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Study on Coarse Recycled Concrete Aggregate

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Abstract The use of recycled concrete aggregate (RCA) is one of the best solutions to mitigate the problem of ecological instability created by concrete waste. RCA has less crushing strength, impact resistance, specific gravity, and more water absorption capacity than the natural aggregate (NA). To overcome the compromised properties of RCA, a comprehensive study supported by the experimental investigation is required. This paper prescribes a methodology based on experimental investigation for the use of coarse-RCA (C-RCA) of size (4.75-20mm) as 100% replacement of coarse-NA in fresh concrete. A “remodified two-stage mixing approach (R-TSMA)” supported by a physical treatment method is proposed here to increase the bond strength between RCA and new mortar. Micro-structure of RCA-C has been studied via optical microscope as well as Scanning Electron Microscope (SEM). Effect of parent concrete quality is influential only at early curing age (7 and 14 days), but after 28 days of curing its influence reduced, such that RCA-C sample showed 5% higher compressive strength and about 4% higher in flexural strength than NA-C. At 90 days of curing, all RCA samples showed higher compressive and flexural strength than NA-C. Similarly, carbonation curing enhanced the strength of RCA-C by higher margin than NA-C.

Keywords Recycled Concrete Aggregate, Compressive Strength, Splitting Tensile Strength, Flexural Strength, ITZ

1. Introduction

Concrete being heterogeneous material comprises 60-70% natural aggregates (NA) by volume. As a result, aggregates generated by recycling concrete waste can be efficiently utilized for the manufacturing of fresh concrete, achieving a dual goal of decreasing construction and demolition (C&D) waste while also preserving natural resources [1].

Aggregates obtained from the concrete waste are classified as “recycled aggregate (RA) and recycled concrete aggregate (RCA)”. RA is defined as a mixture of construction waste like old concrete, bricks, tiles, stone, etc. whereas, RCA strictly contains concrete waste [2]. RCA obtained after primary and secondary crushing produces concrete with improved strength than the RCA produced with only primary crushing [3].

Aggregates obtained after recycling concrete waste always possess a foreign material called old mortar, which has serious ramifications on its physical and mechanical characteristics [4]. Adhered mortar on RCA induces low density/specific gravity, high water absorption, higher abrasion loss, low crushing strength, and lower toughness than NA [5]. In RCA-C, due to the presence of adhered mortar, two ITZ gets developed; old ITZ (between coarse aggregate and old mortar), and new ITZ (between old and new mortar) as compared to a single ITZ in NA-C [6]. ITZ is the strength limiting factor of concrete, the presence of two of them increases the strength and durability limitations of produced concrete.

Research has been done to use RCA in all types of concrete; comparisons were made on the strength and durability parameters. Results show that the properties of concrete reduce on increasing the amount of RCA [7]. Compared to NA-C compressive strength loss of 10 to 40% was observed [8][9][10]. Similarly, splitting tensile as well as flexural strength also gets reduced by including RCA in concrete. With100% RCA, the splitting tensile strength reduces 25-30% [11] and flexural strength reduces by

3-20% [12]. The flexural strength of RCA-C has also been reported to be in close range with NA-C [13][14].

There are also several studies, in which the strength of RCA-C was reported to be equivalent as well as better than NA-C, even by using 100% of RCA. It has been reported that 75% of the RCA-C samples meet the desired target strength if parent concrete has strength more than the target strength of RCA-C by 10 MPa [15]. RCA obtained from high strength old concrete results in better concrete and vice-versa [16]. The performance of RCA-C depends more on the quality rather than the quantity of RCA [17]. With 100% coarse-RCA, a concrete mix designed for 30 MPa of target strength has been reported to reach a compressive strength of 43.1 MPa [15]. While there are also some studies reporting that the RCA produced from old concrete of higher strength contains a considerable amount of adhered mortar due to which lower strength RCA-C is produced and vice-versa [6], [18]. RCA-C has comparable properties to that of NA-C when the RCA is of homogeneous quality, and non-uniformity in the quality of RCA leads to significant strength variation in the resulting concrete [19].

Without application of any treatment method, only up to 25% to 30%, of RCA can be used as NA replacement in concrete [20]. The reduction of adhered mortar from RCA is one of the ways for its improvement, which can be achieved by the acid treatment method, heat grinding (thermal) treatment method, mechanical treatment method, and sometimes their combination [21][22]. Strength improvement of 14% was documented in HCl-treated RCA against untreated RCA- concrete and only 5% lower than NA-C [23]. By adopting the mechanical treatment method and replacing cement with 25% Fly Ash (FA) and 5% Micro Silica (MS), concrete with 100% C-RCA achieved 60.3 MPa after 56-days of curing [24]. All mortar-reducing approaches improve the strength properties and reach around 95% of that of NA-C [25]. Also, no approach could remove 100% of adhered mortar; however, using the combination of suggested treatment methods like thermal-mechanical treatment can result in good-performing concrete [26].

There are some other methods suggested in the literature that proved to improve the properties of RCA. To take advantage of RCA's high water absorption ability, it can be used as an Internal Curing (IC) agent [24]. In a different technique of mix design called "Equivalent Mortar Volume", the amount of mortar (old and new mortar) in RCA-C is tried to keep the same as that of NA-C [27]. Strengthening of RCA in concrete using different mixing techniques has also been developed [16][28]. Like in one mixing method called the "two-stage mixing approach", water is added to the mixer in two parts before and after adding cement to the mixer. The strength of the new ITZ between the new and old mortar in RCA-C is improved using the above mixing approach; as a result, all the physical and mechanical properties are enhanced [22][29].

Three varieties of RCA were used in this experiment to investigate the impact of parent concrete quality; a) RCA obtained from low-strength old concrete, b) RCA obtained from high-strength old concrete, and c) RCA obtained from the mixed type of tested old concrete samples. Three types of mechanical abrasion techniques to remove adhered mortar are compared in this study. In this study, a "Remodified Two-Stage Mixing Approach (R-TSMA)" has been used for mixing RCA-C. To use 100% coarse-RCA in the manufacture of fresh concrete, a combination of treatment techniques and R-TSMA is recommended.

2. Experimental Details

2.1. Materials

2.1.1. Cement

Physical properties of ordinary portland cement (OPC 43) used in the current study confirming to IS (Indian Standard) 8112: 1989 [30], and chemical composition of the same is listed in Table 1.

2.1.2. Natural Aggregates

Crushed dolomite was used for C-NA and for fine natural aggregate (F-NA), natural sand (zone II) available near the outskirts of Varanasi, India was used. Both F-NA and C-NA satisfied the specifications of IS 383:2016 [2].

2.1.3. Recycled Concrete Aggregates

Aggregates were recycled from the two types of old concrete; Plain concrete (without mineral admixtures) and concrete with mineral admixtures. Six distinct RCA samples were made from these two types of concrete to investigate the impact of old concrete quality on the properties of RCA. Types of RCA samples produced are listed in Table 2 which were exposed to an open environment for three months before initiating its crushing process. The schematic flow chart for the production of C-RCA is shown in Figure 1. Mechanical sieving of RCA obtained from jaw crusher was graded into C-RCA (nominal sizes 10 mm and 20 mm) following IS 383 [2], represented in Figure 4. Obtained C-RCA was then treated to reduce the quantity of old mortar adhered from it.

For the production of concrete, RCA samples were prepared as described in Table 4. RCAP1 and RCAP2 were mixed to produce RCAH, RCAP3 and RCAP4 were mixed to prepare RCAL, RCAM1, and RCAM2 were produced by mixing all types of RCA samples. RCAH, RCAL, and RCAM1 were treated with the quenching and abrasion (QA) treatment method and RCAM2 with the dry abrasion (DA) treatment method. The properties of treated and untreated RCAs are shown in Table 7.

Table 1. Physical properties of OPC 43

Chemical composition		Physical Properties	
Compound	**Weight %**	**Properties**	**Value**
CaO	63.09	Blaine's fineness (m^2/Kg)	250
SiO_2	22.19	Soundness (mm)	1
Al_2O_3	34.44	Consistency (%)	34
Fe_2O_3	34.24	Initial setting time (min.)	95
SO_3	1.81	Final setting time (min.)	241
Na_2O	1.45	Compressive strength at 28 days (MPa)	47
MgO	0.3	Specific gravity	3.13
Cl	0.08		
K_2O	0.51		

Table 2. RCA samples and description

Sample	Description
RCAP1	RCA obtained from plain old concrete of 0.40 w/c
RCAP2	RCA obtained from plain old concrete of 0.50 w/c
RCAP3	RCA obtained from plain old concrete of 0.55 w/c
RCAP4	RCA obtained from plain old concrete of 0.60 w/c
RCAPM	RCA obtained by mixing P1, P2, P3, and P4 in equal portion RCA obtained from old concrete of different w/c containing mineral admixtures; ground granulated blast furnace slag (GGBFS), fly ash (FA), and micro-silica (MS)

2.2. Experimental Methods

2.2.1. Treatment Methods

Comparison between three types of mechanical treatment methods, namely; Dry Abrasion (DA), Heating and Abrasion (HA), and Quenching and Abrasion (QA), was made to analyze their capability to reduce adhered mortar content from RCA. Then accordingly, two methods with the highest (HA treatment) and lowest (DA treatment) efficiency was then selected for treating C-RCA for its use in concrete. In the DA treatment C-RCA was ground for 1200 abrasion cycles in the Los Angeles (LA) abrasion machine, with the abrasion cycles being performed without the use of steel balls. The minimum number of cycles for abrasion is suggested up to 300 using steel balls but this result in the 60% loss of aggregate [26]. In HA, heating of RCA at 400°C for 12 hours was done before dry abrasion. In the QA method, quenching (sudden submergence of heated material in cold water) was done before dry abrasion. RCA was kept at the temperature of 400°C for 12 hours followed by submergence into cold water; this process weakens adhered mortar due to the induction of thermal stress, which then, with the help of dry abrasion, can be easily removed. Aggregates obtained from old concrete of 0.4 *w/c* were used for this comparative study. Results of adhered mortar removal are represented in Table 3. The QA method reduced the highest amount of mortar from RCA, followed by HA and DA methods. The test data shows that the smaller size aggregates (10 mm) have a higher reduction of adhered mortar than the larger size of RCA (20 mm). Because a smaller size has a larger specific surface area for the same volume than the bigger size, the presence of more mortar content in smaller size RCA is evident [1][31]. All three treatment methods helped in reducing the considerable amount of mortar from RCA, and its content of less than 44% was achieved. It has been suggested that the RCA-C performs similarly to NA-C if adhered mortar content on RCA is under 44% [4].

2.2.2. Concrete Mix

Description of samples of RCA used for production of concrete are listed in Table 4. Samples were mixed with RCA obtained from different types of concrete to replicate the industrially produced RCA.

Five types of concrete mixes were prepared, one with C-NA and other four using 100% C-RCA. All the concrete mixes were prepared for M30 grade (0.5 w/c) and according to the specifications of IS 10262:2009 [32]. The amount of aggregate, cement and sand quantity per cubic metre is given in Table 5. The slump was maintained between 75-100 mm by using the polycarboxylate ether-based superplasticizer named Sika ViscoCrete 5207 NS having specific gravity of 1.12. Dosage of superplasticizers was fixed to 1% in all RCA-C and 0.7% in NA-C. For NA-C conventional mixing technique was used but for RCA-C a novel proposed R-TSMA. In this mixing approach, water, as well as cement, was added in two parts. Coarse aggregate was added first in the mixer, and then water equivalent to its water absorption capacity was mixed for 120 seconds. Then 10% of the total cement was added and mixed for 60 seconds, followed by premixed sand and cement, further mixing was continued for 120 seconds after adding remaining water. Figure 3 shows the flow chart of TSMA [22][33] and R-TSMA.

2.2.3. Tests on Properties Concrete

Fresh concrete workability was determined using slump cone as per IS 1199 (II) [34]. The fresh concrete density was determined as per IS1199 (III) [35]. Sample size used for compression, split tensile and flexural strength test are 150 mm size cube, 150 x 300 mm size cylinders and 150 x 150 x 700 mm size prism, respectively. All testing was done as per IS 516 [36]. Concrete cubes for compressive strength test were cured for 7, 14, 28, 56 and 90 days, cylinders and prism for splitting tensile and flexural strength were cured for 28, 56 and 90 days respectively. Tap water was used as a curing agent with constant temperature at 27 degree Celsius.

Concrete cubes of 150mm size cured in water for 28 days were used to determine the water permeability. Water permeability test was carried out following IS 3085 [37], permeability coefficient was calculated using equation 1. The setup of the water permeability test is shown in Figure 2.

$$k = \frac{Q}{A\times T\times \frac{H}{L}} \qquad SEQ\ Equation \setminus *\ ARABIC\ 1$$

Where, k = coefficient of permeability (cm/sec.) = ratio of pressure head and concrete cube thickness

A = area exposed side of concrete cube (cm^2)

Q = amount of water percolating through cube (after the steady state) (mm)

T = duration over which ‘Q’ was measured (sec.)

100 mm size cubes were used to determine carbonation depth after curing in water for 28 days. The temperature, relative humidity and CO_2 concentration was maintained at 27 ± 2°C, 65 ± 5 % and 5%, respectively. The cubes were also tested for compressive strength test after being exposed to accelerated carbonation as per IS 516 (I) [36]. Phenolphthalein indicator was used to check the carbonation depth in the carbonated cube samples.

2.2.4. Characterisation

Microstructure as well as topography of hardened concrete was analysed by scanning electron microscopy using FEI NOVA NANOSEM 450 Scanning Electron Microscope (SEM) using ASTM C1723[38].

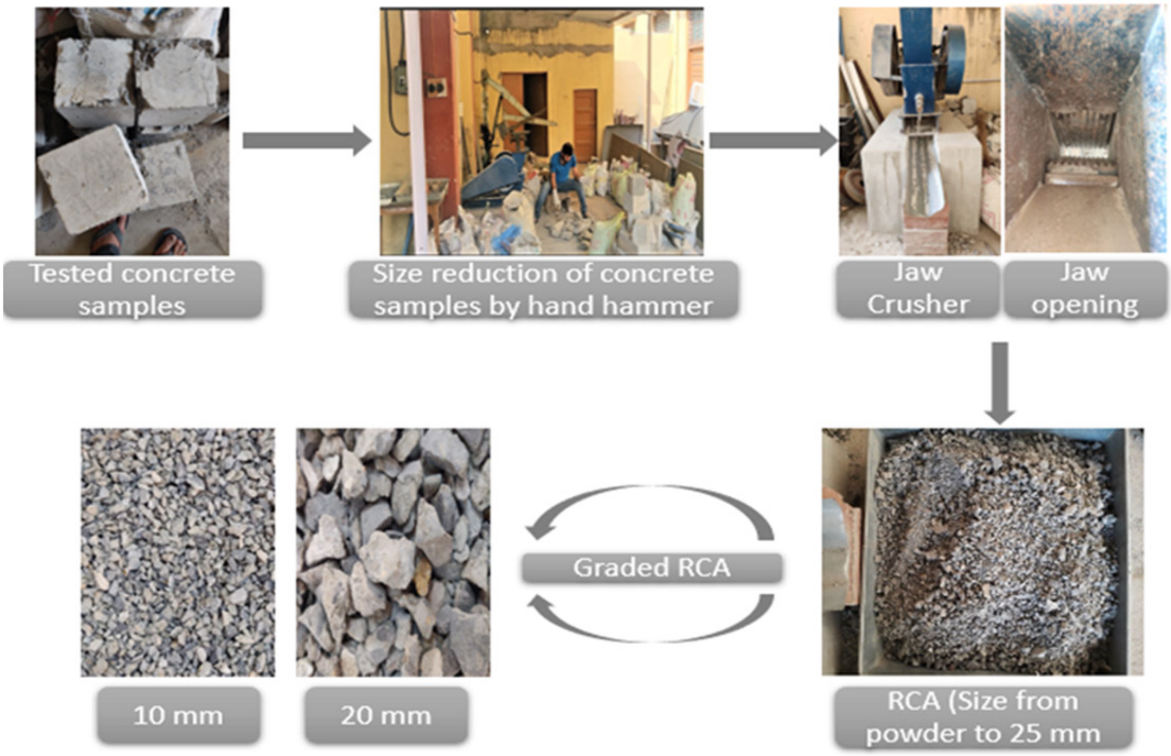

Figure 1. Schematic flow chart for the production of RCA

Table 3. Adhered mortar reduction by treatment methods

Size of aggregate	Mortar content (%) before treatment	Reduction of adhered mortar (%)	Mortar content (%) after treatment	Treatment method
10 mm	56	36.6	35.5	Dry Abrasion (DA)
20 mm	45	28.88	32	
10 mm	56	44.02	31.5	Heating and abrasion (HA)
20 mm	45	33.34	30	
10 mm	56	44.91	30.85	Quenching and abrasion (QA)
20 mm	45	37.22	28.25	

Table 4. RCA samples and description

RCA Samples	Made by mixing prepared RCA samples	Percentage	Remark	Treatment method
RCAH	RCAP1 and RCAP2	50% each	RCA obtained from old concrete having w/c less than or equal to 0.5 old concrete	QA
RCAL	RCA3 and RCAP4	50% each	RCA obtained from old concrete having w/c more than 0.5	QA
RCAM1	RCAP1, RCAP2, RCAP3, and RCAP4	25% each	RCA obtained from old concrete of different w/c	QA
RCAM2	RCAM	100%	RCA obtained from old concrete containing mineral admixtures	DA

Table 5. Mix design of RCA-C and reference NA-C

Sample	Water (l)	Cement (kg)	Sand (kg)	C-RCA (20 mm)	C-RCA (10 mm)	SP (kg)
NA-C	173	345	755	732	467	2.1
RCAH-C	173	345	755	679	421	3.45
RCAL-C	173	345	755	705	436	3.45
RCAM1-C	173	345	755	688	418	3.45
RCAM2-C	173	345	755	665	420	3.45

Figure 2. Water permeability setup

3. Result & Discussion

3.1. Properties of Aggregate

The physical and mechanical properties were examined following IS 2383:1963 (Part III and IV) [39][40]. Properties of C-NA and untreated C-RCA samples are tabulated in Table 6. The difference between C-NA and C-RCA samples are quite evident for all the physical and mechanical properties. From the results, influence of origin of RCA on its properties can be clearly observed. As the w/c of old concrete increases the specific and apparent specific gravity, whereas water absorption capacity increases.

Similarly, the crushing, impact, and abrasion value of C-RCA also showed higher loss than C-NA. The reduction in the mechanical properties of RCA was also observed to increase as the w/c ratio of old concrete increased. This could be understood as RCA obtained from old concrete of higher *w/c* has more amount of weaker and porous adhered mortar than that obtained from old concrete of lower *w/c*. RCA obtained from low strength concrete are expected to possess lower mount of adhered mortar than the same obtained from higher strength old concrete [15][41].

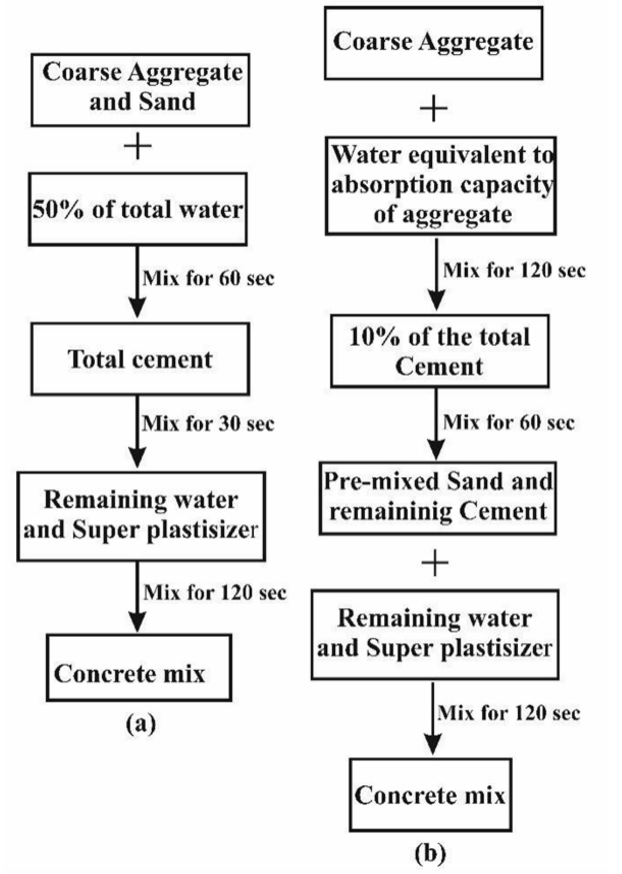

Figure 3. Mixing techniques: (a) Two-stage mixing approach (TSMA) [22], [33]; (b) Remodified two-stage mixing approach (R-TSMA)

Larger size aggregate (20 mm) showed lower variation in the physical and mechanical properties than the smaller size aggregate (10 mm) [8][42][43]. RCA produced from old concrete containing different mineral admixtures showed comparatively better properties than those obtained from old concrete without any mineral admixture. The use of mineral admixtures in the concrete as a partial replacement of cement improves concrete's overall strength [44]. The improved strength of concrete results in the better quality of RCA produced from it [15].

Table 7 represents the physical properties of RCAL, RCAH, RCAM1, and RCAM2 before and after the treatment process. Results show that after the treatment process, there is a considerable improvement in all RCA samples' properties. The property enhancement in RCA was achieved as a result of adhered mortar reduction from its surface. The percentage removal of adhered mortar content from RCAH, RCAL, and RCAM1 was 44.91%, 45.94%, and 43.72% for 10 mm, respectively. Similarly, for 20 mm, it was 37.22%, 39.08%, and 33.79%, respectively. RCAM2 showed the lowest reduction recorded as 30.43% and 37.16% for 20 mm and 10 mm size, respectively; as a result, its physical properties were the weakest of all the RCA samples. Strong mortar due to mineral admixtures in the parent concrete and DA as a treatment process resulted in the lowest reduction of adhered mortar from RCAM2.

The gradation curve of C-NA and C-RCA (RCAH, RCAL, RCAM1 and RCAM2) are given in Figure 4, which shows that the gradation of 10 and 20mm nominal size aggregates. Gradation of 20 mm C-RCA after treatment processes reduced but on small scale as compared to 10 mm C-RCA. It can also be observed that after treatment processes, there is reduction in the nominal size of CRCA. Before treatment application C-RCA had higher content of particle size greater than 10 mm. Table 8 shows the amount of RCA retained before and after treatment process on the sieve size 20mm, 10 mm, and 4.75mm. This was done to acknowledge the changes in weight fraction of C-RCA after the application of treatment. 10 kgs of untreated C-RCA sample was first sieved through to obtain the percentage weight retained, and then the same was repeated after treating those RCA. Results clearly depicts that the aggregate size from 10 to 4.75 mm increases from 45-47% to 58-60% after treatment, whereas RCA greater than 20 mm reduced. This reduction in the percentage weight was also depended on the type of treatment process applied.

Samples treated with the QA method showed better improvement than the samples treated with the DA method; this might be due to the previous method removed a higher amount of adhered mortar than later.

Table 6. Comparison in properties of aggregates

Parameters	Physical properties													
	NA		RCA											
			RCAP1	RCAP2	RCAP3	RCAP4	RCAPM	RCAM	RCAP1	RCAP2	RCAP3	RCAP4	RCAPM	RCAM
	10 mm	20 mm	10 mm						20 mm					
Specific gravity	2.72	2.84	2.28	2.3	2.31	2.35	2.32	2.35	2.48	2.49	2.52	2.54	2.53	2.55
Bulk density	1.65	1.76	1.30	1.29	1.36	1.33	1.34	1.32	1.42	1.43	1.42	1.44	1.47	1.42
Apparent specific gravity	2.81	2.93	2.48	2.53	2.52	2.56	2.52	2.58	2.62	2.64	2.68	2.69	2.68	2.71
Water absorption	0.24	0.21	6.04	5.23	5.1	4.91	5.13	5.05	4.15	3.97	3.8	3.53	3.74	3.54
Fineness modulus	5.93	7.19	6.17	6.16	6.13	6.14	6.15	6.23	7.28	7.19	7.2	7.14	7.21	7.3
	Mechanical properties													
Crushing value %	23.7	16.87	47.9	47.8	49	50.3	49.2	48.2	31.2	31.49	34.84	36.21	36.02	34.03
Impact value %	15.45	12.3	27.42	24.34	27.89	28.95	27.9	26.59	27.48	24.34	27.76	28.24	27.96	26.21
Abrasion value %	19.68	17.54	32.12	30.2	34.8	35.6	35.52	34.12	27	25.72	28.04	30.06	29.21	28.89

Table 7. Properties of RCA samples before and after treatment

Property	10 mm				20 mm			
	RCAH	RCAL	RCAM1	RCAM2	RCAH	RCAL	RCAM1	RCAM2
	Before treatment							
Specific gravity	2.30	2.34	2.32	2.35	2.49	2.52	2.53	2.55
Apparent specific gravity	2.56	2.59	2.56	2.58	2.66	2.74	2.76	2.79
Water absorption	5.27	4.96	5.17	5.05	4.06	3.7	3.75	3.58
Adhered mortar content	56	53	55	56.5	45	43.50	43.80	46
	After treatment							
Specific gravity	2.45	2.54	2.51	2.44	2.68	2.73	2.67	2.64
Apparent specific gravity	2.62	2.67	2.65	2.62	2.78	2.85	2.81	2.72
Water absorption	3.7	3.45	3.65	4.08	2.69	2.01	2.12	2.94
Adhered mortar content	30.85	28.65	30.95	35.5	28.25	26.50	29	32

Table 8. RCA retention on different sieve, before and after treatment (% retained)

Sample	RCAH	RCAL	RCAM1	RCAM2	RCAH	RCAL	RCAM1	RCAM2
Size (mm)	**Before treatment (%)**				**After treatment (%)**			
20	5.12	4.92	4.96	5.1	4.42	4.26	4.1	4.23
10	48.71	48.61	48.51	48.53	36.7	36.41	36.05	36.64
4.75	46.15	54.35	46.52	46.35	58.86	59.33	59.84	59.12

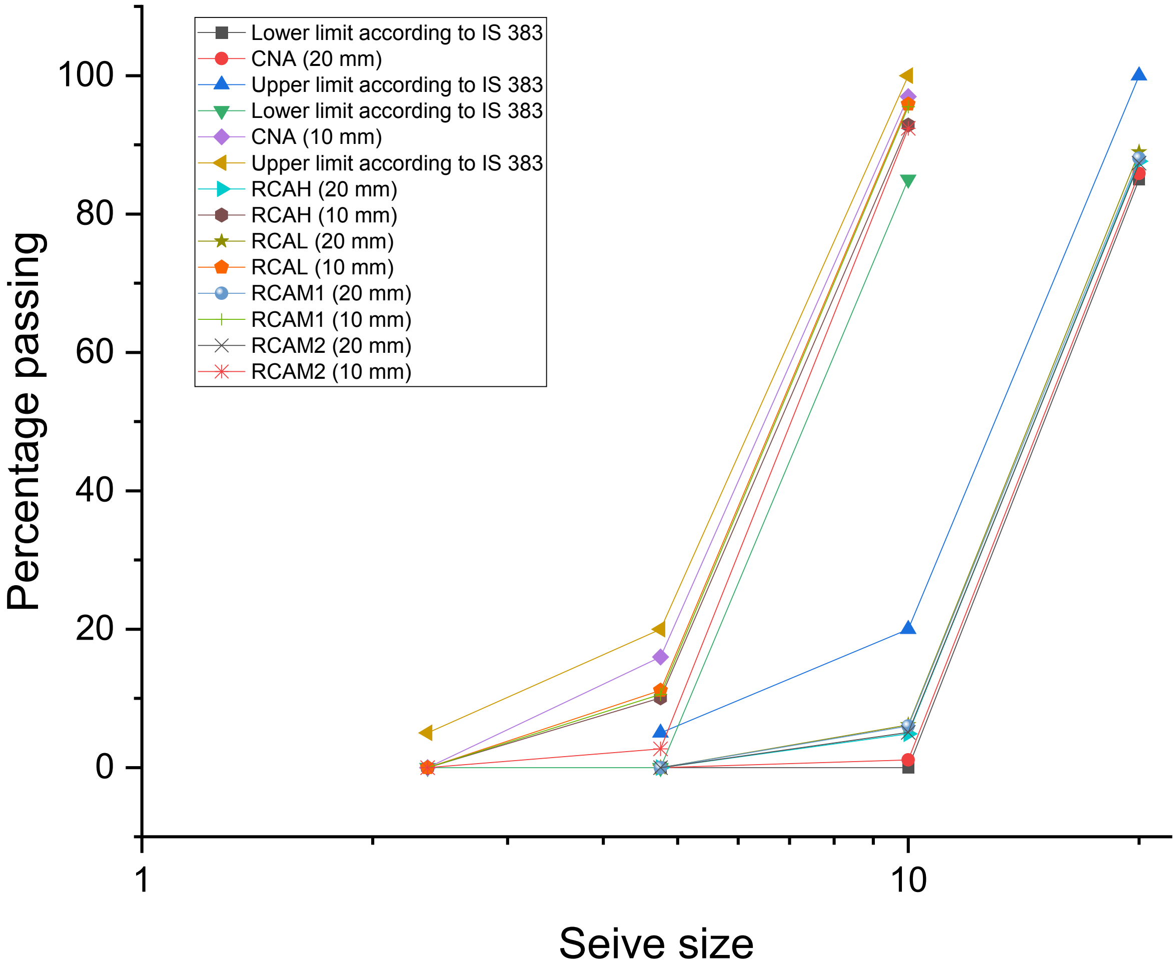

Figure 4. Gradation curves of different types of aggregates3.1.1. X-Ray Diffraction (XRD) analysis

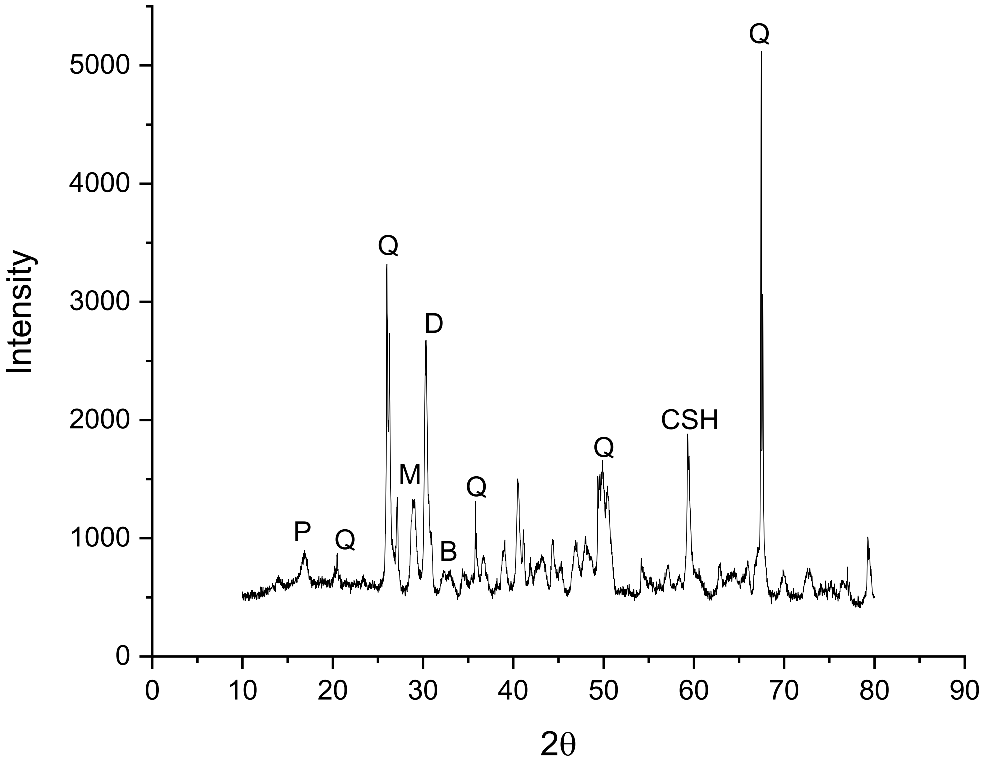

Figure 5. XRD of DA treated RCA (**C** - Calcite; **B** - Belite; **P** - Portlandite; **Q** - Quartz; **CSH** - Calcium Silicate Hydrate; **M** - Microcline; **D** – Dolomite),(2θ: angle between transmitted beam and reflected beam)

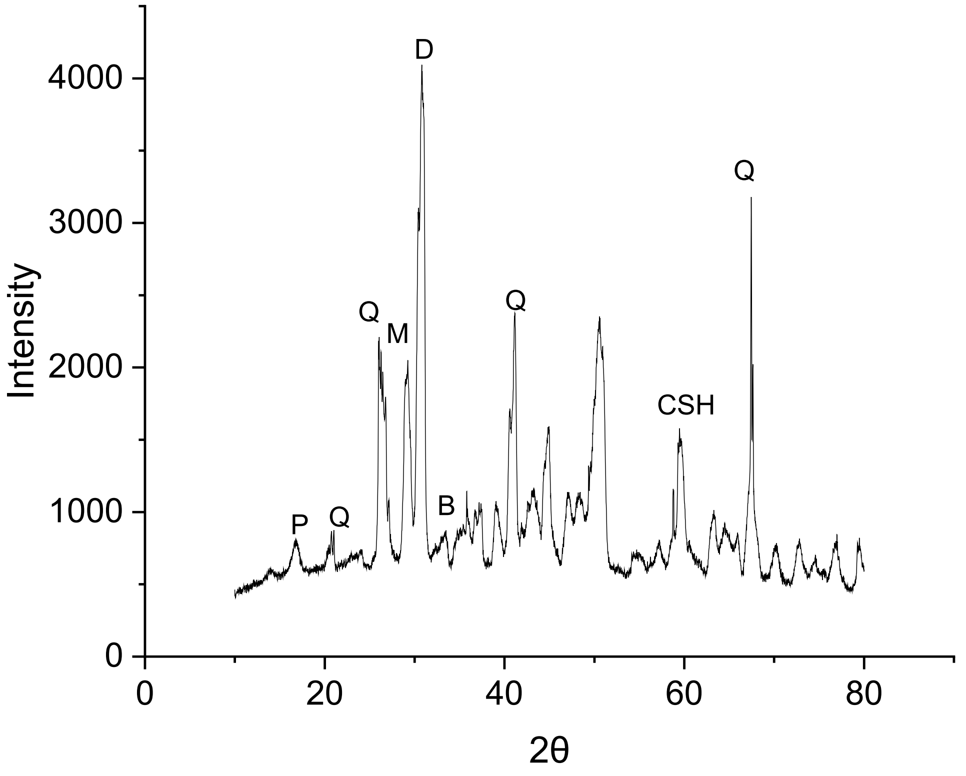

Figure 6. XRD of H&A treated RCA (**C** - Calcite; **B** - Belite; **P** - Portlandite; **Q** - Quartz; **CSH** - Calcium Silicate Hydrate; **M** - Microcline; **D** – Dolomite), (2θ: angle between transmitted beam and reflected beam)

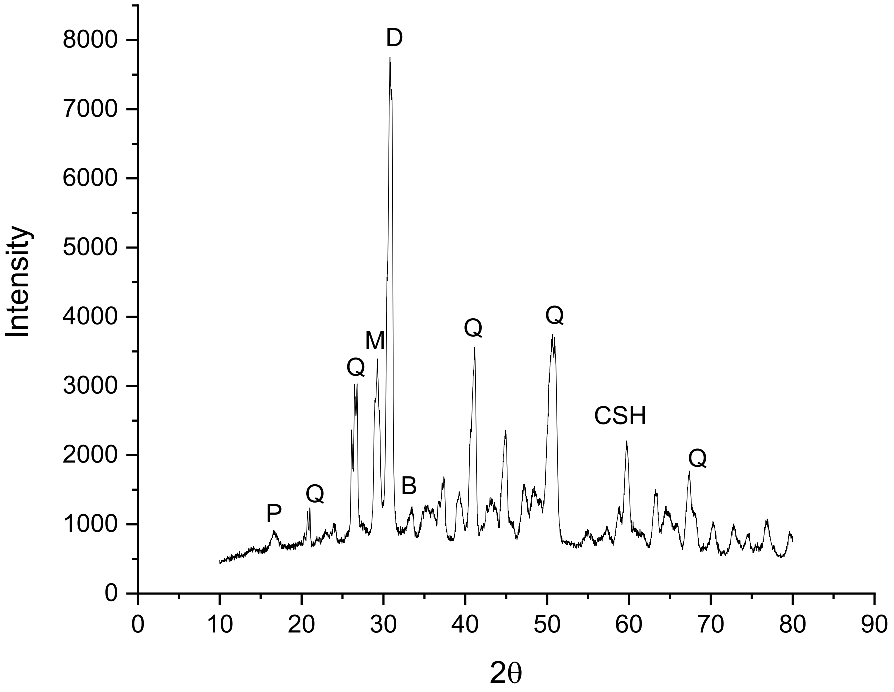

Figure 7. XRD of QA treatment RCA (**C** - Calcite; **B** - Belite; **P** - Portlandite; **Q** - Quartz; **CSH** - Calcium Silicate Hydrate; **M** - Microcline; **D** – Dolomite), (2θ: angle between transmitted beam and reflected beam)

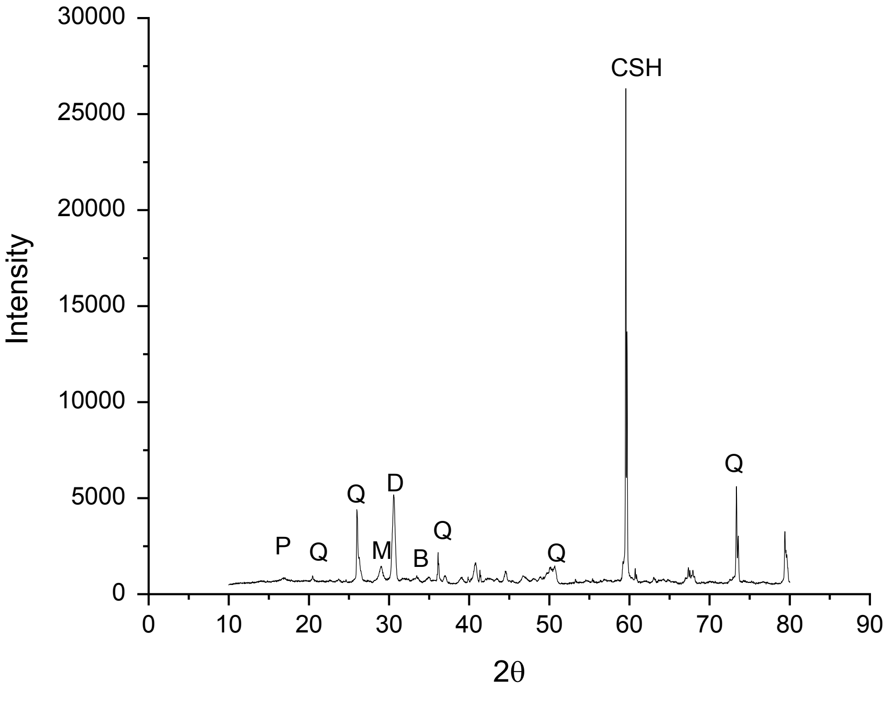

Figure 8. XRD of Untreated RCA (**C** - Calcite; **B** - Belite; **P** - Portlandite; **Q** - Quartz; **CSH** - Calcium Silicate Hydrate; **M** - Microcline; **D** – Dolomite), (2θ: angle between transmitted beam and reflected beam)

To perform the XRD analysis, powdered sample of RCA was used. The aggregates are most easily identified and described in finely ground large-area surfaces. The XRD analysis of RCA treated with different methods is shown in Figure 5 to Figure 8. Figure 8 shows the clear presence of high amount of CSH represented by primary peak in the XRD graph of untreated RCA. This peak of CSH can be clearly observed to decrease in the treated RCA. However, the intensity of calcium silicate hydrate (CHS) is similar in all three RCA treated with respective treatment method, which signifies that, the common step of abrasion in each treatment method played major role in reducing the cement hydration products in RCA. Figure 5 shows the XRD graph of RCA treated with DA method dominated with quartz peaks, followed by dolomite, whereas in RCA treated with HA (Figure 6) and QA (Figure 7) method dolomite peaks are primary followed by Quartz. Dolomite phase i.e., calium magnesium carbonate, is due to the geological origin of NA. Traces of calcite found on all type RCA, which confirms the conversion of portlandite into carbonate phase [45].

Grinding RCA to powdered form for XRD examination releases portlandite from the hydrated cement paste, which then undergoes rapid carbonation when exposed to air carbon dioxide, resulting in the formation of calcite, according to Liu et al. [46]. XRD of untreated and treated C-RCA reveals a tiny dolomite phase, being the geological origin of NA. Presence of C-S-H gel as a result of cement hydration in C-RCA is visible through the minor secondary peaks.

3.2. Fresh Concrete Properties

3.2.1. Workability

High water absorption capacity of RCA in comparison to NA reduces the workability of concrete. For maintaining the workability of RCA-C higher amount of water is required as compared NA-C. However, on increasing the water content the strength of concrete gets compromised, therefore the possible ways to control the desired slump without compromising any concrete properties are suggested in literature: 1) equivalent amount of cement should be added along with water, 2) use of high water reducing superplasticizers, 3) treating RCA to reduce its adhered mortar content, and, 4) by coating aggregate with mineral admixtures before or during mixing.

In this study combination of above mentioned suggestion has been adopted, treatment, use of superplasticizer and coating of RCA with cement (10% of the total cement) was done during mixing. Superplasticizer quantity was fixed 1% of the total cement in all RCA-C, for NA-C it was 0.6%. The slump of RCAH-C, RCAL-C, RCAM1-C and RCAM2-C were in a close range to the slump of NA-C that can be seen in the Figure 9. In fact, RCAM1-C showed better workability than NA-C, lowest slump was observed in RCAH-C followed by RCAM2-C, RCAL-C and RCAM1-C.

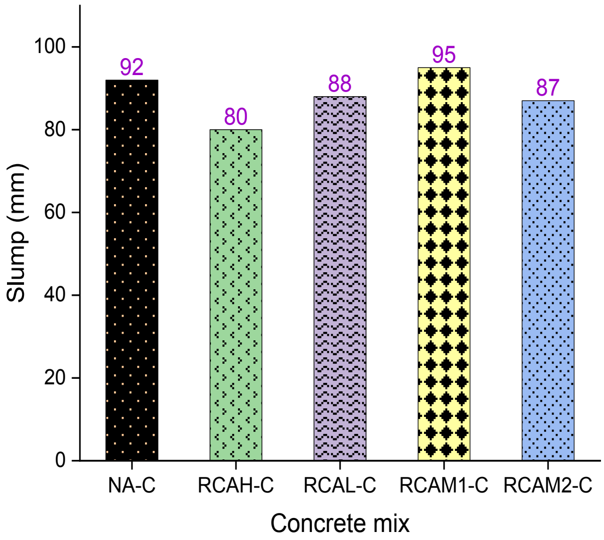

Figure 9. Slump value of NA-C, RCAH-C, RCAL-C, RCAM1-C and RCAM2-C

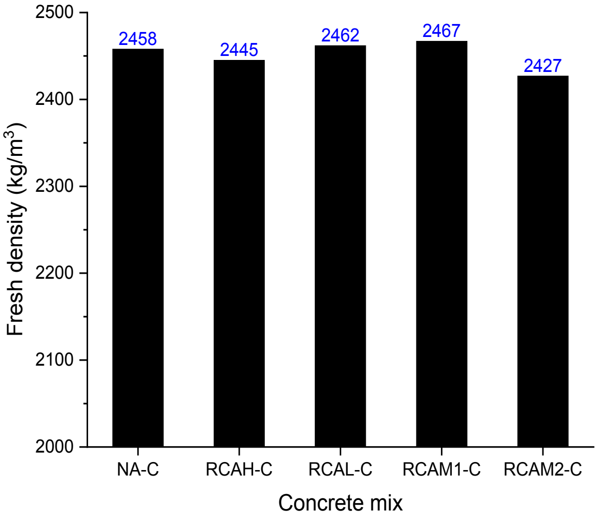

Figure 10. Fresh concrete density of NA-C, RCAH-C, RCAL-C, RCAM1-C and RCAM2-C

3.2.2. Fresh Density

The type of aggregates, w/c, and void content all affect the density of fresh concrete [51]. When a fresh concrete shows lower density, it indicates the lower strength of the same in hardened state. The reduction in density means the higher content of water and voids present in concrete, which ultimately lowers the strength. RCA contains adhered mortar, due to which the density of RCA-C is lower than that of NA-C [52][53]. Figure 10 shows the effects of C-RCA on the density of fresh RCA-C. The density of RCA-C varied with the type of RCA, concrete prepared with RCAM2 showed the lowest value of 2417 kg/m^3, 1.7% lower than NA-C, but the fresh densities of RCAH-C, RCAL-C and RCAM1-C were almost similar to that of NA-C. RCAM2 being treated by DA method showed the lowest removal of adhered mortar content, therefore reduction in its fresh concrete density was observed.

Otherwise, concrete produced with other three RCA samples showed similar density as NAC, which signifies the better removal of adhered mortar content. The combination of treatment method as well as coating of RCA with cement during mixing provided outstanding results in improving the fresh concrete density of RCA-C up to standards of NAC.

3.3. Hardened Concrete Properties

3.3.1. Compressive Strength

Compressive strength increment of concrete samples after curing for 7, 14, 28, 56, and 90 days are presented in Figure 11, and Table 9 illustrates the variation in RCA-C samples compressive strength concerning NA-C at different curing days. The difference between the compressive strength of NA-C and RCA-C was higher at early curing age (7, 14 and 28 days) than at later curing age (56 and 90 days). After curing of 28-days, concrete prepared with RCAM1 represented the highest compressive strength, followed by RCAL, NA, RCAM2, and RCAH. After 90-days of curing, all the RCA-C samples performed better than NA-C. According to the compressive study data, the combination of treatment methods applied on RCA for removal of adhered mortar and adoption of proposed R-TSMA improved the performance of RCA-C. Lower reduction of adhered mortar has been observed in the RCA produced from concrete of higher strength. Hence, RCAH-C exhibited lower compressive strength at early age [16], but showed relatively improved compressive strength after 28-days of curing. RCAM2-C showed similar trend even though the reduction of adhered mortar by DA method is lower than the QA method applied in other samples.

Generally, compressive strength of concrete produced with RCA is expected to be lower than the respective concrete, especially when 100% RCA is used. The reduction is reported to be in the range of 10-40% [8][11][54] depending upon the type of RCA used. But there are also some studies in which the performance of RCA-C are reported to be equivalent or sometimes higher [11][55][56] than NA-C, and this was achieved by applying some treatment process on RCA. In most of the studies treatment processes adopted has limitation to be used on large scale; like increasing the cement content, using costly methods like rapid carbonation, use of chemicals like HCL and H_2SO_4, and other different processes with high energy input. To achieve sustainability, both environmental and economic aspects should be taken into account. In order to use recycled materials with an objective to reduce the carbon footprints, process that itself uses lot of energy should be least motivated.

Use of mechanical treatment for RCA is the lowest carbon generation process that can produce very high quality aggregates with minimum loss. In this study also, two types of treatment method were used which are totally mechanical in nature. Out of the two methods, QA method reduced higher amount of adhered mortar but requires higher energy input as compared to DA method which is a process of low energy input and less time conserving. In the end result, concrete of desired strength was produced by both types of treated RCA, RCAM2-C performed similar to that of NA-C while compressive strength RCAM1-C was 5% more than NA-C after 28 days of curing. This result shows that the application of R-TSMA developed internal curing phenomenon and improved the bonding between aggregate and mortar. The presence of adhered mortar acts as an internal curing agent, which helps strength gain at later stages [24][57]. The presence of unhydrated binding material in the remaining adhered mortar also induces the later age strength gain of RCA-C. Reduced size of treated RCA in comparison to NA also helped good packing and, hence, better compressive strength.

Table 9. Percentage variation in compressive strength of RCA-C compared to NA-C at different curing stage

Days/Sample	7-day	14-day	28-day	56-day	90-day
RCAH	-1.66	-7.60	-0.85	1.11	2.64
RCAL	0.33	-2.00	2.93	3.47	3.79
RCAM1	2.33	-2.68	5.12	5.80	4.51
RCAM2	-3.00	-5.96	-0.24	0.59	0.92

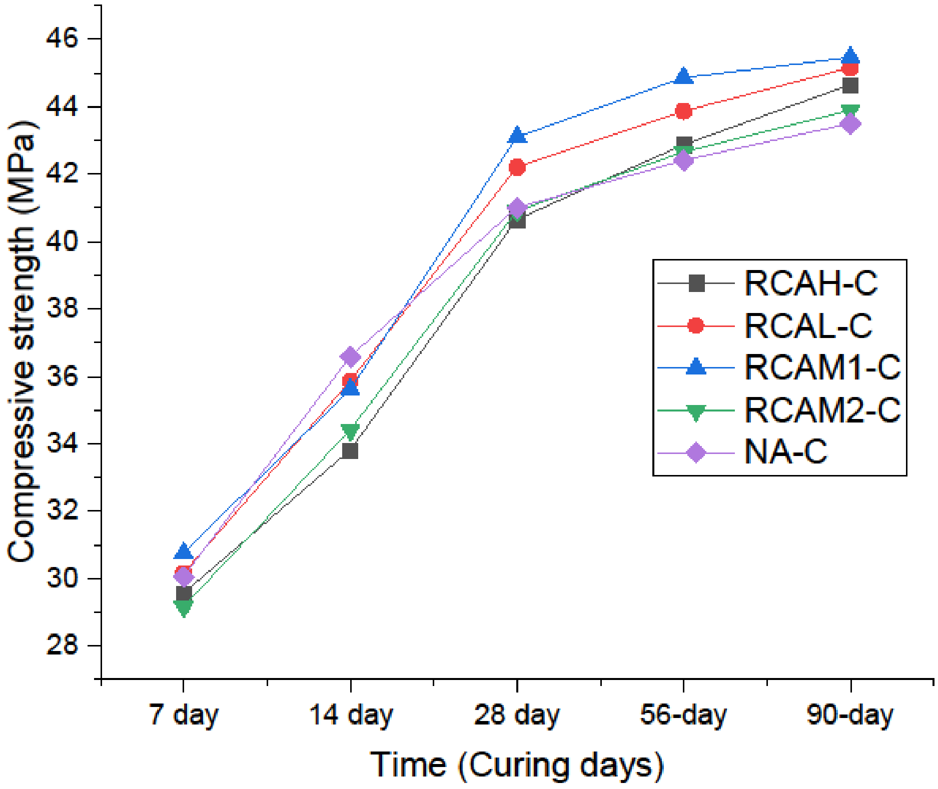

Figure 11. Variation in compressive strength with curing days

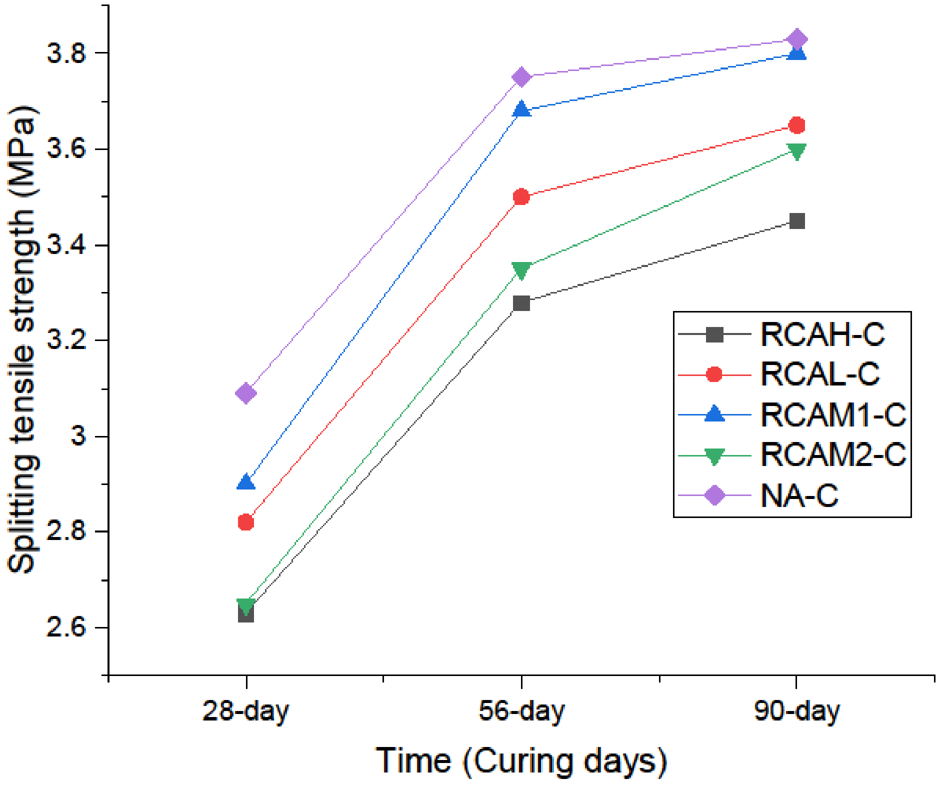

Figure 12. Splitting tensile strength with curing age

3.3.2. Splitting Tensile Strength

Data presented in Figure 12 and Table 10, show that all mixes of RCA exhibited lower tensile strength than NA-C. The splitting tensile strength of concrete produced using RCAH, RCAL, RCAM1, and RCAM2 at 28-days was 14.89%, 8.74%, 6.15%, and 14.24% lower than the NA-C, respectively, after 90-days this difference reduced to 9.92%, 4.70%, 0.78%, and 6.01%, respectively. This demonstrates that the presence of RCA effects more in splitting tensile strength than in compressive strength, but the gain in strength after 28 to 90 days is also explicit. At 28-days, the highest reduction was around 15% which was reduced to 10% at 90-days of testing. At early curing age the effect of adhered mortar is more adverse than at higher curing periods, as the curing age increased its adverse effect reduced. Similarly, as in compressive strength, RCAH-C and RCAM2-C performed the lowest in splitting tensile strength at all testing ages. RCAM1-C performed best among other RCA-C samples, and after 90 days, the results were almost similar as NA-C. RCAM1-C and RCAM2-C contained the same type of RCA but treated with different methods, and the results show that RCA obtained from the QA method produces better concrete than RCA treated with the DA method. A combination of removing adhered mortar and then strengthening it using modified R-TSMA served the purpose well, and concrete with better strength could be produced.

Table 10. Variation of RCA-C samples against NA-C

Sample	28-days	56-days	90-days
Splitting tensile strength			
RCAH-C	-14.89	-12.53	-9.92
RCAL-C	-8.74	-6.67	-4.7
RCAM1-C	-6.15	-1.87	-0.78
RCAM2-C	-14.24	-16.8	-6.01
Flexural strength			
RCAH-C	0.77	-1.75	-0.43
RCAL-C	-1.79	-0.66	1.08
RCAM1-C	4.62	2.4	3.23
RCAM2-C	3.08	1.31	2.37

3.3.3. Flexural Strength

For the flexural strength test, three concrete beams measuring 150 mm x 150 mm x 700 mm were prepared. Figure 13 shows the flexural strength test results for all concrete samples based on curing days; Table 10 shows the difference in flexural strength between RCA-C samples and NA-C samples, which shows that all the RCA-C samples performed similarly to, if not better than, NA-C. Using coarse-RCA as a replacement of coarse-NA does not negatively affect flexural strength [58][59], provided its high impact in tensile strength and marginal in compressive strength. The graph shown in Figure 16 demonstrates that the strength gain rate at different curing ages is also similar for all the concrete samples. Concrete mix prepared with RCAM2, RCAM1, and RCAL resulted in higher flexural strength than NA-C, while RCAH-C showed similar strength. The treatment methods applied to remove the loose and weak adhered mortar from C-RCA in combination with the new mixing technique (R-TSMA) helped produce a better concrete mix and enhanced the mortar aggregate bond.

3.3.4. Water Permeability

One of the most important factors in the concrete durability is its capability to resist water permeability. If water permeability resistance of concrete is low, then it is susceptible to fast deterioration. There are different ways available in literature to test the capacity of concrete to absorb water like saturated water absorption test, water sorptivity test, etc. [60][61]. The procedure to determine the coefficient of permeability ('*k*') provided in IS 3085 [37] was followed in this study, and its values for all concrete samples are shown in Figure 14.

Results clearly exhibit that the RCA obtained from different types of older concrete does not have any clear impact on the water permeability of RCA-C concrete, when the method of treatment is same for the RCA. However, difference in the '*k'* value of RCAM1-C and RCAM2-C is recognizable, with high coefficient value for RCAM2-C than RCAM1-C. Aggregates treated with DA method reduced less amount of adhered mortar as compared to QA method, therefore, old mortar presence in RCAM2-C was higher than RCAM1-C which resulted in higher water absorption.

The '*k*' value of RCAH-C, RCAL-C, RCAM1-C and RCAM2-C after 28 days of curing was approximately 1.56, 1.46, 1.52 and 1.61 times higher than that of NA-C, respectively.

In case of RCA, there is a scope for internal curing due to the presence of adhered mortar, which facilitates the concrete by releasing the absorbed extra water during mixing. However, this effect is significant if the curing of concrete is extended beyond 28-days. The effect of internal curing was also observed in strength results of sample like RCAH-C and RCAM2-C in which the adhered mortar content is higher than other samples. But if the curing period is less than or equal to 28-days, the same absorbed additional water influences the water volume and pore numbers, which in turn damages the matrix of ITZ.

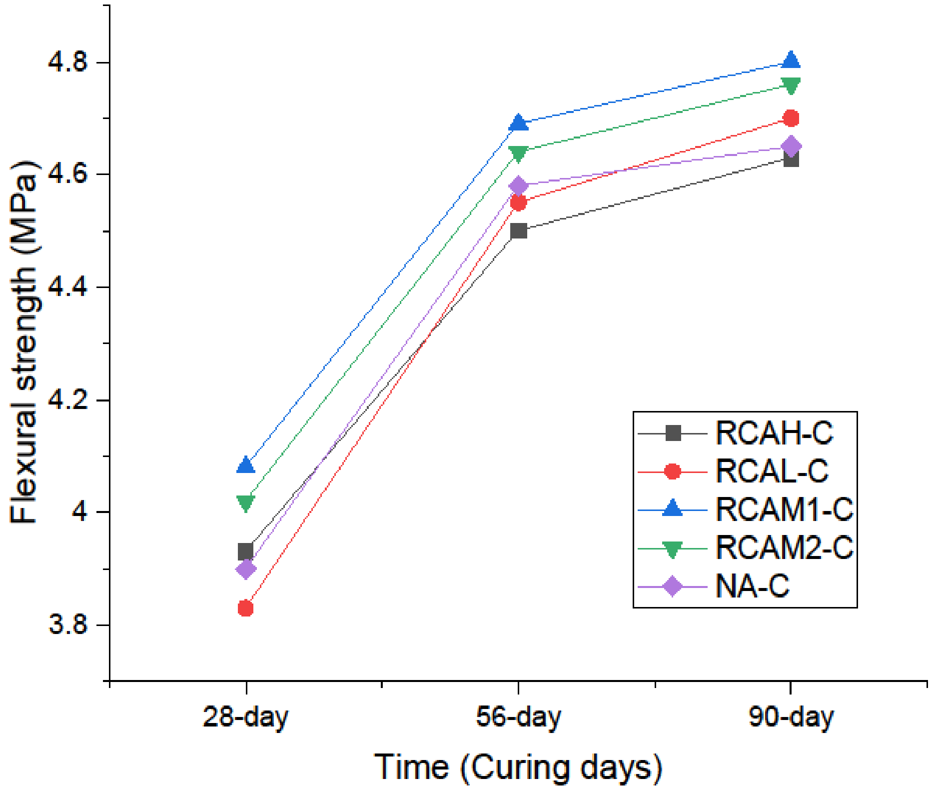

Figure 13. Flexural strength with curing age

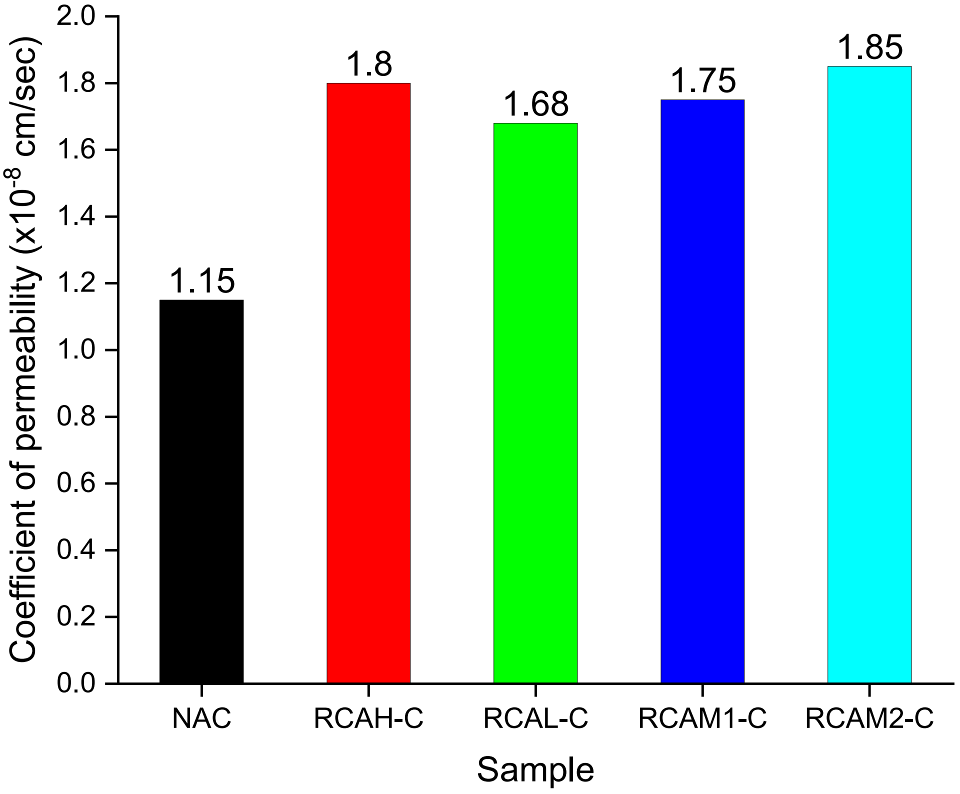

Figure 14. Coefficient of permeability of the concrete mixes

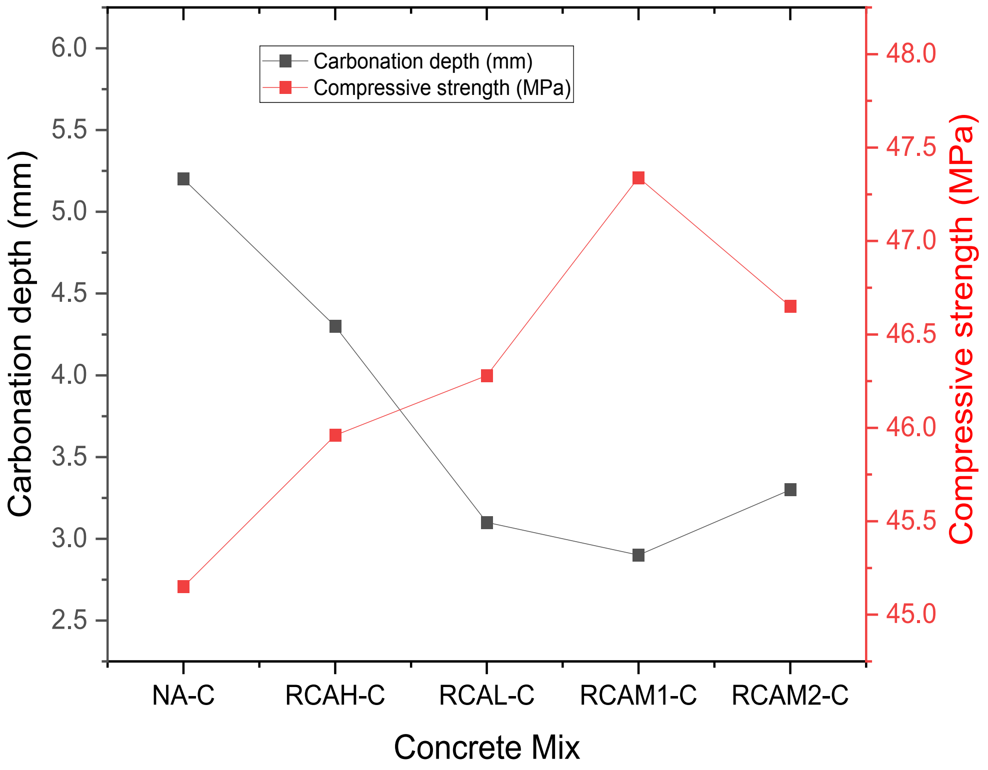

Figure 15. Carbonated compressive strength vs Carbonation depth

3.3.5. Carbonation

In carbonation reaction, the products of cement hydration react with atmospheric CO_2 and humidity to form carbonates ($CaCO_3$). When concrete is purposely exposed to CO_2, however, faster carbonation reactions (C_3S/C_2S interaction with CO_2) occur along with early cement hydration. $CaCO_3$ is formed by both methods of carbonation, and $CaCO_3$ occupies more space than $Ca(OH)_2$, resulting in a denser concrete matrix [64][65].

Nonetheless, carbonation reduces the pH value of the concrete, destroying the passivity of the reinforcement's protective layer. Anyway, it takes a few years for weathering carbonation to reach the level of reinforcement, whereas rapid carbonation could be used on unreinforced/plain concrete to eliminate the risk of reinforcement corrosion in concrete [66][67].

To study the effect of accelerated carbonation, compressive strength comparison was done for concrete samples cured in water for 56-days to the samples (carbonated concrete) cured in water for 28-days additiony subjected to rapid carbonation for another 28-day (Figure 15).

For concrete mix NAC, RCAH-C, RCAL-C, RCAM1-C and RCAM2-C the carbonated concrete had 6.49%, 7.21%, 5.49%, 5.53%, and 6.46% higher compressive strength than concrete cured in water, respectively.

Furthermore, compressive strength of all RCA mix cured in water for 56-days was lower than NAC but after accelerated carbonation curing mix like RCAM1-C, RCAH-C and RCAM2-C showed better strength than NAC. It might be associated with the presence of supplementary hydration products ($Ca(OH)_2$ and C-S-H gel) in the old mortar adhered to RCAs. These hydration products form additional $CaCO_3$ when exposed to CO_2, which as a result make the concrete more compact. The carbonation depth of all the concrete mix is presented in Figure 17. Figure 16 shows that the relationship between carbonation depth and the compressive strength of carbonated concrete is inversely proportional [60]. In general, increased compressive strength is linked to a smaller pore volume and a more compact microstructure. As a result, CO_2 from the atmosphere is unable to reach the water in the pores, and carbonation of concrete is reduced [68].

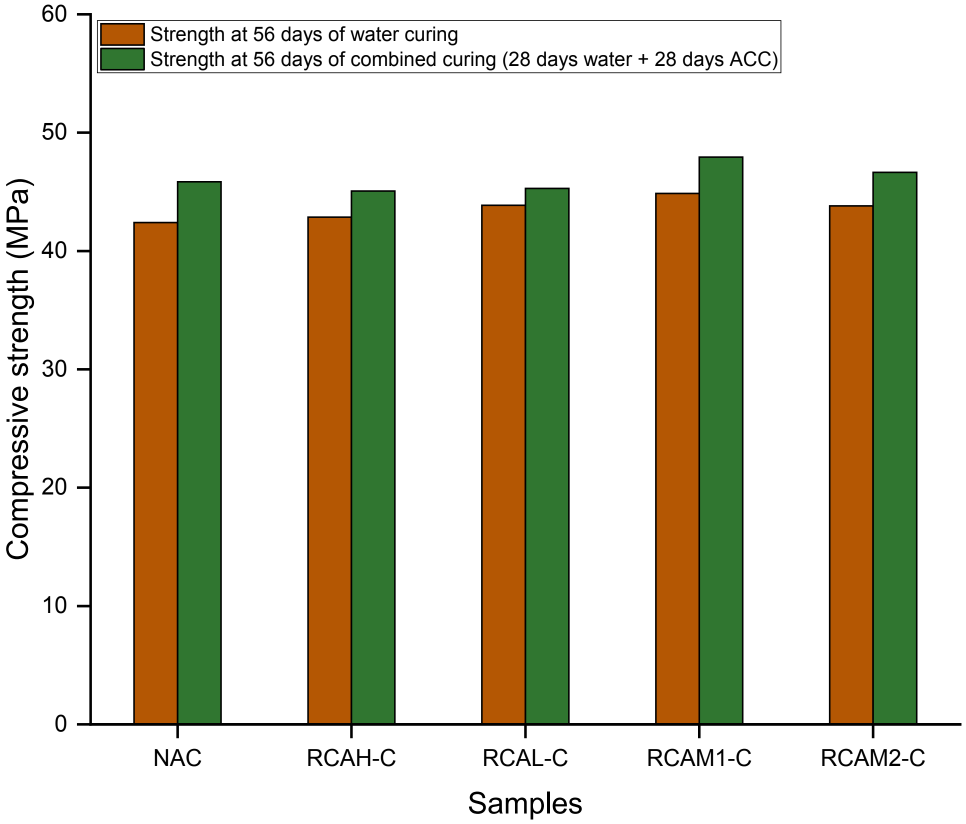

Figure 16. Carbonated compressive strength vs Compressive strength after water curing

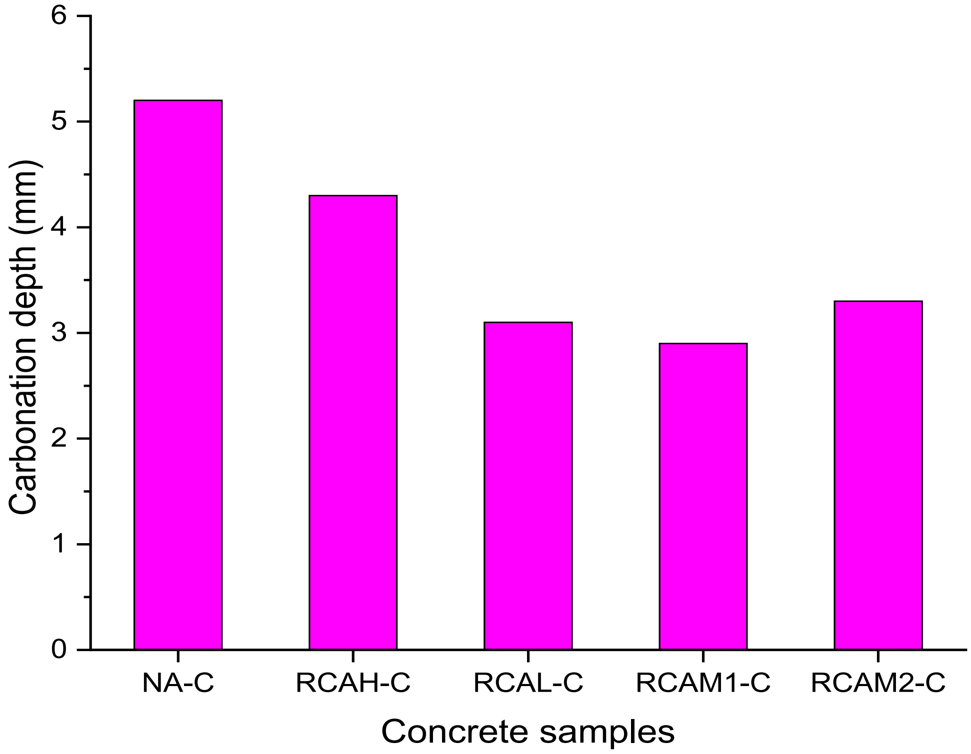

Figure 17. Carbonation depth of NA-C, RCAH-C, RCAL-C, RCAM1-C and RCAM2-C 3.4. Micro-structural property

3.4.1. Scanning Electron Microscopy (SEM)

The microstructural differences between aggregate mortar matrix of concrete produced with NA and different types of RCA have been identified using SEM. Samples of size less than 10 mm X 10 mm were obtained from the fractured concrete at 90 days, which were then gold plated before starting SEM analysis. Figure 18 to Figure 22 shows the SEM micrographs of NA-C, RCAH-C, RCAL-C, RCAM1-C, and RCAM2-C, respectively. Various phases in SEM micrographs of concrete microstructure were identified based on the extensive findings of past studies.

The emergence of additional ITZ in RCA-C due to adhered mortar's presence increases the weak links in concrete. These weak links created more adverse conditions when the RCA obtained are from different types of source concrete. It has been reported that the treated RCA provides more stable ITZ than untreated RCA in concrete; however, if a mixing approach is adopted to provide a coating of cementitious material on RCA, its adverse effect on the resulting concrete can be easily reduced. The reduction of loose adhered mortar plays a significant role in improving RCA's properties, but the strengthening of adhered mortar by a surface treatment method is equally crucial to improving RCA concrete's overall properties.

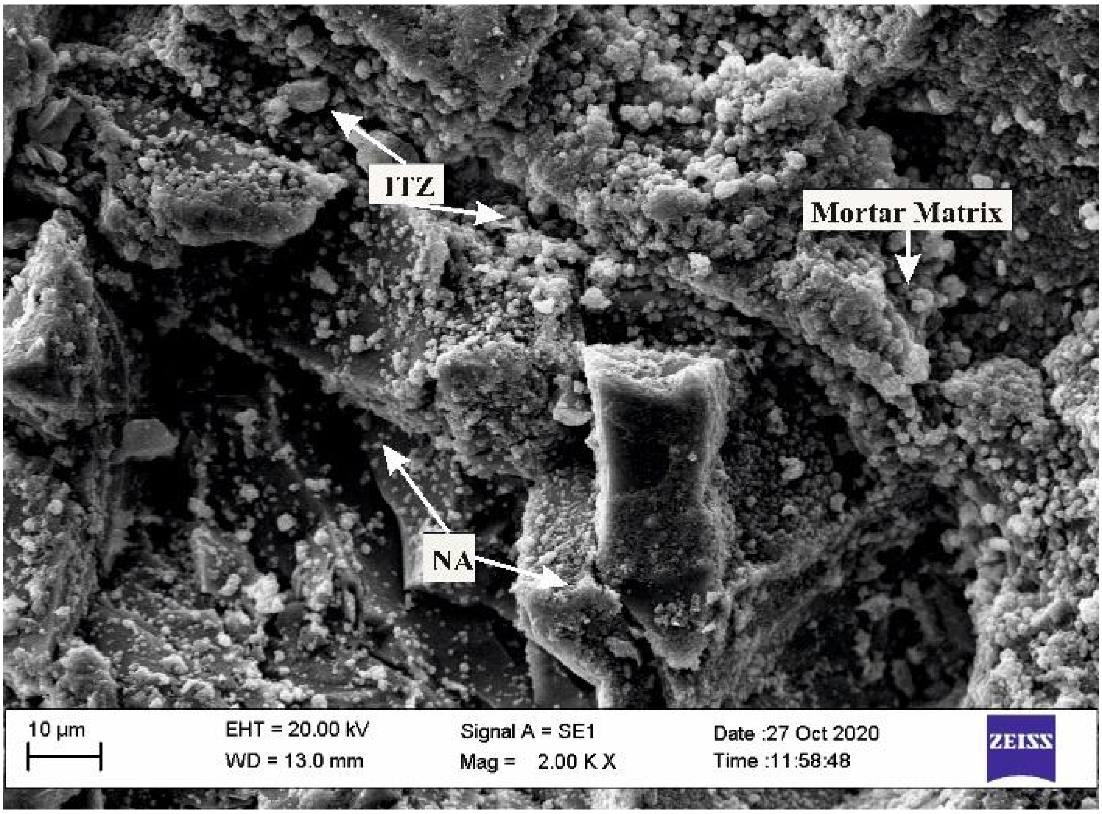

Figure 18. SEM micrographs of NA-C showing strong ITZ bond between coarse-NA and cement paste, at 90 days

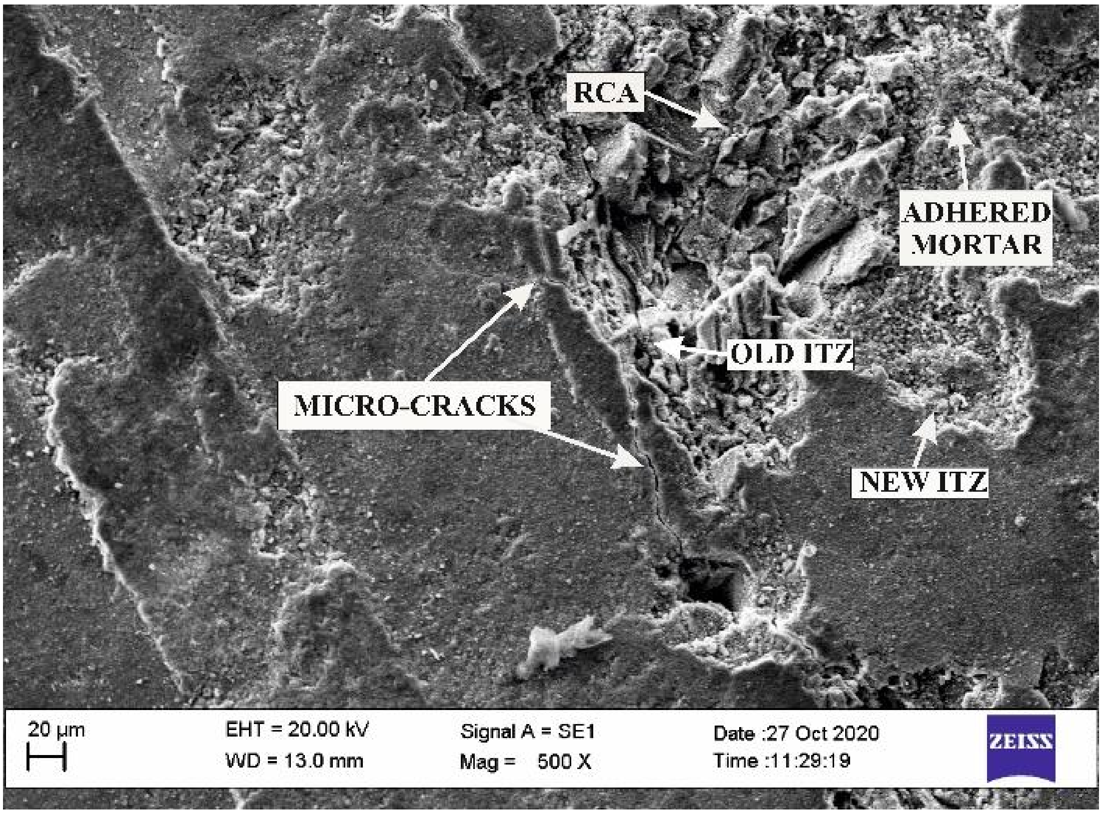

Figure 19. SEM micrographs of RCAH-C showing the presence of adhered mortar, two ITZ and micro-cracks between the coarse-RCA and cement paste at 90 days

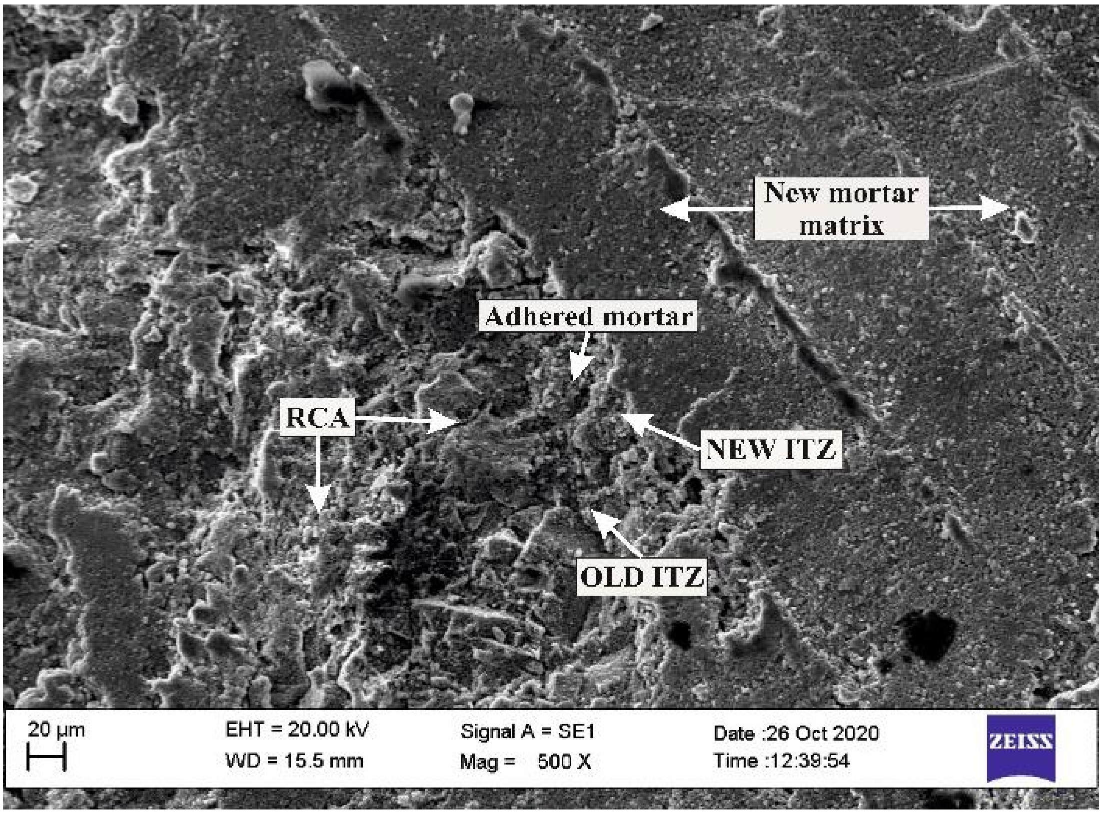

Figure 20. SEM micrographs of RCAL-C show adhered mortar's presence; therefore, the two ITZ but no micro-cracks between the coarse-RCA and cement paste at 90 days

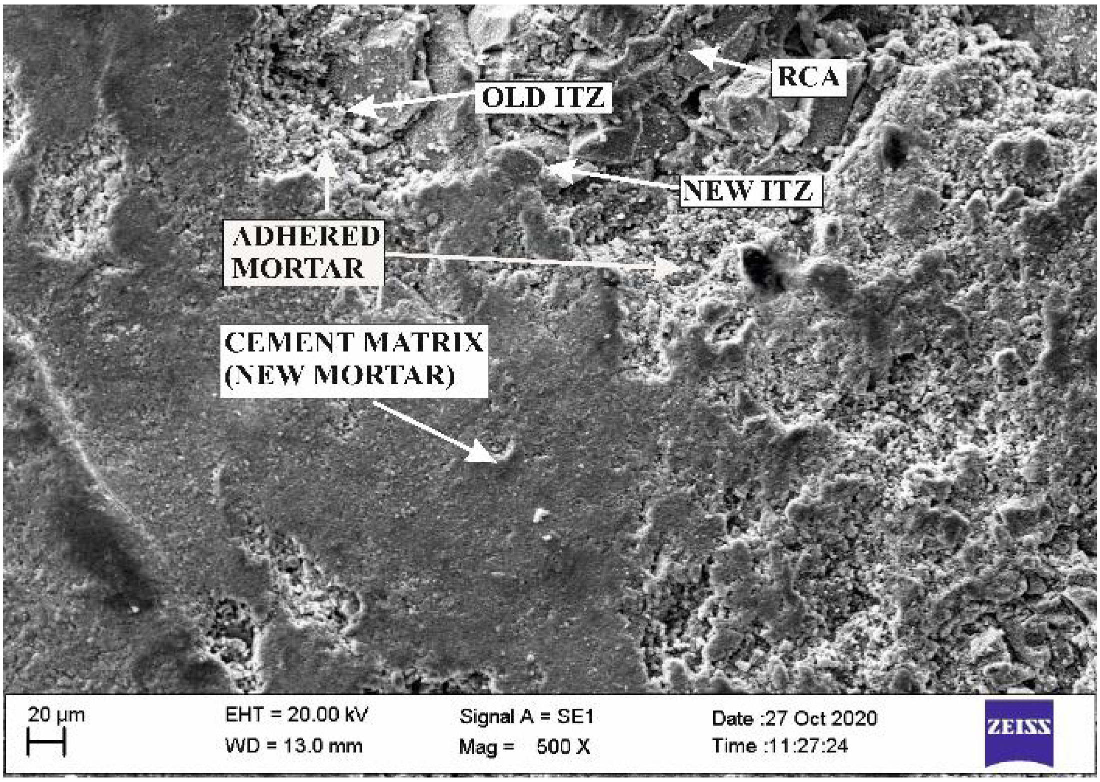

Figure 21. SEM micrographs of RCAM1-C show adhered mortar's presence; therefore, the two ITZ but no micro-cracks between the coarse-RCA and cement paste at 90 days

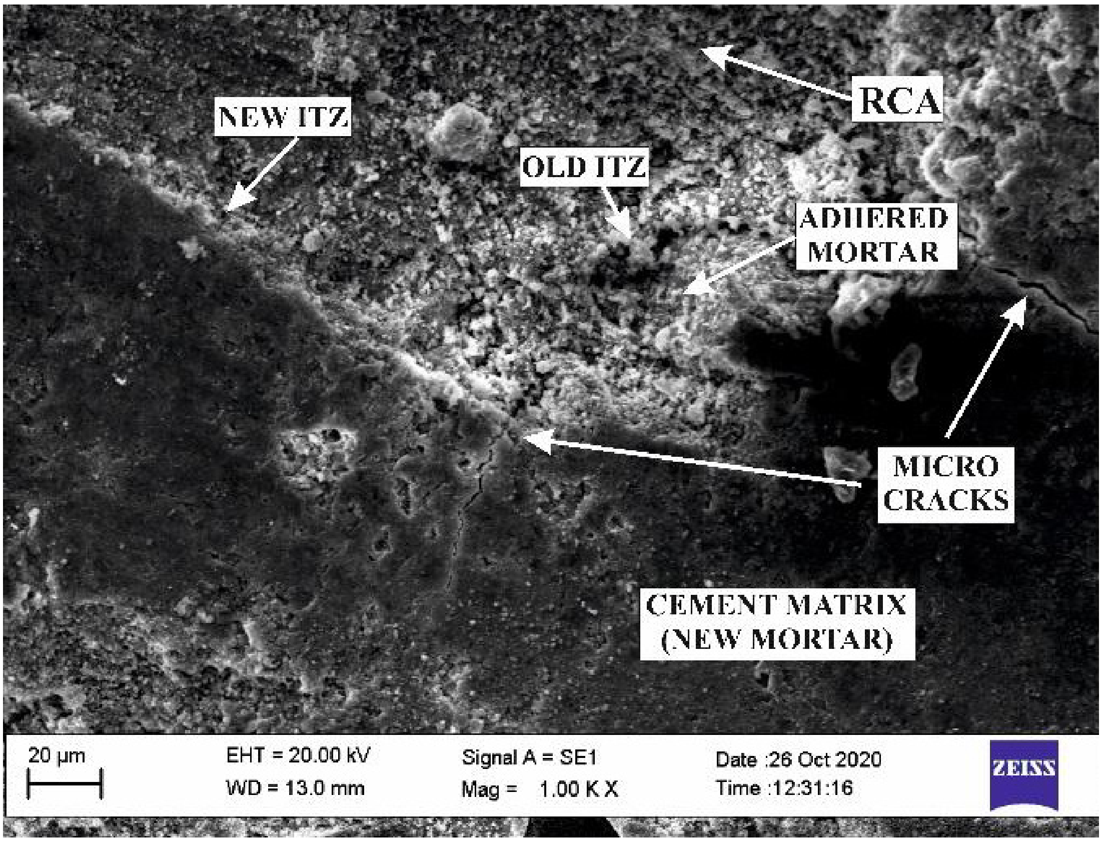

Figure 22. SEM micrographs of RCAM2-C show adhered mortar's presence; therefore, the two ITZ and micro-cracks between the coarse-RCA and cement paste at 90 days

SEM image shown in Figure 18 of NA-C shows that the ITZ is robust, i.e., the cement paste matrix and ITZ displayed a thick microstructure with no signs of microcracks. Few macro-pores with a pore size of 4.6µm were, however, observed. Presence of adhered mortar are visible only in the micrograph of RCAH (Figure 19) and RCAM2 (Figure 22) concrete mixes, but not in other RCA-C. From the result of adhered mortar content in the RCA sample, it is clear that RCAM2 and RCAH had comparatively higher content of adhered mortar than other two RCA-C mixes. Also, the result of compressive strength and its rate of gain in RCAH-C and RCAM2-C are justified by the presence of adhered mortar. Micro-cracks of average width ~ 3µm are also visible at higher magnification may be due to the shrinkage of paste [69]. The cracks are observed to be propagating through new ITZ that signifies the improved bond strength between adhered mortar and new mortar matrix. It also confirms that the failure starts in the new matrix, whereas, generally in RCA-C failure initiates from the old adhered mortar. Micrographs of all sample shows that the mortar matrix around the aggregate is dense with high amount of C-S-H gel and $CaOH_2$ crystals, indicating a good degree of hydration. Microstructure of all RCA-C samples were visualized as compact which justifies their compressive strength being in close range or even better than NA-C after 56 days [70].

4. Conclusions

The following conclusions may be reached based on the experimental research and interpretation of the data:

Untreated RCA has lower physical and mechanical properties as compared to NA. Smaller size RCA shows even more depreciated properties than the larger size.

For reducing adhered mortar, the quenching and abrasion (QA) method removed the highest amount of adhered mortar, followed by the heating and abrasion (H&A) and dry abrasion (DA) method.

The physical and mechanical properties of coarse-RCA were considerably improved after the application of treatment methods. H&A treated RCA showed better performance than DA treated RCA.

Compared to NA-C, the compressive strength of RCA-C samples was lower at an early age, equivalent at 28-days, and higher after 90-days. RCAM1- concrete prepared with QA treated RCA obtained from a mix of old concrete containing different mineral admixture showed the highest compressive strength (>4% than NA-C). RCAM2-C with DA treated RCA resulted the lowest among all RCA-C samples but equivalent to the NA-C.

Splitting tensile strength of RCA-C was lower than NA-C by a more significant margining at 28-day but less than 10% at 90-days. RCAM1- concrete performed best among RCA-C samples and also equivalent to that NA-C. The impact of RCA was negligible for flexural strength; all RCA-C samples performed better than NA-C.

Aggregates treated with the DA method showed lower values than the aggregates treated with the QA method; similarly, the concrete produced with DA treated aggregates performed relatively lower than concrete with QA treated aggregates. Although mechanical properties of concrete with DA treated, RCA is equivalent to that of NA-C.

The application of the R-TSMA in the production of RCA-C has very high significance.

A new combined approach that includes the recycling process, primary and secondary crushing, treatment, and R-TSMA, concrete with 100% RCA, shows similar properties equivalent to natural aggregate (NA) concrete.

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