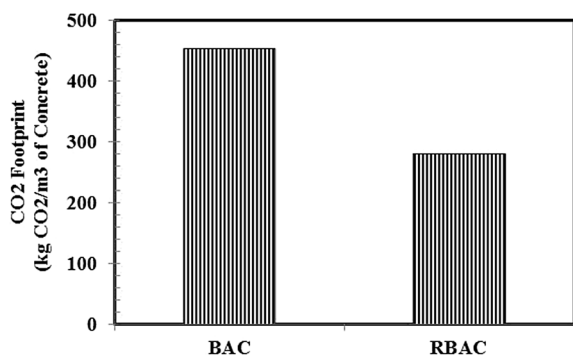


Fig. 22 CO₂ Footprint for BAC and RBAC

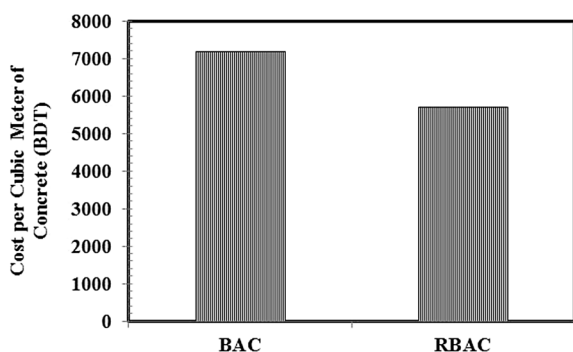


Fig. 23 Cost for BAC and RBAC

data, the cost of RBA is assumed to be the half of the cost of virgin BA. In CO₂ footprint calculation, the CO₂ emission from cement production, production of BA, crushing of aggregate, collection of fine aggregate was considered. It is found that for RBAC, the cost of concrete can be reduced by 20% and CO₂ footprint can be reduced by 40% compared to the BAC. In Bangladesh, brick aggregate is generally used in construction works to avoid the pressure of import of stone chips from abroad. More than 7000 brick kilns are in operation to produce 23 billion brick blocks annually by burning 5.7 million tons of coal [31]. For production of brick, about 3.35 billion cubic feet of brick earth is necessary that is collected from the top layer of valuable agricultural land. Considering the depth of cutting of topsoil as 0.25 m, it can be estimated that every year 400 km² of land is necessary for top soil collection. This process greatly influences agricultural production in Bangladesh, the one of the major economic factors. In addition, the burning process of bricks emits 15.7 million tons of CO₂. By proper recycling of demolished concrete made with RBA, it will be possible to reduce cost of concrete, CO₂ footprint, and increase agricultural production. These will eventually help toward achievements of several SDGs) of the UN.

Conclusions

Based on this extensive experimental investigation conducted over a period of 20 years on RBA collected from 50 different demolished reinforced concrete buildings, the following conclusions are drawn:

- RBA shows less water absorption, less unit weight, and less wear compared to BA. Based on the abrasion resistance of RBA, RBA is classified as excellent (abrasion value less than 45%), good (abrasion value between 45 to 50%), and poor (abrasion value more than 50%)
- RBA can be used for producing different grades of structural concrete ranging from 21 to 34 MPa
- Several relationships between different mechanical properties of concrete were developed
- A linear regression model is developed for evaluation compressive strength of RBAC from water to cement ratio, cement content, age of RBAC, and abrasion of RBA
- Utilization of RBA will reduce the cost of concrete by 20% as well as the carbon dioxide footprint by 40% compared to the virgin brick aggregate.

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Declarations

Conflict of interest The authors declare that there are no conflicts of interest.

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