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ORIGINAL ARTICLE

Old residual mortar as a quality indicator of recycled brick aggregate

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Abstract: Old residual mortar (RM) on recycled aggregate surfaces is a major factor contributing to its lower quality. The present study aims to quantify the effect of old mortar on the properties of recycled brick aggregates (RBA) and recycled concrete (ReC) made with them. The process involves collecting and crushing discarded concrete blocks from seven sources to create recycled brick aggregates. A chemical-thermal combined process removes old mortar, and with varying RM contents, the aggregate properties are determined. C-25-grade concrete specimens are prepared using RBA with different RM content and tested for workability, compressive strength, splitting tensile strength, flexural strength, water absorption, bulk density, and voids in hardened concrete. Regression models expressing the change in properties with RM content are presented. The study reveals that the quality of RBA and concrete worsens with increasing RM, with a 20% RM value being considered a limiting value to maintain minimal variation in properties. The regression models suggest that every 10% increase in RM may result in an 11% increase in water absorption of RBA, an 8% increase in aggregate crushing value (ACV), a 3.6% increase in Los Angeles (LA) value, a 10% loss in compressive strength of ReC, a 7% loss in tensile strength, and a 9% loss in flexural strength, approximately. The developed models may be used to predict the expected quality of RBA and ReC based on their attached old RM, which would be helpful in deciding their usage for different applications.

Keywords: Recycled brick aggregate; residual mortar; concrete recycling; regression model

1 Introduction

One of the building supplies that is most frequently used is concrete, and as a result of its widespread usage, its constituent components are becoming scarce. The concrete industry is the biggest user of natural resources, consuming 12.6 billion tons of raw ingredients annually [1]. Several studies are being conducted to find out a possible replacement of concrete ingredients with recycled materials. One of the main components of concrete that gives it strength and volume is coarse aggregate (CA). About 65% of total concrete volume is occupied by the CA and its global annual requirement is more than 13 billion tons which is expected to increase up to 48.3 billion tons [2, 3]. CAs are usually produced by breaking down the rocks and bolder stones. In countries like Bangladesh, where the natural reserve of stone is limited, stone aggregates are to be imported at a high cost. A comparatively lower cost

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alternative to the stone aggregates is the crushed brick aggregate which is popularly used in low-rise construction works. Production of CA from either bolder stone or brick consumes energy as well as results in the depletion of natural resources. That's why the replacement of CA by various recycled materials such as waste plastic, rubbers, tire chips, steel slags, coconut shells, and many more are being tested by the researchers, and in most cases promising outcomes are evident [4-7]. However, the massive output of garbage from building and demolition has emerged as another inevitable obstacle for the waste management industry. An ancient statistic states that the annual production of demolition trash is approximately 20 billion tons [8]. These wastes are creating disposal problems occupying large landfill areas and they are found to be responsible for environmental positions as well [9, 10]. Demolished concrete has the potential to be reused. The easiest way to make use of the discarded concrete may be breaking it down to smaller aggregate size and use as a replacement of CA. The aggregates thus produced are said to be recycled coarse aggregate (RCA). A number of studies presented promising aspects of using RCA in concrete as a partial replacement of CAs. Several studies reported that within certain limit of replacement, usually 20-50%, RCA can replace natural CA and produce concrete with acceptable compressive, tensile and flexural performances [11-13]. Good performance of RCA in pavement work and asphalt concrete is also reported [14]. Zhang et al. (2023) examined the axial compression behavior of square steel tube columns filled with recycled aggregate concrete and reinforced with basalt fiber. Findings indicate that the replacement ratio of RCA material did not significantly impact the specimen's peak load [15]. However, some study also reported several shortcomings of RCA. According to Carneiro et al. (2013), RCA impacted the stress-strain characteristic of ReC, demonstrating a more brittle character than natural aggregate concrete [16]. 2% loss of compressive strength for every 10% replacement of recycled aggregate was reported [17]. Yang et al. (2008) reported a severe strength reduction of more than 30% because of the use of 100% recycled aggregate [18]. Many researchers limited the use of RCA to a certain percentage because of their inferior quality. Datta et al. (2022) found that increasing the RCA percentage to 15%, 30%, and 45% resulted in worse values for electrical resistivity, rebound number, compressive strength, MOE, and UPV for RAC. These inferior values were particularly noticeable for concrete mixes that replaced 45% of the original RCA [19]. Weaker interfacial bond with cement paste, presence of old mortar and lower quality of RCA are some major limitations of recycled aggregate [20]. A piece of recycled aggregate usually consists of two parts, the original virgin aggregate and old RM layers attached to the surfaces of the original aggregate [21]. ReC has two interfacial transition zones (ITZ), in contrast to natural aggregate concrete. There are two types of ITZs: the old one is between the old mortar and the original virgin aggregate, and the new one is between the new mortar and the RCA. For natural aggregate concrete, only new ITZ can be found. ReC typically has a higher volume of ITZ than natural aggregate concrete, which causes it to have a higher porosity than the latter. This leads to the inferior mechanical performance of ReC such as lower compressive, tensile, and bending strength, higher permeability, and poor durability. Additionally, the old mortar that was affixed to the RCA could contain cracks from the manufacturing process, and a service load might easily cause the pre-existing ruptures to propagate, ultimately leading to the failure of the concrete [22]. Among the several factors responsible for the lower quality of recycled aggregates, the attached old RM is the most affecting one [23-25]. A thorough assessment of the literature led to the conclusion that it is important to determine this old mortar and detail how it affects recycled aggregate. The few studies that have been done on this topic have all focused-on stone aggregates; however, in nations like Bangladesh, the majority of the old concrete produced by demolished buildings is constructed with brick aggregates, which have different properties than stone aggregates. The purpose of this investigation is to examine the effects of different proportions of old RM material on RBA properties and the ReC generated from them. Furthermore, numerical correlations are developed between RM and the expected properties of RCA and ReC that are created from them.

2 Experimental Program

2.1 Materials

2.1.1 Recycled Brick Aggregate

Several buildings and bridges were found to be demolished in the locality. During the demolition work, concrete blocks were collected from the sites and carried to the laboratory premises. Aggregates from 7 different sources were collected and experimented with. Information about the source concrete was collected and tabulated in **Table 1**.

Table 1. Details of RBA sources

Sl. No.	Source Type	Demolition Reason	Age (years)	Source Identifier
1	Residential Building (2-story)	Highrise construction	20	S1
2	Commercial Building (2-story)	Highrise construction	35	S2
3	Highway culvert	Road widening	20	S3
4	Highway culvert	Road widening	4	S4
5	Office building (2-story)	Highrise construction	80	S5
6	Residential Building (3-story)	Highrise Construction	25	S6
7	Commercial Building (1-story)	Road expansion	35	S7

Most of the building sources except the S7 were demolished to replace them with new high-rise buildings. The source of S7 was partially demolished as it was fallen on the way of highway expansion. The information about the demolished structure was obtained by questioning the owner of the building or authority of the bridge and culvert. The collected concrete blocks are broken into aggregates manually and also using a brick crusher. The maximum size of RBA was kept at 25 mm which is conventional in regular concreting works. **Fig. 1** shows the process of collecting and breaking down the concrete blocks into aggregates.

Fig. 1. Collection of concrete blocks and processing them to RBA.

It is to be noted that, the brick crusher produced a higher quantity of finer materials and as a result, for the same volume of demolished concrete production of usable CA in a brick crusher was lower than that produced by manual breaking. The prepared RBA materials were sieved with standard sieves as specified in ASTM E11-17 following the sieve analysis procedure as presented in ASTM C136-14 [26]. The aggregates of different sizes as separated by sieve analysis were stored in individual storage sacks.

2.1.2 Ingredients for Concrete

Other ingredients for concrete such as fine aggregates, binder, and water were managed locally. **Table 2** shows some properties of these materials.

2.1.3 Chemical for RM Removal

Anhydrous sodium sulfate was used to prepare salt solutions that separates the old mortar from RBA.

Table 2. Properties of concreting ingredients

Ingredient	Parameter	Details Information
Fine Aggregate (Natural coarse sand)	Fineness Modulus	2.60
	Specific Gravity	2.65
	Water absorption	2.5 %
Binder (Ordinary Portland Cement)	Specification and Standard	CEM-1, 52.5 N ASTM C150, Type – 1
Water		Potable tap water

2.2 Experimental Methodologies

2.2.1 Non-destructive Test of Parent Concrete

Parent concretes were subjected to non-destructive rebound hammer testing at the materials collection stage. A few technical standards that provide the testing and assessment processes are ISO 1920-7, ASTM C805, ASTM 597, and CSN EN 12504-4 [27]. Among them, this study uses the ASTM C805 Standard Test Method [28]. The Schmidt hammer, sometimes called the rebound hammer, is a test tool that employs a spring to determine the concrete surface's hardness by applying the rebound principle. For this investigation, an N-type classic concrete hammer with an impact energy of 2.207 N/m was employed.

2.2.2 Separation and Quantification of RM

In an earlier publication, the authors established that a chemical-thermal combined treatment involving freezing and thawing cycles keeping the RBA immersed in 26% sodium sulfate is suitable for complete removal of RM and thus quantifying it [29]. The same technique was adopted in the present study. Removed old mortar after the last cycle of treatment was considered as the total RM content of the sample under test. RM contents at any intermediate point of the treatment process were calculated later using the total RM content and RM removed (mass loss) up to that point. If the percentage mass loss after cycle-n and that after the last cycle are $\mathrm{ML_n}$ and $\mathrm{ML_l}$, respectively, then see Eq. (1-3)

Mass loss after treatment cycle-n,

$$ML_{\mathrm{n}}\left(\%\right)=\left(M_{\mathrm{I}}-M_{\mathrm{Rn}}\right)/M_{\mathrm{I}}\times 100 \tag{1}$$

Total RM content,

$$RM\left(\%\right)=ML_{\mathrm{l}}=\left(M_{\mathrm{I}}-M_{\mathrm{Rl}}\right)/M_{\mathrm{I}} \tag{2}$$

RM content after cycle-n,

$$RM_{\mathrm{n}}\left(\%\right)=ML_{\mathrm{l}}-ML_{\mathrm{n}} \tag{3}$$

Here, M_{I} = Initial mass recorded before treatment (gm) and M_{Rn} = Mass of RBA recorded after treatment cycle-n (gm).

RM contents of all 7 different RBA samples were calculated after the last cycles of treatment. Additionally, for the RBAs from S1 and S2, the remaining RM contents after every cycle of treatment were determined to obtain partially treated RBAs with known RM content. These two samples were used to find correlations among several properties and RM content. **Fig. 2** depicts the flowchart of research outline.

2.2.3 Testing the Properties of Aggregate

Untreated, fully treated, and partially treated RBA were tested to determine their properties. The properties that are required in the concrete mix design process and that indicate the strength and durability of aggregates were determined. To compare the results, normal brick aggregate (NBA) was also tested under similar configurations. **Table 3** shows a list of properties that were tested in this study:

Table 3. Tests of aggregate and their standards

Property under test	Test Standard
Specific gravity	ASTM C128 – 15 [30]
Water absorption	ASTM C128 – 15 [30]
Unit weight	ASTM C29 / C29M - 17a [31]
Aggregate Crushing Value	BS 812-110:1990 [32]
Los Angeles Abrasion Value	ASTM C131/C131M-14 [33]

2.2.4 Concrete Mix Design

Concrete mixes were designed following the standard procedures recommended by the American Concrete Institute in ACI 211.1 [34]. The ACI method was selected as this method was found to give the best result for ReC [35]. Five different concrete mixes were considered as presented in **Table 4**.

Using the properties of aggregates tested in the laboratory, concrete mix design calculations were made and the proportions of ingredients were worked out. For all cases, workability corresponding to 75 mm to 100 mm slump value was considered. Well-graded aggregates having sizes 9.5 mm to 25 mm conforming to ASTM C33/C33M-18 [36] were used for all mixes.Higher strength grades (more than 35 MPa) of concrete were not considered as brick aggregates usually produce low to medium-strength concrete. NBA and RBAs from sources S5 and S6 were used to prepare ReC of selected strength grades as shown in **Table 4**. From the test results, it was observed later that C-25 grade ReC yielded expected quality parameters for both the cases of S5 and S7 and based on this observation, C-25 concrete specimens were made with RBAs from all 7 different sources before and after RM removal. For each case, based on material properties, mix design calculations were made. **Table 5** summarizes the mix proportions for different ingredients.

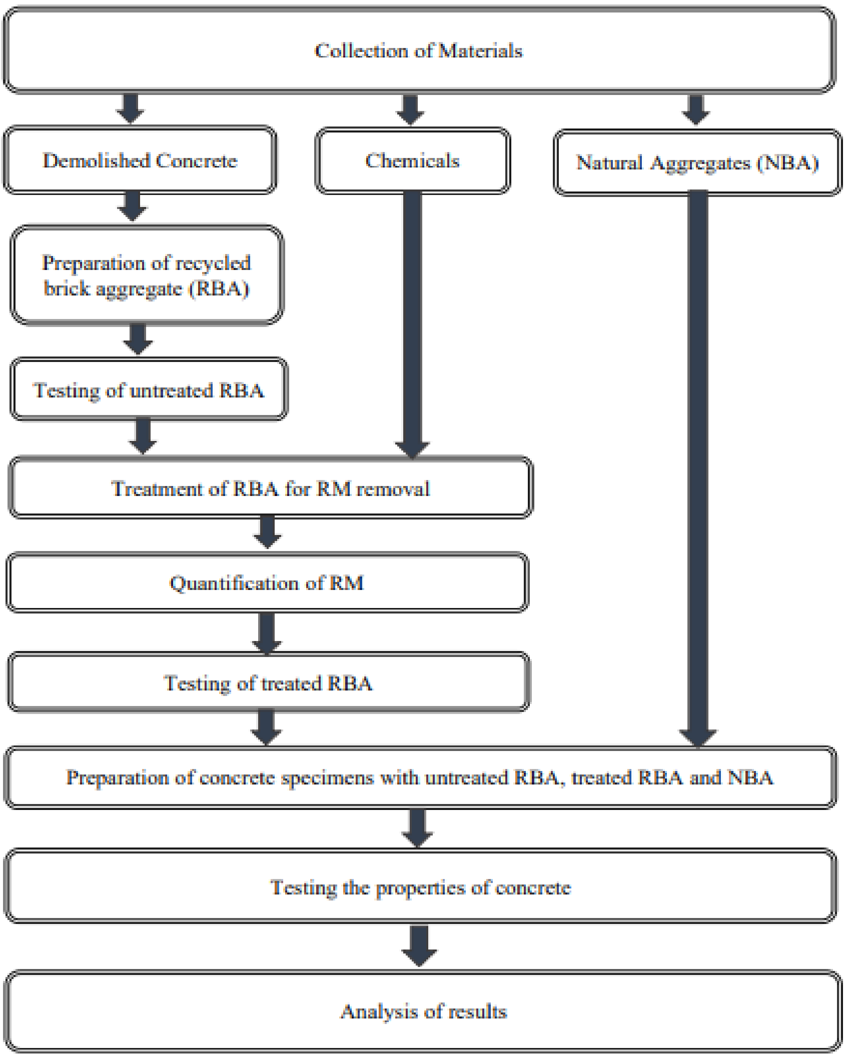

Fig. 2. Flowchart of the study outline.

2.2.5 Preparation of concrete specimens

In order to conduct compressive strength testing, concrete cylindrical specimens that complied with ASTM C39 and had a diameter of 100 mm and a total height of 200 mm were molded [38]. For the purpose of conducting spit tensile strength tests, cylindrical specimens according to ASTM C496 with an overall diameter of 150 mm and a height of 300 mm were created [39]. To conduct flexural strength tests, beam specimens having dimensions 150 mm X 150 mm X 600 mm conforming to ASTM

C78 were prepared [40]. Concrete specimens were made with untreated RBA, partially treated RBA, treated RBA, and NBA (as control). A motorized concrete mixer was used to mix the ingredients. **Fig. 3** shows the specimens for different laboratory tests.

Table 4. Ingredients for concrete of different strength grades using RBAs (S5 and S6) and NBA

Mix Name	Concrete strength grade	Water cement ratio	Unit contents (Kg/m^3)				
			water	Cement	CA		Fine Aggregate
					Type	Amount	
C15UTS5	C-15	0.66	193	293	RBA S5	745	827
C15UTS7					RBA S7	742	842
C15NBA					NBA	787	828
C20UTS5	C-20	0.58	193	334	RBA S5	745	793
C20UTS7					RBA S7	742	807
C20NBA					NBA	787	794
C25UTS5	C-25	0.50	193	387	RBA S5	745	748
C25UTS7					RBA S7	742	763
C25NBA					NBA	787	749
C30UTS5	C-30	0.44	193	435	RBA S5	745	708
C30UTS7					RBA S7	742	722
C30NBA					NBA	787	709
C35UTS5	C-35	0.39	193	491	RBA S5	745	661
C35UTS7					RBA S7	742	675
C35NBA					NBA	787	662

Table 5. Proportion of ingredients in concrete mixes evaluating the effect of source variation

Mix Name	Concrete strength grade	Water cement ratio	Unit contents (Kg/m^3)				
			water	Cement	CA		Fine Aggregate
					Type	Amount	
C25UTS1	C-25	0.50	193	387	RBA S1 UT[a]	693	569
C25TS1					RBA S1 T[b]	776	604
C25UTS2					RBA S2 UT[a]	703	643
C25TS2					RBA S2 T[b]	780	682
C25UTS3					RBA S3 UT[a]	740	715
C25TS3					RBA S3 T[b]	795	754
C25UTS4					RBA S4 UT[a]	749	713
C25TS4					RBA S4 T[b]	778	755
C25UTS5					RBA S5 UT[a]	745	748
C25TS5					RBA S5 T[b]	761	798
C25UTS6					RBA S6 UT[a]	746	746
C25TS6					RBA S6 T[b]	790	790
C25UTS7					RBA S7 UT[a]	742	763
C25TS7					RBA S7 T[b]	780	793
C25NBA					NBA	787	749

[a] Untreated (UT) [b]Treated (T)

Fig. 3. Concrete specimens for different laboratory tests

2.2.6 Testing of Concrete Specimens

Concrete specimens were tested to determine their properties following ASTM standards. **Table 6** lists the tests conducted along with the standards followed.

Table 6. Tests of concrete and their standards

Property under test	Test Standard
Workability	ASTM C143 [37]
Compressive strength	ASTM C39 [38]
Splitting tensile strength	ASTM C496 [39]
Flexural strength	ASTM C78 [40]
Density, water absorption and void	ASTM C642 [41]

2.2.7 Test Instances

Fig. 4a-f shows some instances of the laboratory experiments. Fig. 4(a) and 4(b) show the experimental setup for compressive strength and splitting tensile strength tests on concrete cylinder specimens using a concrete testing machine. Fig. 4(c-f) shows how standard test techniques are utilized to conduct flexural strength tests, compressive strength from rebound number, workability testing, and Los Angeles abrasion tests.

Fig. 4. Tests of RBAs and ReC made with them.

3 Results and Discussions

3.1 Strength of Parent Concrete

The results of non-destructive strength tests conducted on parent concrete is presented in **Table 7**.

It is advised to estimate the strength of concrete on construction sites using a rebound hammer to gauge the consistency of the material [42]. Though it may underestimate the true strength, the computation of compressive strength depending on surface hardness may be accurate for determining the overall state of the structure and the uniformity of concrete [43]. In an earlier study, the compressive strength of brick aggregate concrete obtained by the rebound hammer NDT method was found to be about 1.38 times higher than the corresponding strength obtained by the destructive test [44]. The estimated strengths of concrete obtained from different sources in this study are meant to assess the condition of concrete immediately before its demolition. The compressive strength of parent concretes from 7 different sources is found to vary from 13 MPa to 28 MPa. The oldest concrete from source S5 yielded a low strength of 18 MPa. However, the lowest strength was observed for the 20 years old source S1, which was only 13 MPa. The highway culvert source S3 and the 3-story building source S6 showed maximum strength as 28 MPa. As the strength of parent concrete largely depends on the primary mix design, which is mostly unknown, a specific pattern of strength in parent concrete is difficult the establish.

3.2 RM Content of RBA Samples

RM content of RBA samples from all the 7 sources are presented in **Fig. 5.**

Among the 7 samples, the RBAs from S1 and S2 are treated partially and their RM contents are determined after each cycle of treatment as presented in **Table 8**.

Table 7. Rebound number and compressive strength of parent concrete

RBA source	Hammer position	Average rebound number	Estimated Compressive strength (MPa)
S1	A	23.6	13
S2	A	34.1	26
S3	B	32.9	28
S4	C	38.1	25
S5	A	27.0	18
S6	B	32.7	28
S7	B	28.0	22

3.3 Influence of RM Content on RBA Quality

The quality parameters of RBA such as water absorption, ACV, and LA were determined. Considering the fully treated RBA with 0% RM, i.e. the source aggregate as control, % changes in the properties for increasing RM were worked out and plotted graphically. **Fig. 6-8** shows the % changes in water absorption, ACV and LA with increasing RM content. For each case three plots were obtained, one for the partially treated RBA from S1, one for the partially treated RBA from S2 and another one combining all the available data (S1 to S7).

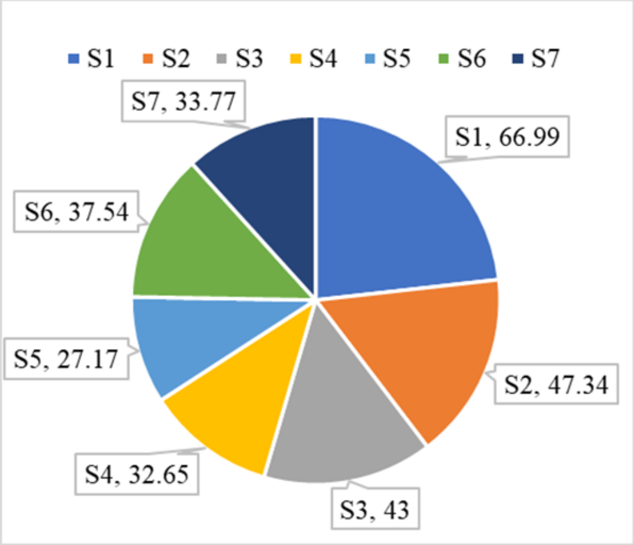

Fig. 5. Average RM content (%) of RBA from different source.

Table 8. RM content in partially treated RBA (from S1 and S2)

Cycle	RBA Source: S1 Cumulative Mass Loss (%)	RBA Source: S1 Remaining RM content (%)	RBA Source: S2 Cumulative Mass Loss (%)	RBA Source: S2 Remaining RM content (%)
0	0.00	64.90	0	46.87
1	2.00	62.90	2.04	44.83
2	7.03	57.87	6.11	40.76
3	12.79	52.11	22.14	24.73
4	27.24	37.66	39.42	7.45
5	46.72	18.18	45.98	0.89
6	56.64	8.26	46.57	0.3
7	60.02	4.88	46.87	0
8	62.94	1.96	-	-
9	64.90	0.00	-	-

Aggregates derived from bricks usually shows greater water absorption than stone aggregates. In some earlier studies, 6-19% water absorption was reported for crushed brick aggregates [45-50]. The natural brick aggregates used in this investigation had a water absorption of 9.08% which was much lower than any of the RBAs. On the other hand, recycled aggregates show high water absorption because of their porosity [51]. Water absorption of RBAs from 7 different sources were found to range between 13.35 - 24.88%. A study on 33 RBA samples showed water absorption in the range of 9-23% [52].

In some other studies, RBAs were found to have water absorption of 11-13% [17,53,54]. Increased water absorption in RBA provides internal water flow that breaks the cement – aggregate bond and increases water-cement ratio in the interfacial transition zone which is responsible for the degradation of concrete properties [51]. Therefore, the higher water absorption in untreated RBA may lead to poor performance of concrete. The increase in water absorption in RBA (expressed as a percentage of water absorption for fully treated RBA) is found to be proportional to RM content. The increase in water absorption for the presence of RM was very significant. As high as 73% increase in water absorption was observed for an RM content of 67%. Old mortar usually contains a large number of voids and pore spaces which leads to increased water absorption in RBA. The more the RM content, the more the water absorption. The relation of RM and water absorption was claimed to be proportional for stone recycled aggregates [55], but for RBAs the relation may not be an exactly proportional one because of wide variability in RBAs properties as well as variation in absorbance of original brick aggregates which is minimal for stone aggregates. Another observation can be made that at lower RM contents, the effect on water absorption is minimal. A very nominal increase in water absorption was found up to 10% RM content for both RBAs from S1 and S2 compared to be large increase for higher RM contents.

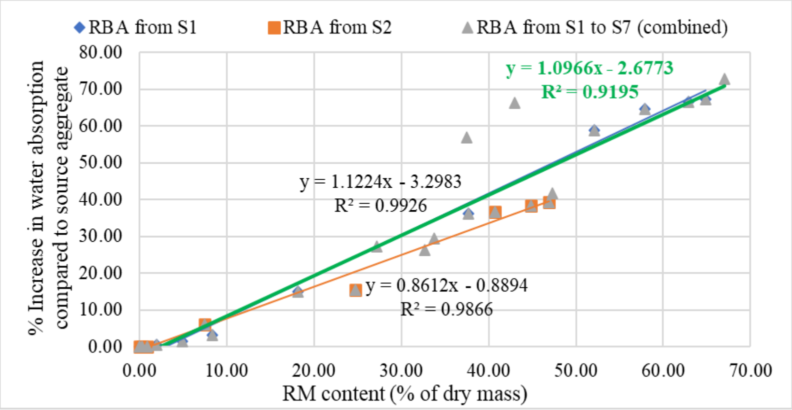

Fig. 6. Increase in water absorption with increasing RM content.

Aggregate crushing value was found to be reduced with RM removal for all cases. ACV of less than 30% is recommended for concreting work [56-58]. All the recycled aggregates under test had high ACV values ranging from 31% to 45%. After separating from the old mortar, the ACV values were found to decrease below the acceptable limit. To investigate the effect of RM on ACV increment, the percentage increase in ACV compared to the source aggregate at different RM content levels was worked out and plotted against RM content as shown in **Fig. 7**. However, at lower RM levels below 20%, the increase in ACV was less than 5% compared to the large 55% increase for 67% of RM. At lower RM levels, the effect of RM on ACV can be considered tolerable. LA values of RBAs were found to be more than that of NBA in all cases. 37-53% LA values for RBA are reported in literature [52-54]. The presence of RM in RBA is responsible for its higher LA value. During an LA test of RBA, the attached mortar is powdered in addition to abrasion faced by the original source aggregate and as a result, the LA value rises [55]. Concrete with higher strength is expected from aggregates having better abrasion resistance [59]. According to the Spanish structural concrete code, the LA value of aggregates for structural concrete should be limited to 40% [60]. None of the RBAs met this condition in an untreated state. However, after the removal of RM, most of them satisfied the requirement. The impact of RM to increase the LA value of RBAs is analyzed and the percentage increase in LA of RBA compared to the source aggregate for RM content is shown graphically in **Fig. 8**.

The trendlines of percentage increase in LA for RM content obtained from the results of this study indicate a proportional relationship between LA and RM. However, a lower R^2 value was found compared to other relations obtained in previous sections. This indicates that LA value is influenced by other factors along with RM content. Moreover, for up to 10% RM content, the effect of RM on LA value was almost zero and for RM content below 20%, the effects are very nominal.

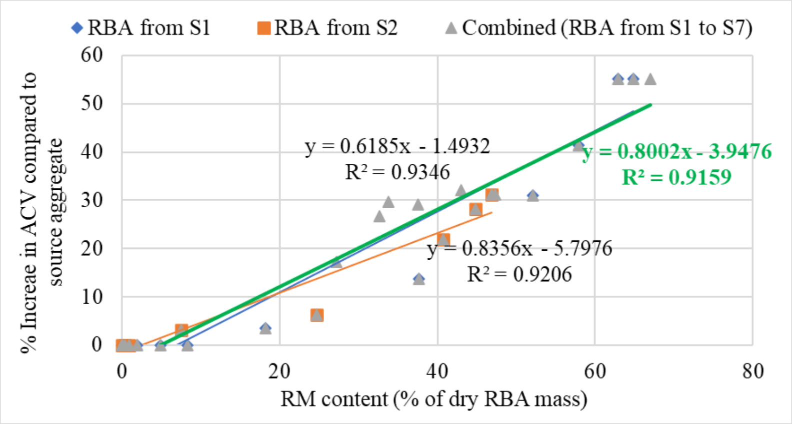

Fig. 7. Increase in ACV with increasing RM content.

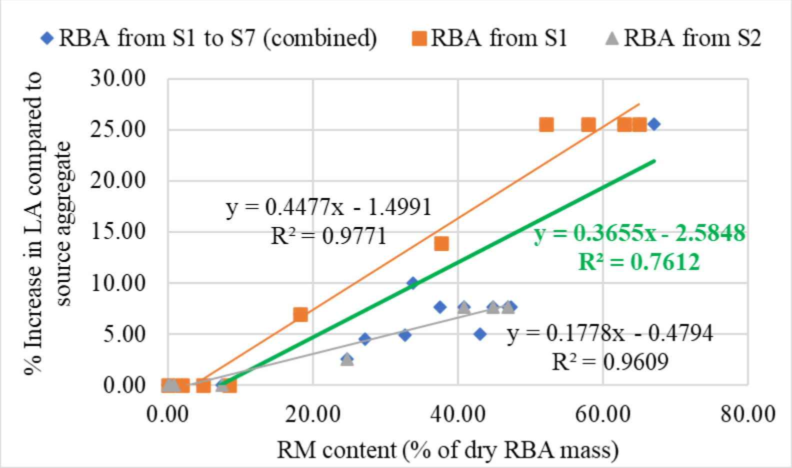

Fig. 8. Increase in LA with increasing RM content.

3.4 Influence of RM Content on the Quality of ReC

3.4.1 Influence of RM on Workability

Three different aggregate conditions were tested such as,

a. Aggregates in dry condition and no adjustment in mixing water was made for water absorption of aggregates

b. Aggregates in dry condition and mixing water were adjusted by the addition of water equivalent to water absorption of aggregate

c. Aggregate in SSD condition and mixing water was used the same as the estimated quantity

Fig. 9 shows the workability test results of concrete specimens made with RBAs form S5 and S7. Results of concrete specimens made with NBA is also shown as control. Concrete workability was found to be reduced for the usage of RCA in previous studies and the sharper geometries of RCA that reduce the slip between particles and higher water absorption of RCA that captures a portion of mixing water were identified to be the reason [21, 61]. However, the ACI 211.1 standard practice for concrete proportioning adopted in this study has a provision to adjust mixing water for water absorption of aggregate which should eliminate the effect of high-water absorption for RBA [34].

As seen in **Fig. 9**, the slump values were found to be lowest when dry aggregates were used and the corresponding adjustment for water absorption was not made. In such cases, slump values of concrete made with RBAs were found to be less than that in the case of concrete made with NBA. The slump values for ReC were well below the target slump. This finding is aligned with the findings of earlier studies. However, when the quantity of mixing water was adjusted by adding water equivalent to water absorption of aggregates, opposite scenarios were encountered. After making adjustments in mixing water, the workability of the resulting ReC was found to increase significantly and the slump values were found to be more than that for concrete made with NBA. Similar observations were obtained for concrete prepared with RBAs in saturated surface dry (SSD) conditions. Old mortar is suspected to be responsible for this observation. The presence of old mortar resulted in a higher water absorption but the added water equivalent to water absorption of RBA could not be absorbed fully during the shorter mixing period which resulted in extra water in the mix making it more workable. For SSD aggregates, the presence of excessive pores filled with water may contribute to the mixing water causing a rise in slump value. Higher workability of recycled brick concrete than 1st class brick aggregate concrete was reported in an earlier study which supports this finding [62]. To pinpoint the precise cause, further research has to be done. Slump value in all mixes is found to be reduced for stronger concrete. Although the mixing water is kept constant, the lower water-cement ratio results in a higher cement content are the mix that utilizes more water than the weaker mixes, making the concrete less workable. Increased workability for a higher water-cement ratio is reported in several reports [63-65]. It was also noticed that for C-25 grade concrete with a water-cement ratio of 0.50, the observed slump values of ReC were nearer to the target slump values. Additionally, a research found that a minimum water-to-cement ratio of 0.5 is necessary to make cement mortar workable [65]. For these reasons, the C-25 concrete grade was chosen for evaluating the effect of RM on workability. **Fig. 10** shows the workability test results of C-25 concrete specimens made with untreated and treated RBAs from all 7 sources. For these workability tests, SSD aggregates were used. It can be seen that after workability of concrete made with treated aggregates is nearly the same as that of concrete made with NBA. However, as the NBA has a sharper texture than treated RBA which has smooth surfaces as a result of chemical treatment, a slightly higher value of slump was observed for concrete made with treated RBAs than that made with NBA.

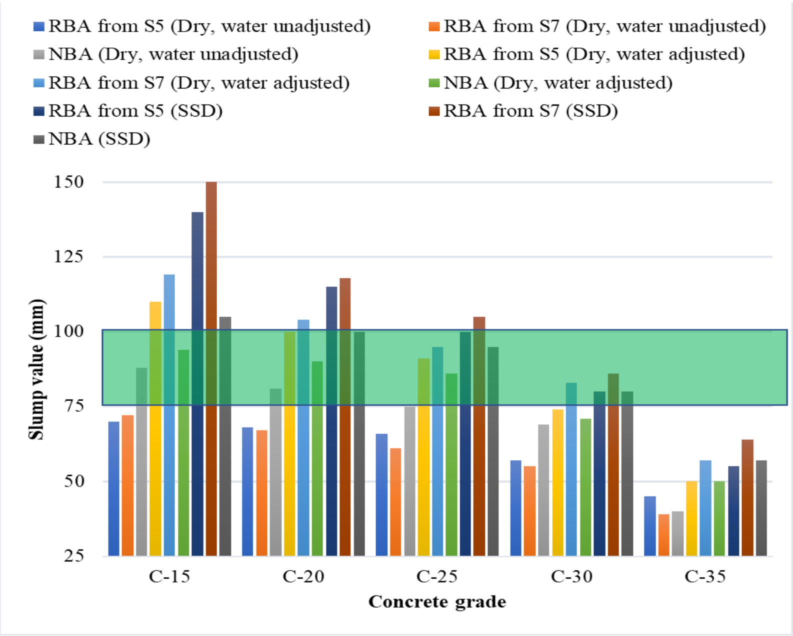

Fig. 9. Workability of concrete with different grades made with RBAs from S5 and S7.

A relationship of increase in slump value due to the presence of RM in RBA with corresponding RM content is shown in **Fig. 11**. A proportional relation between workability and RM content can be noticed in Fig. 10. However, the workability of concrete is influenced by several other factors such as aggregate size, shape, surface texture etc. [66,67] which are not addressed in this study and that's why a lower R^2 value for the trendline was found in **Fig. 11**.

For lower RM content, say for 29% of RM content, a minimum 3% increase in the workability was observed indicating that at lower RM levels, the RBA may behave like natural aggregates in terms of the workability of concrete.

3.4.2 Influence of RM on Compressive Strength

Table 9 displays the findings of compressive strength tests performed on concrete specimens of varying strength grades manufactured using RBA from S5 and S7. According to ACI 214-R11, if fewer than 15 specimens are to be tested, the required average compressive strength to be adopted in designing concrete mixes, f'_{cr} should be $f'_{cr} = \left(f'_{c} + 7\right)$ MPa for $f'_{c} < 21$ MPa and $f'_{cr} = \left(f'_{c} + 8\right)$ MPa for 21MPa≤ f'_{c} ≤35MPa [11]. The provisions were made in mix design accordingly and the concrete mixes were designed to achieve the f'_{cr}. It can be noticed that, none of the ReC achieved the target required average compressive strength, but all of them achieved the specified strength f'_{c} except for the case of C-35.

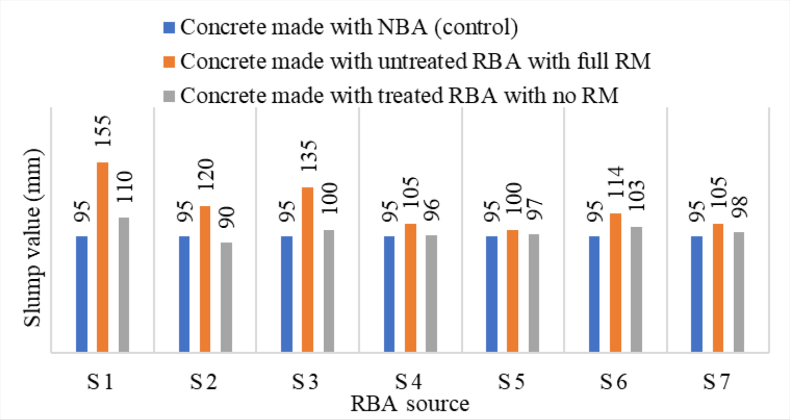

Fig. 10. Workability of ReC made with untreated and treated RBAs.

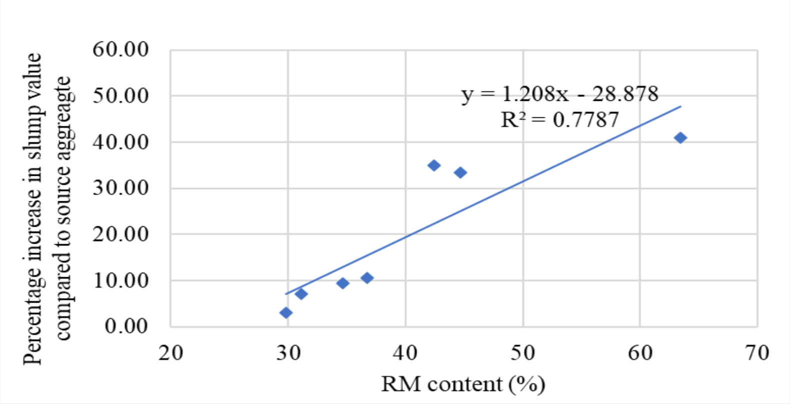

Fig. 11. Increase in slump value of ReC for RM content.

Even the concrete made with NBA could not achieve the requirement for C-35. This indicates that RBA are not suitable to produce higher strength concrete in conventional practice. Also, for lower strength concrete like C-15, deviation from target strength is the highest which indicates that RBAs are not suitable for very low strength concrete. On the other hand, for the moderately strong concrete C-25, deviation from the target strength was found to be minimal. Therefore, C-25 grade concrete would be suitable for utilizing RBAs. An extensive study carried out on RBAs from 33 different sources suggested that RBAs perform well at a water-cement ratio of about 0.45 [52]. For C-25 concrete, in this study, the water-cement ratio was taken as 0.50 which is similar to the previous finding. As C-25 grade was found to be suitable for making ReC with RBA, the effect of RM on C-25 grade concrete was evaluated in the next phase of the study. Compressive strength test results of C-25 concrete specimens made with treated and untreated RBAs from 7 different sources along with their RM content (tested individually) are presented in **Table 10**.

Significant compressive strength values were obtained for all the ReC specimens made with treated and untreated RBAs. 7-days strength of ReC s was found to be nearer to that of NBA concrete, in most cases, but for 28-days strength, the values for ReC were found to fall below that of NBA concrete indicating a higher early strength in ReC. In a previous study, keeping the water cement ratio 0.45 and 0.55, concrete with compressive strength 20.7 to 31.0 MPa was produced [13]. Concrete made with treated recycled aggregates attained almost equal strength in 28 days compared to NBA concrete.

However, rough textured or crushed aggregates give higher strength in concrete [68]. The smooth texture of treated recycled aggregate may result in a slightly lower strength in ReC made with treated RBAs.

Table 9. Compressive strength test results of specimens made with RBAs from S5 and S7

Mix Name	Target compressive strength (MPa)		Achieved compressive strength		Remarks	
	Specified strength, $f_c^{'}$	Required average strength, $f_{cr}^{'}$	7 days	28 days	Specified strength, $f_c^{'}$	Required average strength, $f_{cr}^{'}$
C15UTS5	15	22	13.46	18.45	23.00	-16.14
C15UTS7			13.35	18.02	20.13	-18.09
C15NBA			17.67	23.18	54.53	5.36
C20UTS5	20	27	20.67	24.28	21.40	-10.07
C20UTS7			17.02	22.13	10.65	-18.04
C20NBA			20.30	28.08	40.40	4.00
C25UTS5	25	33	26.95	32.23	28.92	-2.33
C25UTS7			24.55	30.90	23.60	-6.36
C25NBA			26.71	33.50	34.00	1.52
C30UTS5	30	38	27.91	33.19	10.63	-12.66
C30UTS7			23.70	30.83	2.77	-18.87
C30NBA			28.62	36.17	20.57	-4.82
C35UTS5	35	43	27.08	33.42	-4.51	-22.28
C35UTS7			24.03	28.70	-18.00	-33.26
C35NBA			29.59	35.10	0.29	-18.37

All the concrete specimens except that made with RBA from S1 meet the requirement of specified compressive strength, i.e., 25 MPa for this case. Most of the samples met the criteria for required average strength as well. A significant rise in compressive strength is noticeable after RM removal, especially for the samples having higher RM content. **Fig. 12** shows the decreasing trend of compressive strength with increasing RM content.

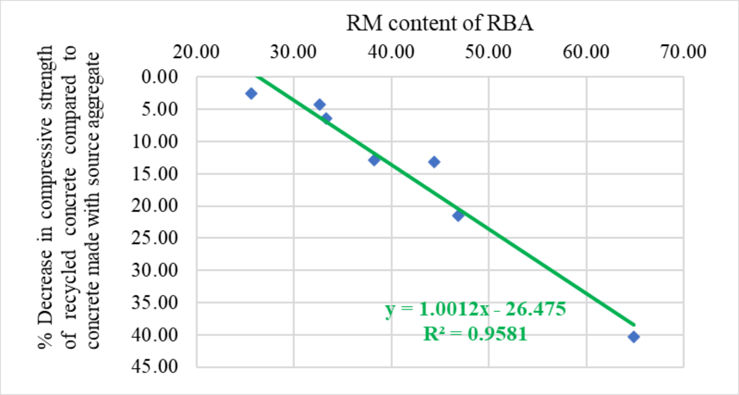

Fig. 12. Decrease in compressive strength with RM content.

The test result indicates that compressive strength is minimally reduced up to 25% of RM content. Compressive strength decreased by 40% with a 65% RM content. A further significant finding may be drawn from the 7-day and 28-day strength data. As seen in Fig. 13, concrete formed with untreated RBA has a considerably smaller improvement in compressive strength from 7 to 28 days compared to treated RBA concrete.

Also, for RBA from S5 having RM content of about 25%, loss of strength was only about 2.5% which gives an indication that, at low RM content, loss of compressive strength may be tolerable. In other words, ReC attains higher early strength in 7 days than normal concrete. This may be another effect of RM on the behavior of ReC. Higher early strength in ReC was reported in a previous study carried out on recycled stone aggregates [11].

Table 10. Compressive strength tests results of ReC made with RBAs from different sources

RBA Source	Mix Name	Actual compressive strength		% Deviation from	
		7 days	28 days	$f_c^{'}$ =25MPa	$f_{cr}^{'}$ =33MPa
S1	C25UTS1	16.41	18.93	-24.28	-42.64
	C25TS1	21.92	31.72	26.88	-3.88
S2	C25UTS2	22.83	26.05	4.20	-21.06
	C25TS2	22.54	33.2	32.80	0.61
S3	C25UTS3	25.69	29.58	18.32	-10.36
	C25TS3	25.71	34.05	36.20	3.18
S4	C25UTS4	26.41	30.78	23.12	-6.73
	C25TS4	26.12	32.16	28.64	-2.55
S5	C25UTS5	26.95	32.23	28.92	-2.33
	C25TS5	26.44	33.04	32.16	0.12
S6	C25UTS6	26.61	31.68	26.72	-4.00
	C25TS6	26.87	36.34	45.36	10.12
S7	C25UTS7	24.55	30.9	23.60	-6.36
	C25TS7	24.75	33.03	32.12	0.09
NBA	C25NBA	26.71	33.5	34.00	1.52

3.4.3 Influence of RM on Tensile and Flexural Strength

The results of the tensile strength test for splitting and the flexural strength test for various concrete specimens are displayed in **Table 11.**

Table 11. Splitting tensile strength test result

RBA Source	Mix Name	Split tensile strength (MPa)	Modulus of rupture (MPa)
S1	C25UTS1	1.27	2.72
	C25TS1	2.00	4.54
S2	C25UTS2	1.51	4.08
	C25TS2	2.44	5.29
S3	C25UTS3	1.70	3.23
	C25TS3	2.48	4.91
S4	C25UTS4	1.66	4.66
	C25TS4	2.15	5.24
S5	C25UTS5	1.92	4.57
	C25TS5	2.26	4.98
S6	C25UTS6	2.07	3.96
	C25TS6	2.48	5.52
S7	C25UTS7	2.22	5.13
	C25TS7	2.38	5.28
NBA	C25NBA	2.74	4.58

None of the tested concrete specimens could reach the tensile strength of normal concrete, not even after the removal of RM. Although the treated RBA performed equal or to some point better than the natural aggregates in terms of compressive strength, they were found to be inefficient in providing resistance against tensile stresses. However, tensile strength was also increased for treated RBA, and hence an effect of RM on tensile strength is prominent which is shown in **Fig. 14.**

A study on brick aggregate concrete reported that, at a water-cement ratio of 0.45, the splitting tensile strength of brick aggregate concrete with 30 MPa strength might be about 2.5 [46]. However, the average splitting tensile strength of normal-weight concrete is 2.8 MPa [39] which was not achieved by any of the ReC. Loss of tensile strength was found to be more severe than that of compressive strength. About 15% loss of tensile strength was encountered for about 25% RM content.

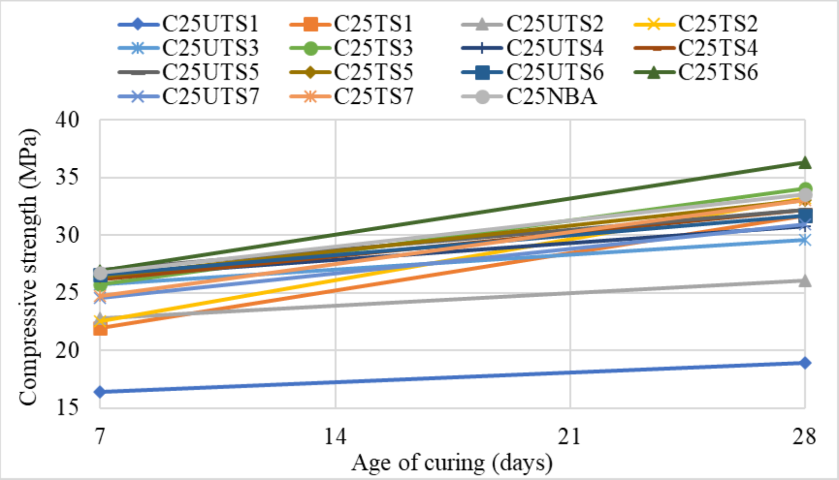

Fig. 13. Increase in compressive strength of ReC with curing age.

Table 11 lists the modulus of rupture for the beam specimens manufactured using RBA from various sources as determined by the third point load test. It can be seen that the magnitudes of modulus of rupture for concrete specimens made with untreated RBAs containing higher RM contents (such as from S1, S2, and S3) were below that made of NBA. On the other hand, the values in the cases of ReC made with RBA having lower RM contents (such as from S4, S5, and S7) lie above that of NBA concrete. Higher modulus of rupture for RBA concrete was observed in a previous study that justifies the later finding [69]. After RM removal from RBA in all the cases, the modulus of rupture of RBA concrete exceeds the value attained by NBA concrete. Studies reported the flexural strength of ReC ranging from 3.96 to 6.39 MPa [69,70]. As flexural strength was improved after RM removal for all RBA samples, there is an effect of RM on flexural strength which is shown in **Fig. 15**. 3 to 40% decrease in flexural strength due to RM content ranging from 25.62 to 64.9% was observed. When RM was around 25 to 30%, the loss of flexural strength was about 3 to 10%. At higher RM levels, severe loss as high as 40% was encountered.

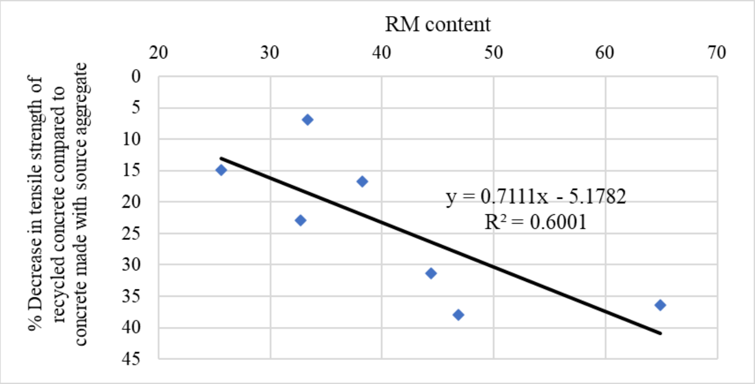

Fig. 14. Decrease in tensile strength of ReC with RM content of RBA.

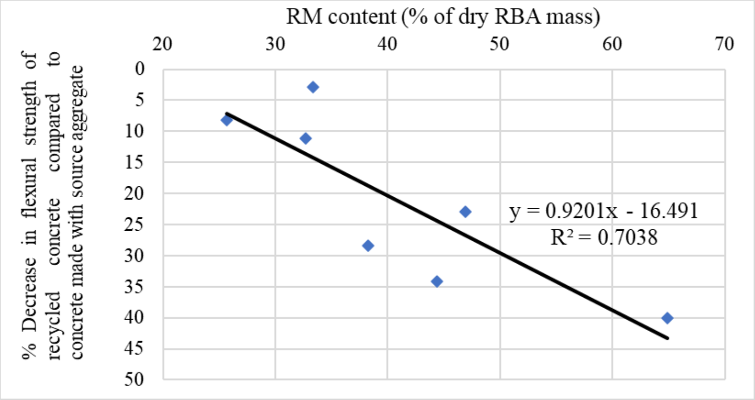

Fig. 15. Decrease in flexural strength (MPa) of ReC with RM content of RBA.

3.4.4 Influence of RM on Water Absorption, Bulk Density and Void in Hardened Concrete

Table 12 shows the results of the tests for water absorption, bulk density and void in hardened concrete. Although the density of normal-weight concrete lies between 2200 to 2600 kg/m^3 [71], brick aggregates usually produce concrete with lower density than stone aggregates [72]. About 2000 kg/m^3 density of concrete was found to be produced with brick aggregates having a unit weight of 1170 kg/m^3 [72]. In the present study, the unit weight of NBA was 1140 kg/m^3 whereas the density of corresponding C-25 concrete made with that NBA was 2043.48 kg/m^3. All the untreated RBAs produced concrete with lower density than NBA. The densities of ReC specimens made with RBAs after RM separation, however, were nearly the same as that of concrete made with NBA.

The treated RBAs from S3 and S6 produced concrete denser than that produced with NBA, possibly because they had a higher unit weight than the NBA. Water absorption and voids in hardened concrete, on the other hand, were found to be decreased in the concrete specimens made with treated RBAs than that made with untreated RBAs. For a similar water-cement ratio of 0.50, absorption and void of normal concrete made with stone aggregate were reported to be about 5.5% and 14% respectively [73]. The tested absorption and voids of concrete made with NBA in this study were 8.37% and 17.1% which are slightly more than the reported value for stone aggregate concrete. However, when untreated RBAs are used, the values were found to be increased significantly. The use of treated RBAs lowered the values, but none of them could reach the values obtained for NBA. As the properties were changed in a similar manner for concrete specimens made with untreated and treated RBAs, RM should be responsible for this change. Percentage change in the properties and corresponding RM is plotted in **Fig. 16** and **Fig. 17**.

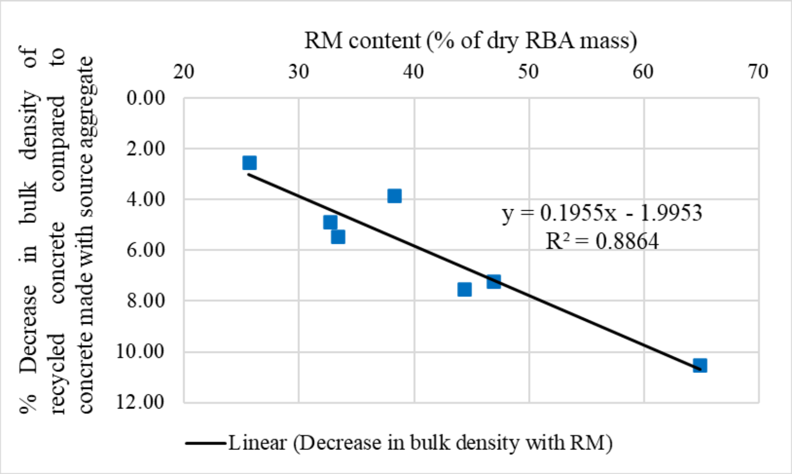

Fig. 16. Decrease in density of ReC with RM content of RBA.

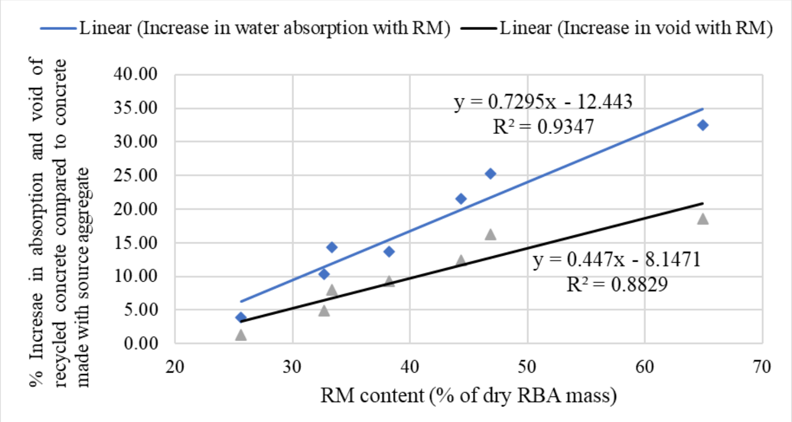

Fig. 17. Increase in water absorption and void of ReC with RM content of RBA.

Among the three tested properties, water absorption was found to be most affected by RM. As high as 32.5% increase in water absorption was noticed for an RM content of 64.9%. Although water absorption is not reliable in estimating the durability of concrete accurately, it is used as a practical compliance criterion with regard to the durability of concrete in countries like Belgium [74]. Higher water absorption and void denote poor concrete and hence the RM attached to RBAs are found to be responsible for increasing these properties. When the RM content of RBA was below 30%, the increase in water absorption and void compared to source aggregate concrete was very low and can be considered negligible.

Table 12. Results of water absorption, bulk density and percentage voids test

RBA Source	Mix Name	Water absorption (%)	Bulk density (kg/m^3)	Voids in hardened concrete (%)
S1	C25UTS1	12.89	1767.84	22.79
	C25TS1	9.73	1975.83	19.22
S2	C25UTS2	11.28	1865.87	21.04
	C25TS2	9.00	2010.84	18.09
S3	C25UTS3	9.77	1960.56	19.15
	C25TS3	8.04	2120.09	17.05
S4	C25UTS4	9.47	1940.95	18.38
	C25TS4	8.58	2040.32	17.51
S5	C25UTS5	9.90	1946.73	19.28
	C25TS5	9.53	1997.16	19.03
S6	C25UTS6	10.61	1979.34	20.99
	C25TS6	9.33	2058.00	19.20
S7	C25UTS7	11.67	1906.25	22.25
	C25TS7	10.21	2016.45	20.59
NBA	C25NBA	8.37	2043.48	17.10

3.5 Regression models

Analyzing the results, linear regression models were obtained to evaluate the effect of RM on the properties of RBA and ReC. **Table 13** summarizes the obtained regression models and their coefficients of determination, R^2.

All the models have some negative intercepts which indicate that, up to a certain low RM content, there will be no change in the properties.

Table 13. Regression models with R^2 value

Property of	% Change (increase/ ecrease) in	Regression Equation	R^2	Increase/ Decrease
RBA	Specific gravity, ∇G	$\nabla G = 0.1994\text{RM}-0.6432$	0.9842	decrease
	Water absorption, ∇w	$\nabla w = 1.0966\text{RM}-2.6773$	0.9195	increase
	Unit weight, $\nabla \gamma$	$\nabla \gamma = 0.1717\text{RM}-0.5483$	0.9103	decrease
	Aggregate crushing value, ∇ACV	$\nabla ACV = 0.8002\text{RM}-3.9476$	0.9159	increase
	Los Angeles Abrasion value, ∇LA	$\nabla LA = 0.3655\text{RM}-2.5848$	0.7612	increase
Recycled concrete	Workability (SSD), ∇S	$\nabla S = 1.208\text{RM}-28.878$	0.7787	increase
	Compressive strength, $\nabla f_c^{'}$	$\nabla f_c^{'} = 1.0012\text{RM}-26.475$	0.9581	decrease
	Tensile strength, ∇f_t	$\nabla f_t = 0.7111\text{RM}-5.1782$	0.6001	decrease
	Flexural strength, ∇f_r	$\nabla f_r = 0.9201\text{RM}-16.491$	0.7038	decrease
	Water absorption, ∇W_c	$\nabla W_c = 0.7295\text{RM}-12.443$	0.9347	increase
	Bulk density, $\nabla \rho_c$	$\nabla \rho_c = 0.1955\text{RM}-1.9953$	0.8864	decrease
	Voids, ∇V_c	$\nabla V_c = 0.447\text{RM}-8.1471$	0.8829	increase

4 Conclusions

A series of laboratory and field tests on RBA and ReC made with them led to the following findings:

The study found that increasing RM content in RBAs leads to increased water absorption, aggregate crushing value, and Los Angeles abrasion value. However, at lower RM content below 20%, quality loss is tolerable. According to the regression models, about 11% increase in water absorption, 8% increase in ACV, and 3.6% increase in LA abrasion may be expected for every 10% of RM content in RBAs.

Poor performance of RBA concrete was observed at the low and high water-cement ratios as achieved strengths deviated greatly from target strengths. At a moderate water-cement ratio of 0.5, performance was good with achieved strength nearer to the target strength.

The study also found that treated RBAs increased the compressive, tensile, and flexural strengths of ReC, suggesting that RM content may be responsible for lower concrete strengths. However, at lower RM contents up to 30%, the effects are not that significant. According to the regression models, a 10% decrease in compressive strength, a 7% decrease in tensile strength, and a 9% decrease in flexural strength may be expected for every 10% increase in RM.

Old RM attached to RBA was found to be responsible for the quality degradation of RBAs and ReC. The effects were tolerable at lower RM levels. RM up to 20% had a minimal effect on the properties of ReC. At higher RM level more than 40% severe degradation of properties were encountered.

The coefficients of determination, R2 for the obtained linear models expressing the effects of RM on the properties of RBAs and ReC were very high for the RBA of individual sources. When RBAs from multiple sources were considered altogether the values of R2 were reduced to some lower magnitudes because of source-to-source variation in the original brick aggregate. However, in most cases, sufficiently high R2 values were obtained indicating the acceptability of the models for any RBA specimen.

The use of recycled aggregates to produce new concrete is a profitable technique that would save natural resources and reduce import costs for countries like Bangladesh. To overcome the challenges related to the usage of recycled materials, the possible factors behind their lower quality need to be known and well understood. The present study identified RM as mostly responsible for lower quality of RBA and ReC made with RBA. RBAs should be tested to determine their RM prior to their use in concreting or other engineering applications. The proposed regression models can be used to estimate the expected deterioration of quality which will help to make decisions about the suitability of their usage, the amount to be used, and so on. The study results show that at lower RM contents, the detrimental effects on the properties of RBAs and ReC are tolerable. A 20% RM content may be accepted without much degrading the quality of RBAs. The study also reveals that C-25 grade concrete can be produced with RBAs having around 25% RM without compromising the strength parameters. When some RBAs with higher RM contents are to be used, their proportion of usage can be restricted to a certain limit according to their RM content and the expected loss of properties determined by the proposed regression models. However, the durability of ReC was not properly addressed in this study; further works are recommended to test the performance of RBA concrete in adverse exposures. Plain concrete is studied in this work, and the interaction of recycled aggregate with reinforcement needs to be evaluated. As RM is identified to be mostly responsible for quality degradation and a safe RM limit of about 20% is established, pre-treatment of RBAs to reduce their RM below an acceptable limit might be another important scope of further study in this theme.

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CRediT authorship contribution statement

Md Roknuzzaman: Conceptualization, Methodology, Formal analysis, Writing – original draft. **NHM Kamrujjaman Serker**: Supervision, Investigation, Validation, Writing – review and editing. **Md Mahabub Rahman**: Software, Data Curation, Visualization, Writing – review and editing.

Conflicts of Interest

The authors declare no conflicts of interest.

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