Chapter 5

Study on the treatment methods and effect of parent concrete strength

5.1 General

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 has more water absorption capacity as compared to the natural aggregate (NA). To overcome the compromised properties of RCA, a comprehensive study supported by experimental investigation has been done. A methodology based on experimental investigation has been prescribed in this study for the use of coarse-RCA of size (4.75-20 mm) as 100% replacement of coarse-NA in fresh concrete. The objective of this study is to analyse the effect of C-RCA type (based on the strength/water-cement ratio of old concrete) on the performance of concrete produced. RCA samples produced after crushing laboratory prepared old concrete of different strength as discussed in section 4 (Table 4.2) were mixed in desired proportions to obtain aggregates samples of different strength history. Sampling of different type of C-RCA used in this phase of experimental study is discussed in chapter 4, and the sample detailing is tabulated in Table 4.8. RCAH represents the aggregate obtained from old concrete of comparatively higher strength, RCAL represents the aggregate obtained from comparatively lower strength concrete, and RCAM are the mixture of aggregates from different sources of concrete. To infuse the impact of treatment method application on C-RCA and its corresponding concrete, RCAM was first treated with QA method (RCAM1) and then

Table 5.1: Mix design of RCA-concrete and reference NA-concrete

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

with SDA method (RCAM2). QA method removed highest amount of adhered mortar whereas SDA method removed lowest in the comparative study of treatment method as discussed in chapter 4. A “re-modified two-stage mixing approach (R-TSMA)” supported by physical treatment method is proposed here to increase the bond strength between C-RCA and new mortar. Properties of RCA-concrete has been compared with NA-concrete and found to be performing similar or even better with longer curing days. Based on the experimental investigation, prediction models for the strength properties with respect to days of curing have also been proposed in this section. Micro-structure of RCA-concrete was studied via optical microscope as well as Scanning Electron Microscope (SEM). The suggested methodology produces good performing RCA-concrete and moreover some samples even show better compressive and flexural strength as compared to NA-concrete.

5.2 Concrete Mix

Description of RCA samples used in this study are listed in Table 4.8. Samples were mixed with RCA obtained from different types of concrete to replicate the industrially produced RCA, in which there is always a mixture of more than one source of old concrete. RCAM2 was treated with the SDA method (which removed the least amount of adhering mortar), while the other three samples were treated with the QA method to see how treatment methods affected the performance of RCA concrete.

Five types of concrete mixes were prepared, one with C-NA and other four using 100% C-RCA which are listed in Table 5.1. All the concrete mixes were prepared for 0.5 w/c and M30 grade according to the specifications of IS 10262:2009 [109]. Cement and sand quantity was fixed to 345 kg/m^3 and 755 kg/m^3 for all the concrete samples, and amount of aggregate per cubic meter is given in Table 5.1. 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 were 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 which, along with addition of water in two stages as in TSMA, cement was also added in two phases.

5.3 Comparison between the different types of Aggregates

5.3.1 Properties of aggregate

The physical and mechanical properties were examined following IS 2383:1963 (Part III and IV) [104] and [106]. Table 5.2 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 SDA 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 Fig. 5.1, which shows that the gradation of 10 and 20 mm nominal size C-NA were comparatively on the finer and coarser side, respectively, within the limits of Grading Zone II of IS 383 [20]. Gradation of 20 mm C-RCA after treatment processes reduced but on small scale as compared to 10 mm C-RCA. It can be also be observed that after treatment processes, there is reduction in the nominal size of C-RCA. 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

Table 5.2: 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 (AM) 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 (AM) content	30.85	28.65	30.95	35.5	28.25	26.50	29	32

sieve size 20 mm, 10 mm, and 4.75 mm. 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, 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. The gradation of aggregates used in this part of the study is shown in Fig.5.1

RCA obtained from low strength concrete are expected to possess lower mount of adhered mortar than the same obtained from higher strength old concrete [24, 116]

Larger size aggregate (20 mm) showed lower variation in the physical and mechanical properties than the smaller size aggregate (10 mm) [36, 47, 49]. The use of mineral admixtures in the concrete as a partial replacement of cement improves concrete's overall strength [117]. The improved strength of concrete results in the better quality of RCA produced from it [116].

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

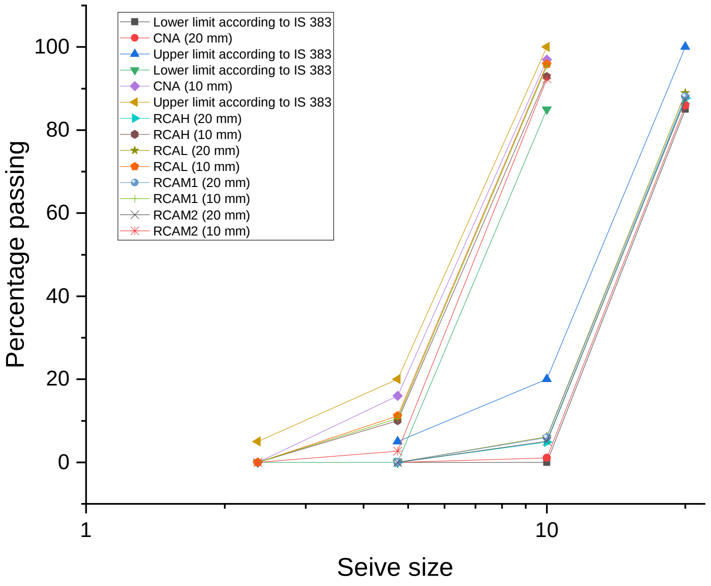


Figure 5.1: Gradation curves of different types of aggregates

Table 5.3: 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

5.3.2 XRD analysis

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 from Fig.5.2 to Fig.5.5. Fig.5.2 shows the clear presence of high amount of calcium silicate hydrate (CSH) represented by the highest peak (¿25000 counts) in the XRD graph of untreated RCA. This peak of CSH can be clearly observed to decrease after the treatment of RCA. However, the intensity of CHS is similar (ranges between 1500 to 2500 counts) in the C-RCA treated with three different treatment methods (QA, HA and SDA). This result signifies that, the common step of dry abrasion in each treatment method played major role in reducing the cement hydration products from C-RCA. Fig.5.5 shows the XRD graph of C-RCA treated with

DA method dominated with quartz peaks, followed by dolomite, whereas in RCA treated with HA and QA method dolomite peaks are primary followed by Quartz. Dolomite phase i.e., calium magnesium carbonate, is due to the geological origin of NA. No portlandite peaks were observed in treated RCA, which could be attributed to its conversion to calcite or carbonate phase since the traces (minor intensity peaks) of calcite were observed in all types of C-RCA [120]. Through XRD analysis of C-RCA treated with different treatment methods, it can be understood that the minerological composition of C-RCA is not changing with the treatment methods. On comparing the XRD graphs, it can be clearly seen that the CSH peak was highest in untreated C-RCA whereas in all other aggregates it was among the lower peaks, this clearly signifies the reduction of adhered mortar by large amount. The improvement in the physical and mechanical properties treated C-RCA is the result of adhered mortar reduction.

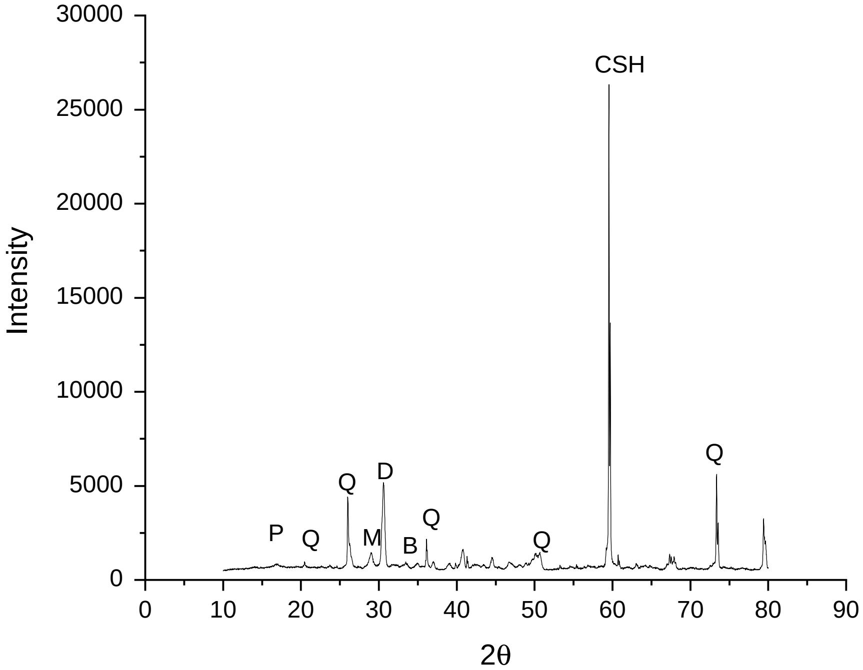


Figure 5.2: XRD of DA treated RCA

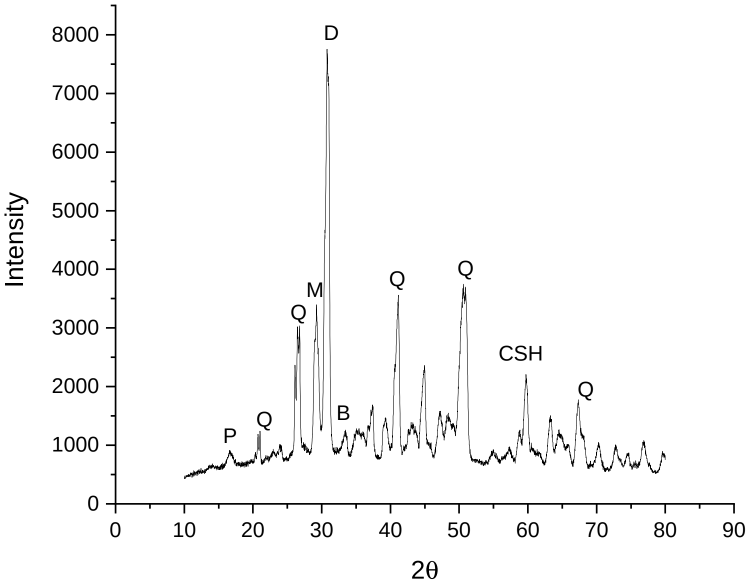


Figure 5.3: XRD of H&A treated RCA

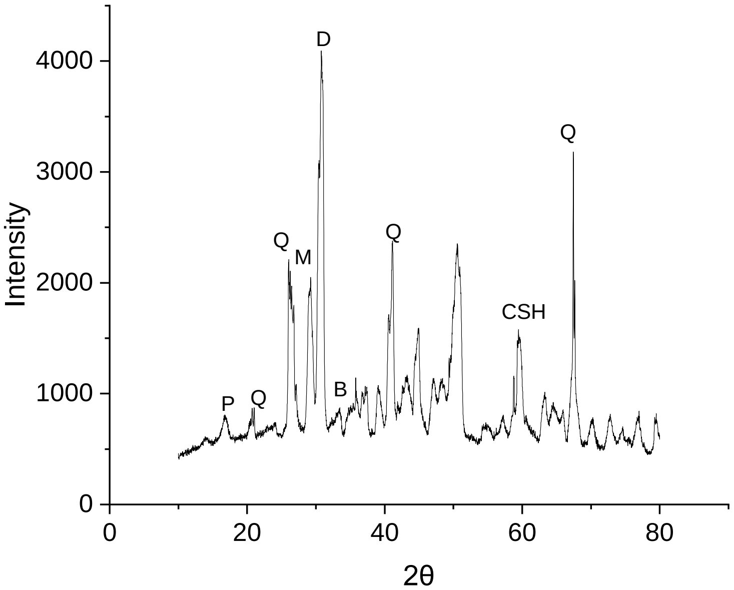


Figure 5.4: XRD of QA treatment RCA

5.4 Fresh concrete properties

5.4.1 Workability

High water absorption capacity of RCA in comparison to NA reduces the workability of concrete. For maintaining the workability of RCA-concrete higher amount of water is

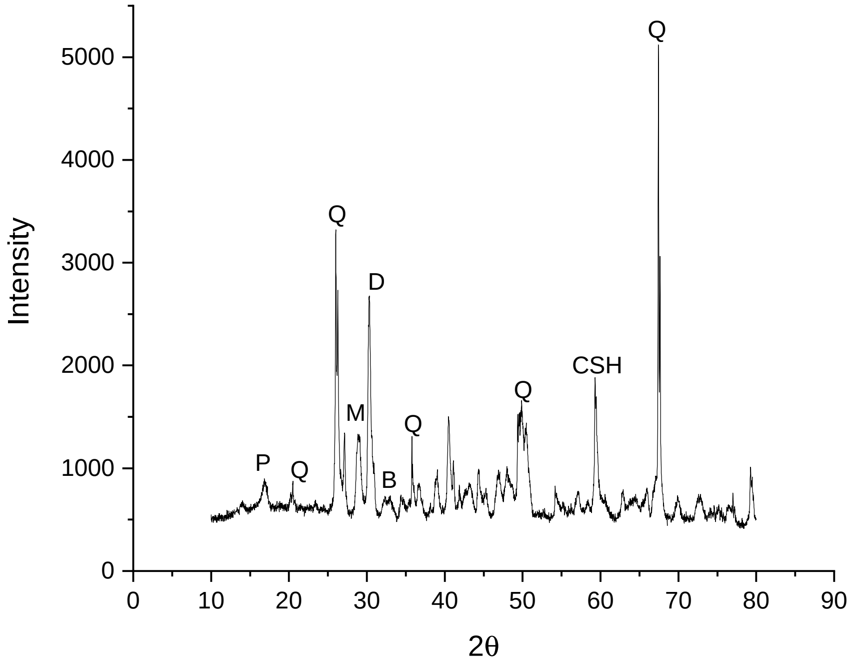


Figure 5.5: XRD of Untreated RCA

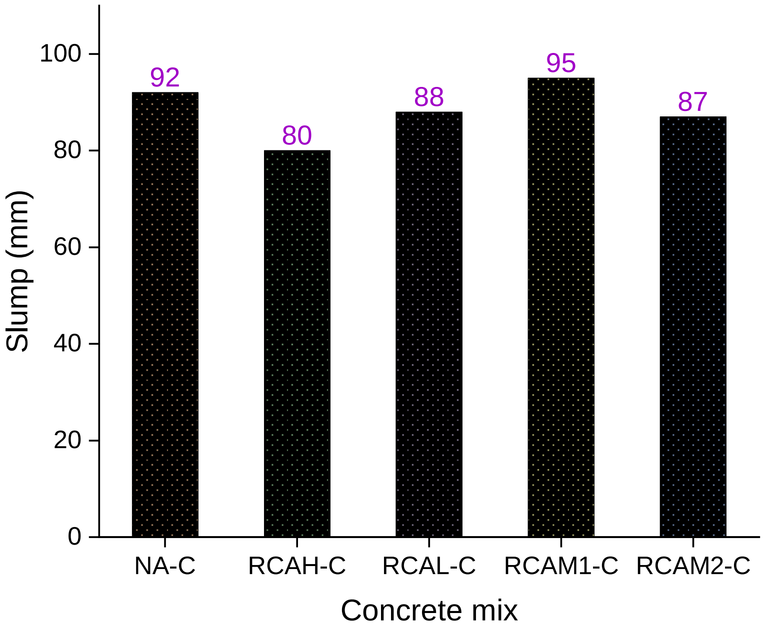


Figure 5.6: Slump value of NA-C, RCAH-C, RCAL-C, RCAM1-C and RCAM2-C

required as compared NA-concrete. 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 methods mentioned above to produce good quality concrete has been adopted i.e., treatment of aggregate, use of superplasticizer and coating of C-RCA with with cement (10% of the total cement) was done during mixing. Mix design approch adopted in this study is detailed in the section 3.2.6.1 and Fig.3.8.

Superplasticizer quantity was fixed to 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 NCA-C that can be seen in the Fig.5.6. Infact, RCAM1-C showed better workability than NCA-C, lowest slump was observed in RCAH-C followed by RCAM2-C and RCAL-C. RCAM2-C 87 mm, RCAM1-C 94 mm, RCAL-C 90 mm, RCAH-C 80 mm.

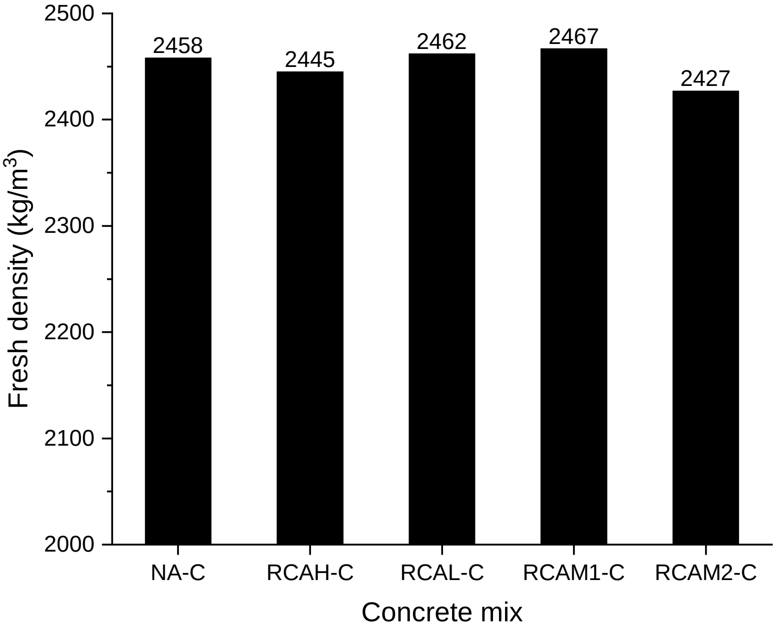


Figure 5.7: Fresh concrete density of NA-C, RCAH-C, RCAL-C, RCAM1-C and RCAM2-C

5.4.2 Fresh density

The density of fresh concrete depends on the type of aggregates, w/c and void content [116]. These factors are also responsible for the hardened concrete properties. The low density of fresh concrete can be associated with its low strength at a hardened state because the reduction in density indicates an increment in the water and voids content of concrete. In general, the density of RCA-C is lower than that of NA-C due to the presence of low-density adhered mortar [121, 122]. Fig.5.7 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 lowest value of 2417 kg/m^3 , 1.% 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 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 upto standards of NAC. The density of ordinary concrete and semi-lightweight concrete varies between 2240 to 2400 kg/m^3 and 1840–2240 kg/m^3, respectively. Therefore, all the concrete mixes can be termed as ordinary concrete and hence can be used as a structural concrete.

5.5 Hardened Concrete Properties

5.5.1 Compressive Strength

Compressive strength increment of concrete samples after curing for 7, 14, 28, 56, and 90 days are presented in Fig.5.8, and Table 5.4 illustrates the variation in RCA-concrete samples compressive strength concerning NA-concrete 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. And, after 90-days of curing, all the RCA-concrete samples performed better than NA-concrete. 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-concrete. Lower reduction of adhered mortar has been observed in the RCA produced from concrete of higher strength. Hence, RCAH-concrete exhibited lower compressive strength at early age [78], but showed relatively improved compressive strength after 28-days of curing. RCAM2-concrete 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 are 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% [47, 63, 65], 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 [63, 78, 89] 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 economics 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 are lowest carbon generation process that can produce very high quality aggregates with minimum loss. In this study also, two types of treatment method was 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 but reduced sufficient amount of mortar and less time conserving. In the end result, concrete of desired strength was produced by both type of treated RCA, RCAM2-C performed similar to that of NA-C while compressive strength of 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 [123, 124]. The presence of unhydrated binding material in the remaining adhered mortar also induces the later age strength gain of RCA-concrete. Reduced size of treated RCA in comparison to NA also helped in good packing and, hence, better compressive

Table 5.4: 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

Table 5.5: Compressive strength prediction model in the form of logarithmic equation w.r.t curing days

Sample	Logarithmic equation (f_c = a + b ln t)	R^2
RCAH-concrete	$f_c = 9.9033 \ln t + 28.822$	0.9688
RCAL-concrete	$f_c = 9.8149 \ln t + 30.046$	0.9785
RCAM1-concrete	$f_c = 9.9666 \ln t + 30.411$	0.9555
RCAM2-concrete	$f_c = 9.703 \ln t + 28.909$	0.9754
NA-concrete	$f_c = 8.5938 \ln t + 30.477$	0.9833

strength. The prediction model as a logarithmic function for the compressive strength of concrete samples concerning curing days is tabulated in Table 5.3.

$$f_c = a + b \ln t$$

Where a and b are the constants, t represents time in days and f_c represents compressive strength. The correlation coefficient R_2 of all the samples is greater than 0.95, which shows that the prediction for compressive strength of RCA-concrete samples can be done easily corresponding to curing days.

5.5.2 Splitting Tensile Strength

Data presented in Fig. 5.9 and Table 5.6, show that all mixes of RCA exhibited lower tensile strength than NA-concrete. 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-concrete, respectively, after 90-days this difference reduced

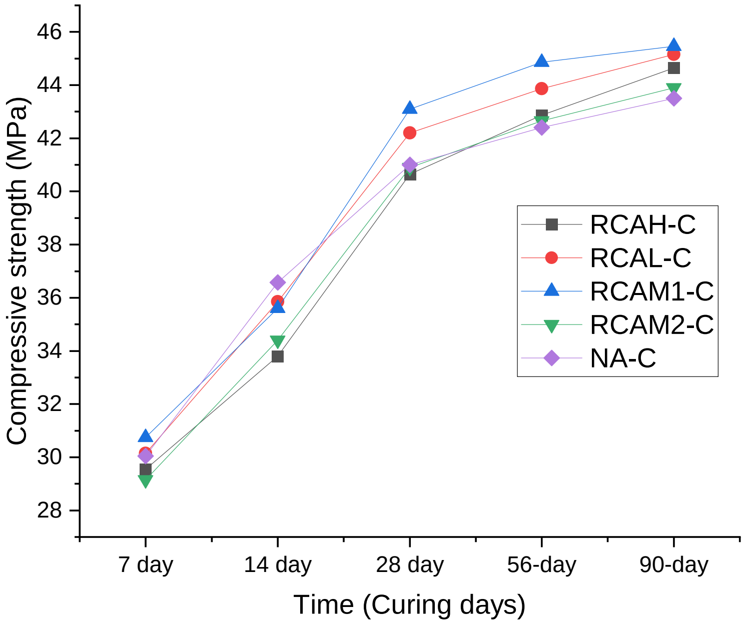


Figure 5.8: Variation in compressive strength with curing days.

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-concrete and RCAM2-concrete performed lowest in splitting tensile strength at all testing ages. RCAM1-concrete performed best among other RCA-concrete samples, and after 90 days, the results were almost similar as NA-concrete. RCAM1-concrete and RCAM2-concrete 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 R-TSMA served the purpose well, and concrete with better strength could be produced. The prediction model as a logarithmic function for the splitting tensile strength of concrete samples in relation curing days is tabulated in Table 5.5.

$$f_{st} = a + b \ln t$$

Table 5.6: Variation of RCA-concrete samples against NA-concrete

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

Table 5.7: Prediction model in the form of logarithmic equation with respect to the curing days

Sample	**Logarithmic equation**	**R^2**
Splitting tensile strength		
RCAH-concrete	$f_{st} = 0.767\ln(t) + 2.6619$	0.97
RCAL-concrete	$f_{st} = 0.7798\ln(t) + 2.8576$	0.96
RCAM1-concrete	$f_{st} = 0.8522\ln(t) + 2.951$	0.94
RCAM2-concrete	$f_{st} = 0.7264\ln(t) + 2.9695$	0.97
NA-concrete	$f_{st} = 0.7036\ln(t) + 3.1365$	0.93
Flexural Strength		
RCAH-concrete	$f_{fs} = 0.6571\ln(t) + 3.9609$	0.96
RCAL-concrete	$f_{fs} = 0.8185\ln(t) + 3.8712$	0.95
RCAM1-concrete	$f_{fs} = 0.6796\ln(t) + 4.1175$	0.94
RCAM2-concrete	$f_{fs} = 0.6974\ln(t) + 4.0568$	0.95
NA-concrete	$f_{fs} = 0.7148\ln(t) + 3.9497$	0.92

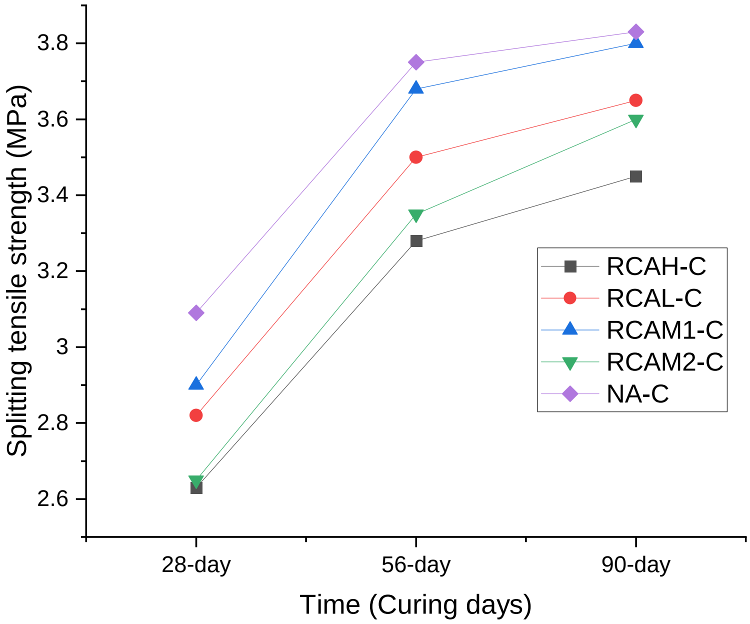


Figure 5.9: Splitting tensile strength with curing age

Where, a and b are the constants, f_{st} represents splitting tensile strength, and t represents time in days. The correlation coefficient R^2 of all the samples is greater than 0.90, which shows that the splitting tensile strength of concrete samples can be predicted easily concerning curing days.

5.5.3 Flexural Strength

For the flexural strength test, three concrete beams measuring 150 mm x 150 mm x 700 mm were prepared. Fig. 5.10 shows the flexural strength test results for all concrete samples based on curing days; Table 5.6 shows the difference in flexural strength between RCA-concrete samples and NA-concrete samples, which shows that all the RCA-concrete samples performed similarly to, if not better than, NA-concrete. Using coarse-RCA as a replacement of coarse-NA does not negatively affect flexural strength [125], provided its high impact in tensile strength and marginal in compressive strength. Concrete mix prepared with RCAM2, RCAM1, and RCAL resulted in higher flexural strength than NA-concrete, while RCAH-concrete 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 with enhanced the mortar aggregate bond. The prediction model as a logarithmic function for the flexural strength of concrete samples corresponding curing days is tabulated in Table 5.7.

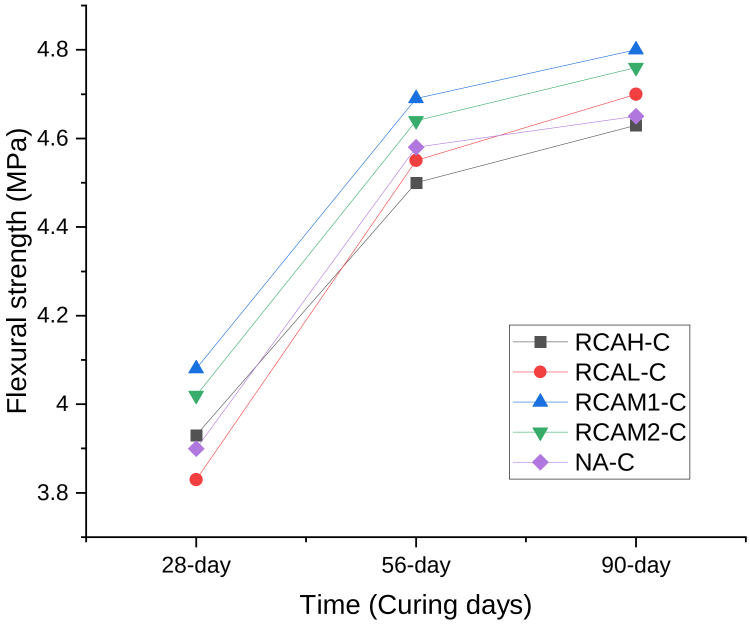


Figure 5.10: Flexural strength with curing age

$$f_{fs} = a + b \ln t$$

Where, a and b are the constants, f_{fs} represents flexural strength, and t represents time in days. The correlation coefficient R^2 of all the samples is greater than 0.90, which shows that the flexural strength of concrete samples can be predicted easily concerning curing days.

5.5.4 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 [37,126,127]. The procedure to determine the coefficient of permeability ('k') provided in IS 3085 ([114]) was followed in this study, and its values for all concrete samples are shown in Fig. 5.11. 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 SDA method reduced less amount of adhered mortar as compared to Q&A method, therefore, old mortar presence in RCAM2-C was higher than RCAM1-C which resulted in higher water aborption. 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.

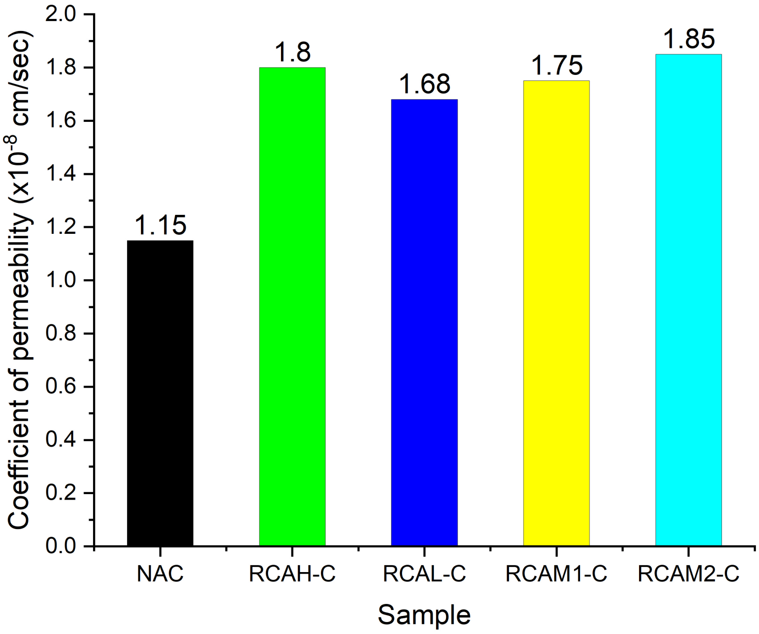


Figure 5.11: Coefficient of permeability of the concrete mixes

In case of RCA, there is 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 inturn damages the matrix of ITZ.

For improving the durability of concrete containing RCA, past studies have recommended low w/c, utilisation of superplasticisers and supplementary cementitious materials [45, 128]. According to [128] replacing 10% cement with an equal weight of metakaolin in RCA reduces the volume of capillary pores and results in pore refinement, thereby reducing water permeability of RCA-concrete, bringing it at par with that of control concrete.

5.5.5 Carbonation

Weathering carbonation is the reaction that occurs when cement hydration products mix with CO_2 in the atmosphere and moisture to create $CaCO_3$. 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 [129, 130] . 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 [131, 132]. 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 additionally subjected to rapid carbonation for another 28-days (Fig. 5.12). 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 RCA_s. 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 Fig. 5.14. Fig. 5.13 shows that the relationship between carbonation depth and the compressive strength of carbonated concrete is inversely proportional [126]. In general, increased compressive strength is linked to a smaller pore volume and a more

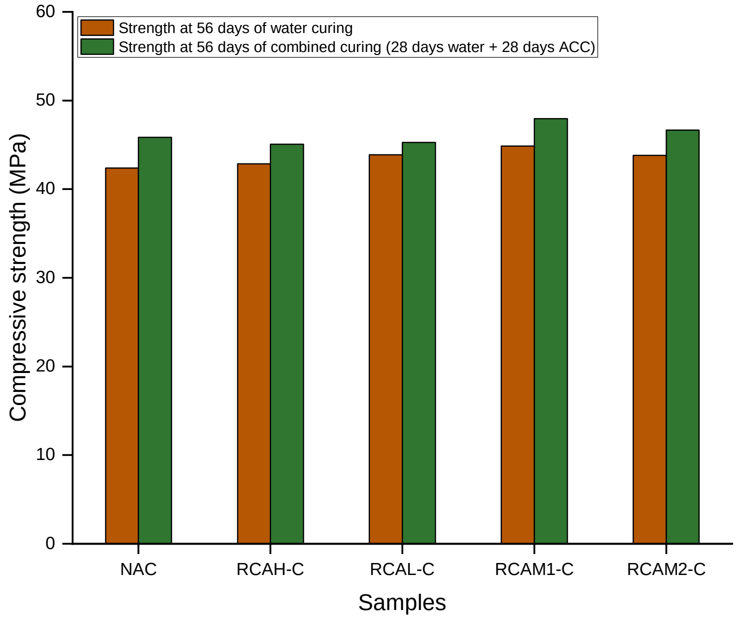


Figure 5.12: Carbonated compressive strength vs Compressive strength after water curing

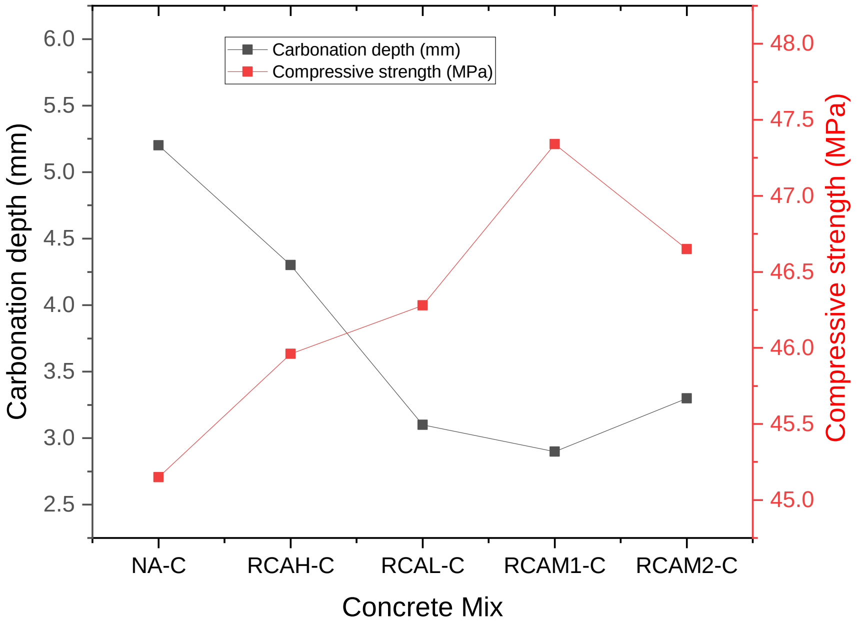


Figure 5.13: Carbonated compressive strength vs Carbonation depth

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 [133].

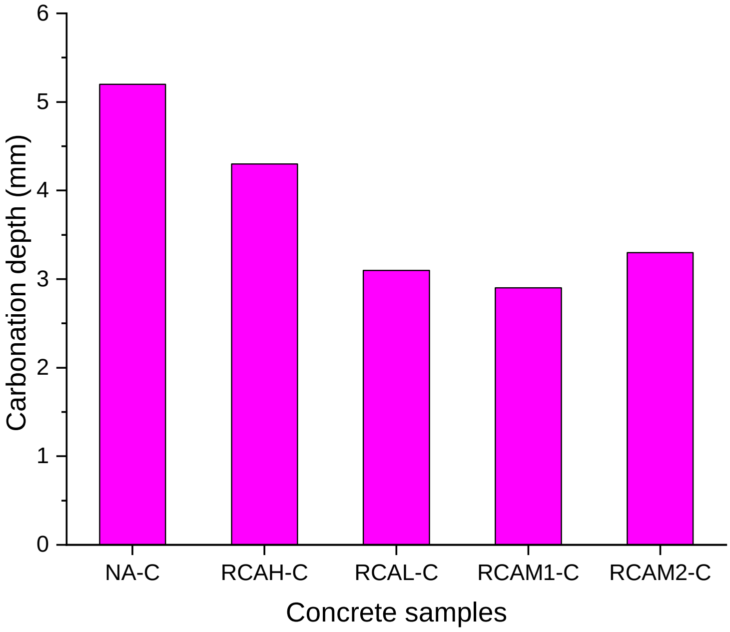


Figure 5.14: Carbonation depth of NA-C, RCAH-C, RCAL-C, RCAM1-C and RCAM2-C

5.5.6 Fracture Surface

The fracture surface of RCA-concrete and NA-concrete samples are presented in Fig. 5.15. The crack formation depends on the interaction between aggregates and the mortar matrix. By observing the fracture surface of concrete elements, concrete quality can be estimated, whether it belongs to high strength or normal strength concrete. The fracture surface of RCAM1-concrete (Fig. 5.15d) is comparable to that of high strength NA-concrete (Fig. 5.15a. The presence of blank aggregate surface indentation and broken aggregate indicates that crack propagation is going around the aggregate and running through it. This type of crack propagation represents the high-quality strength of concrete, and it also signifies that concrete is low in ductility. The fracture surface of RCAH-concrete (Fig. 5.15b), RCAL-concrete (Fig. 5.15c), and RCAM2-concrete (Fig. 5.15e) resembles the failure pattern of normal strength NA-concrete. There is very little sign of aggregate fracture, but it can be seen that propagation of crack is around the aggregate signifying the weakness of mortar matrix than aggregate as in normal strength concrete. All the RCA-concrete samples were designed for the normal strength; only the type of RCA was varied. By analyzing the fracture surface and strength results, it can be concluded that all the samples performed as normal strength concrete. The treatment method combined with the new mixing approach reduced variability in the type of RCA.

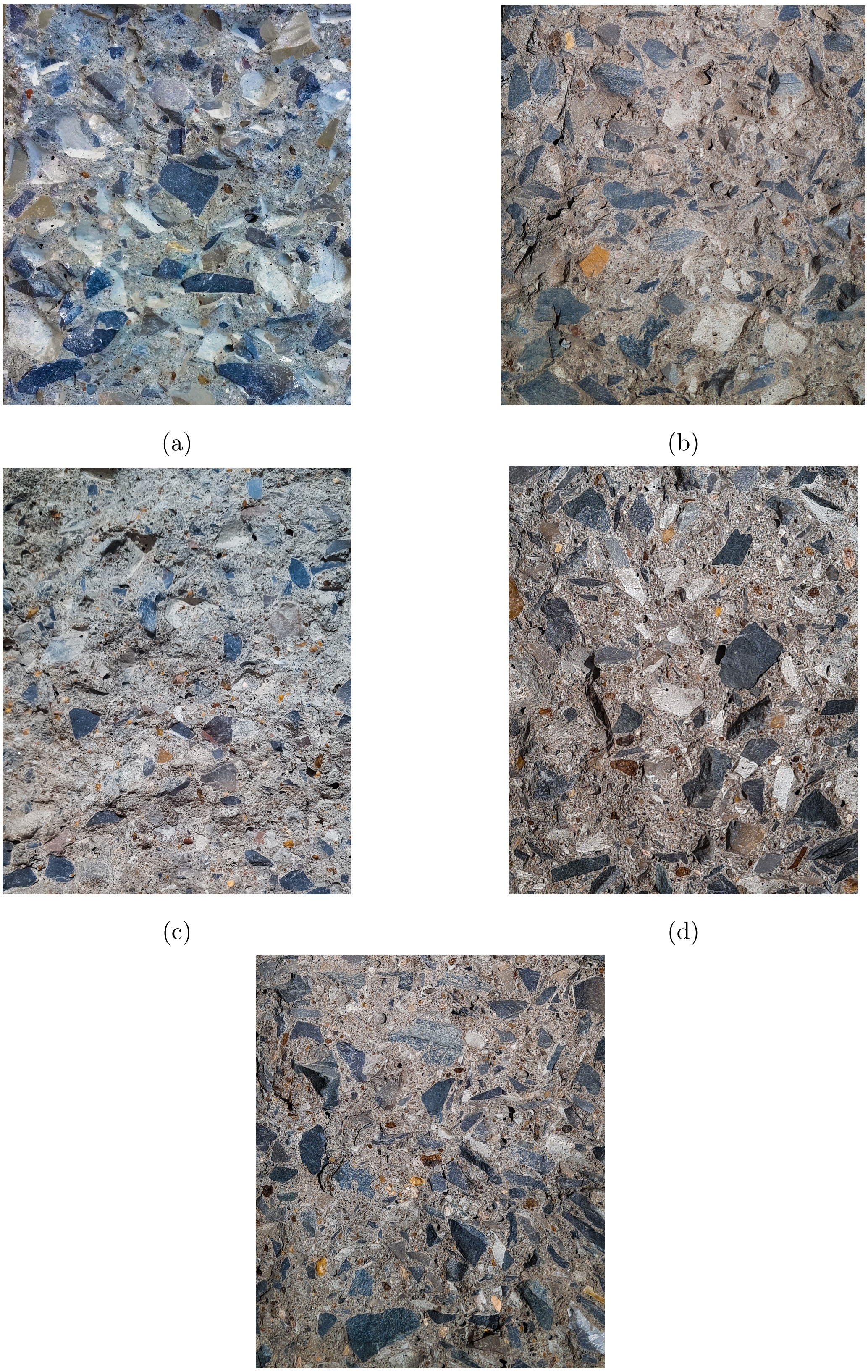
5.5.7 Petrography

Petrography is the microscopical examination for the composition and state of the concrete [134]. Petrographical study helps identify the type of minerals present in fine and coarse aggregate, provide details about the nature of bonding between the aggregate and mortar mix, and helps identify the microstructural behavior like micro-cracks, voids, formation of gel [135–137] . This petrological study examination was carried out to study the difference between the microstructure of concrete samples prepared with different aggregate samples. (Fig. 5.16) to (Fig. 5.20) shows the photomicrograph of NA-concrete, RCAH-concrete, RCAL-concrete, RCAM1-concrete, and RCAM2-concrete, respectively.

Photomicrograph all samples shows that the coarse aggregate and minerals of fine aggregate are enclosed within the black-colored cementitious groundmass. The C-S-H gel is accompanied by a lot of whitish freckles, which are Calcium Hydroxide produced during the hydration reaction. Quartz and feldspar (i.e., Kfledspar and plagioclase feldspar) are the main constituents present in the groundmass of cementing materials. Quartz grains are generally medium to coarse-grained, anhedral to subhedral, and sub-rounded in shape. Quartz and feldspar grains generally show sharp contact with the cementing materials. The medium-sized white partially infilled voids visible in Fig. 5.17 and Fig. 5.19 signify almost empty voids with very less cementitious material inside them. Older mortar that can be visualized as grey (less dark) in colour is present around the periphery of coarse aggregate, visible in Fig. 1.4 and Fig. 5.20 of RCAH-concrete and RCAM2 concrete, respectively. It is important to point here that micro-crack and small to large voids are frequently observed in all the concrete specimens, which signifies an almost negligible difference between the microstructure of NA-concrete and RCA-concrete.

5.5.8 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



(a) (b)

(c) (d)

(e)

Figure 5.15: Fracture surface of (a) RCAH-C, (b) RCAL-C, (c) RCAM1-C, (d) RCAM2-C and (e) NA-C Micro-structural property

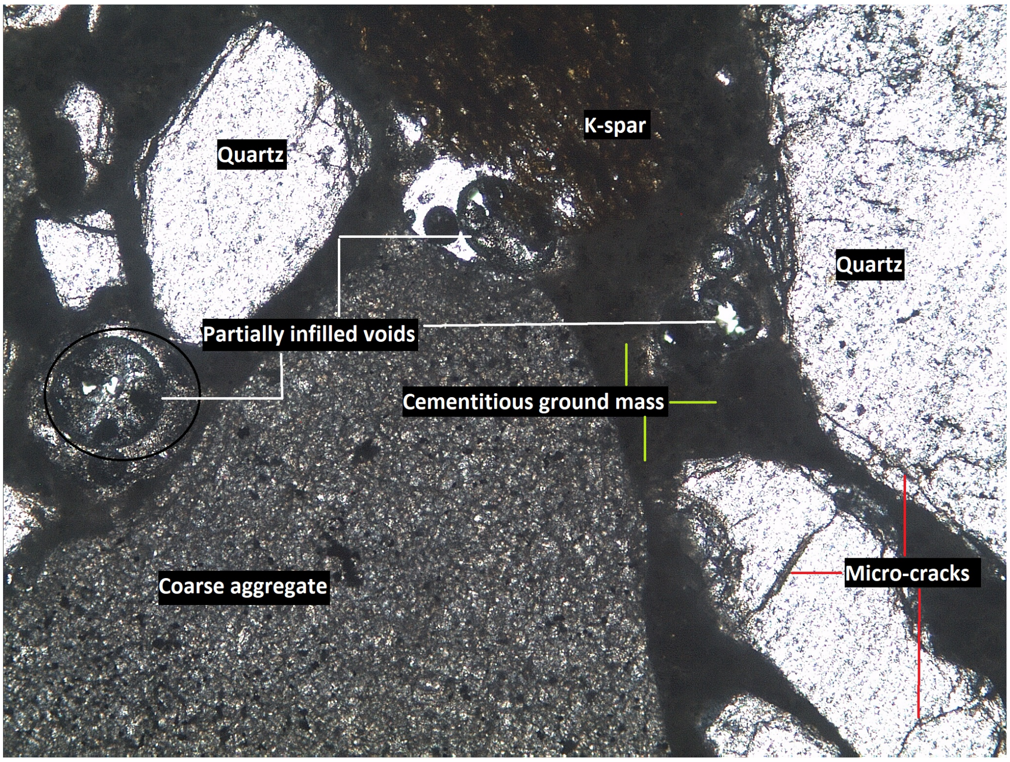


Figure 5.16: Photomicrograph NA-concrete O.L. x 2.5X

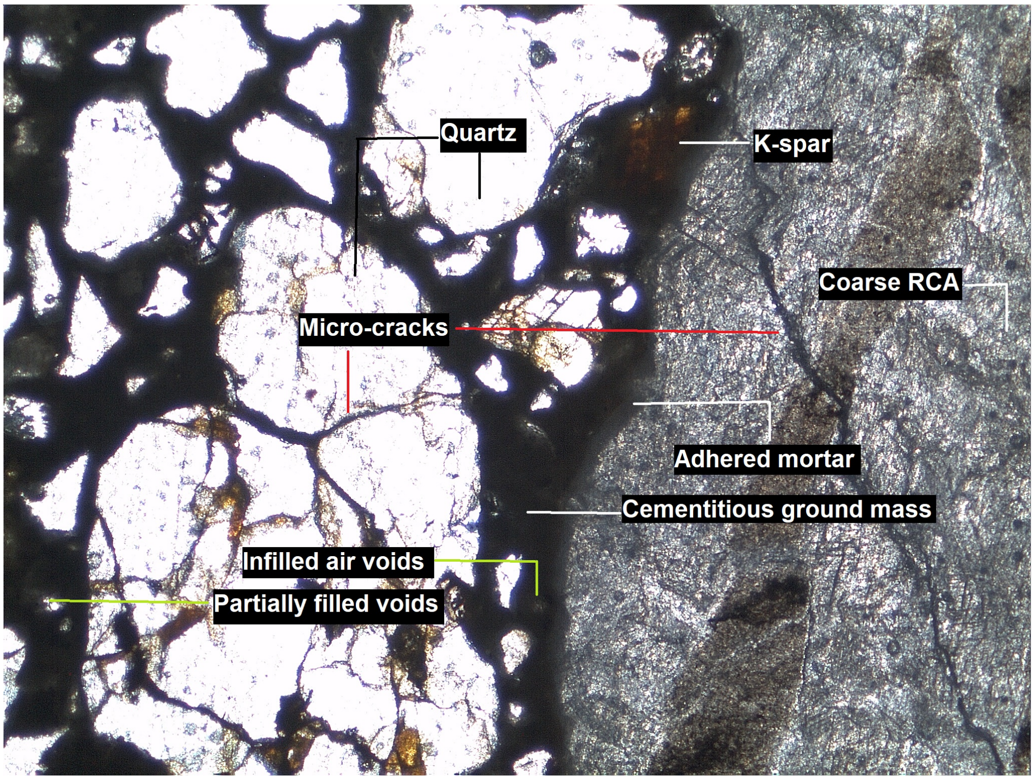


Figure 5.17: Photomicrograph RCAH-concrete O.L. x 2.5X

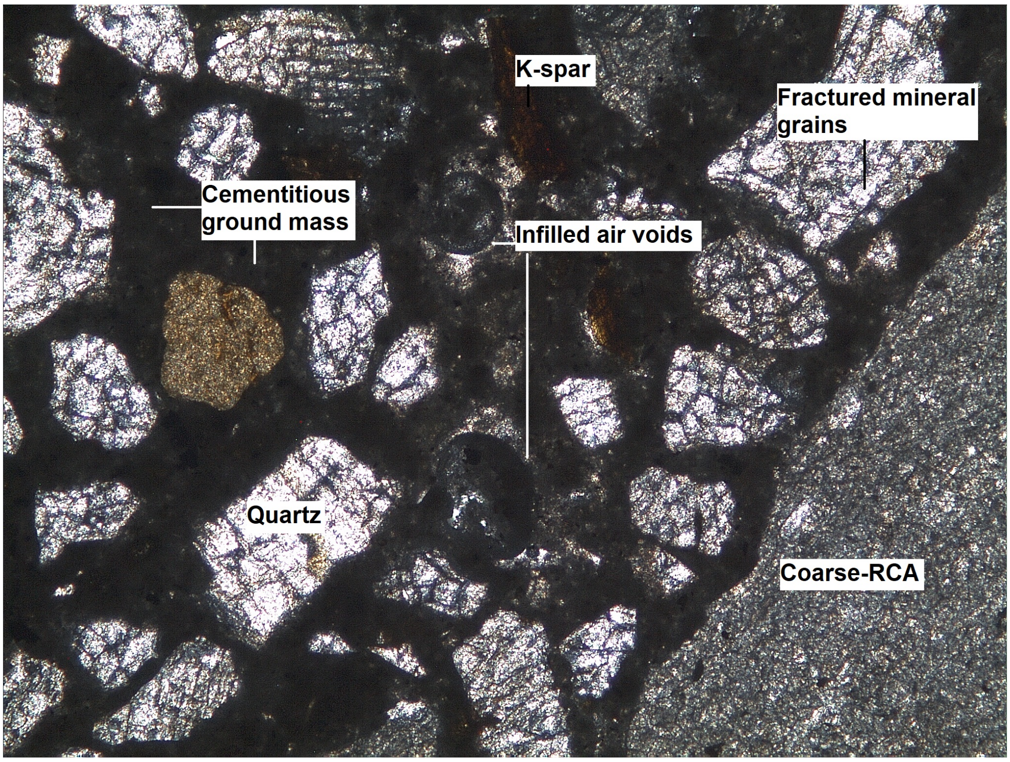


Figure 5.18: Photomicrograph RCAL-concrete O.L. x 2.5X

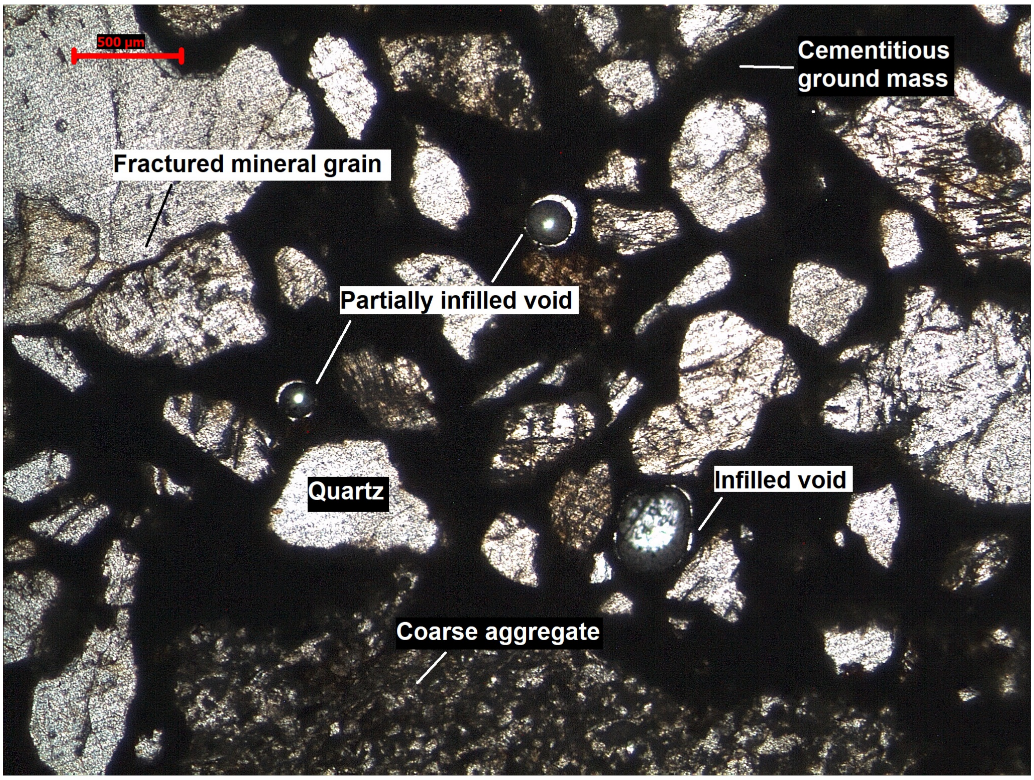


Figure 5.19: Photomicrograph RCAM1-concrete O.L. x 2.5X

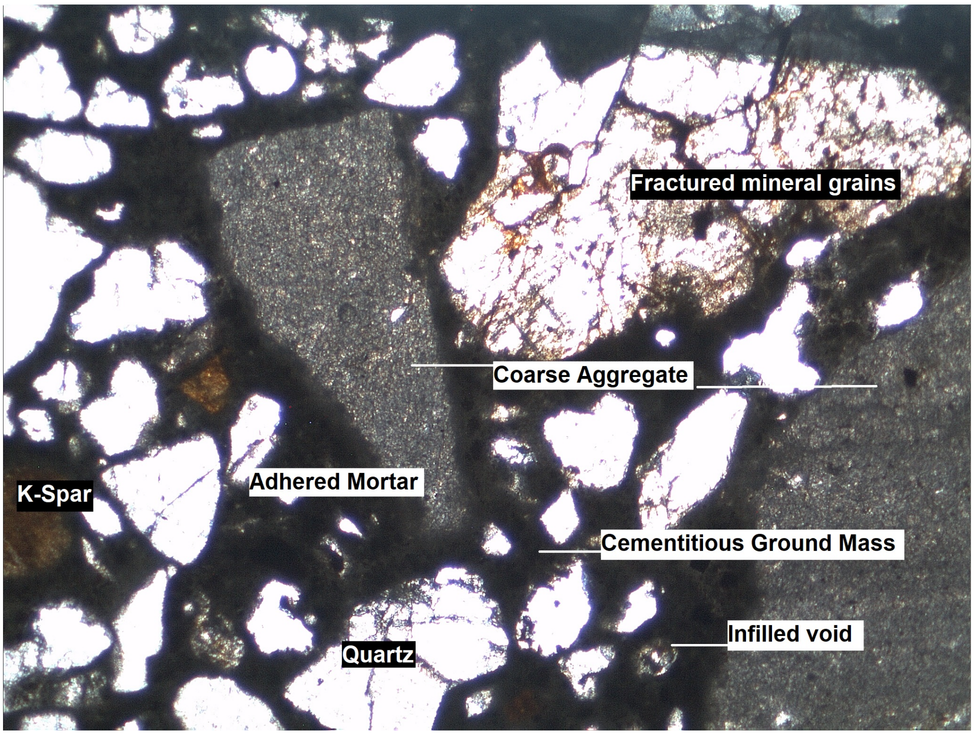


Figure 5.20: Photomicrograph RCAM2-concrete O.L. x 2.5X

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. Fig. 5.21 to Fig. 5.25 shows the SEM micrographs of NA-concrete, RCAH-concrete, RCAL-concrete, RCAM1-concrete, and RCAM2-concrete, 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-concrete 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. SEM image shown in Fig. 5.21 of NA-concrete 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 4.6 $\mu\ m$ were, however, observed. Presence of adhered mortar are visible only in the micrograph of RCAH (Fig.

5.22) and RCAM2 (Fig. 5.25) concrete mixes, but not in other RCA-C. From the result of adhered mortar content in the C-RCA sample, it is clear that RCAM2-C and RCAH-C 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 3 μ m are also visible at higher maginification may be due to the shrinkage of paste [138]. 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 $Ca(OH)_2$ 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 [139] .

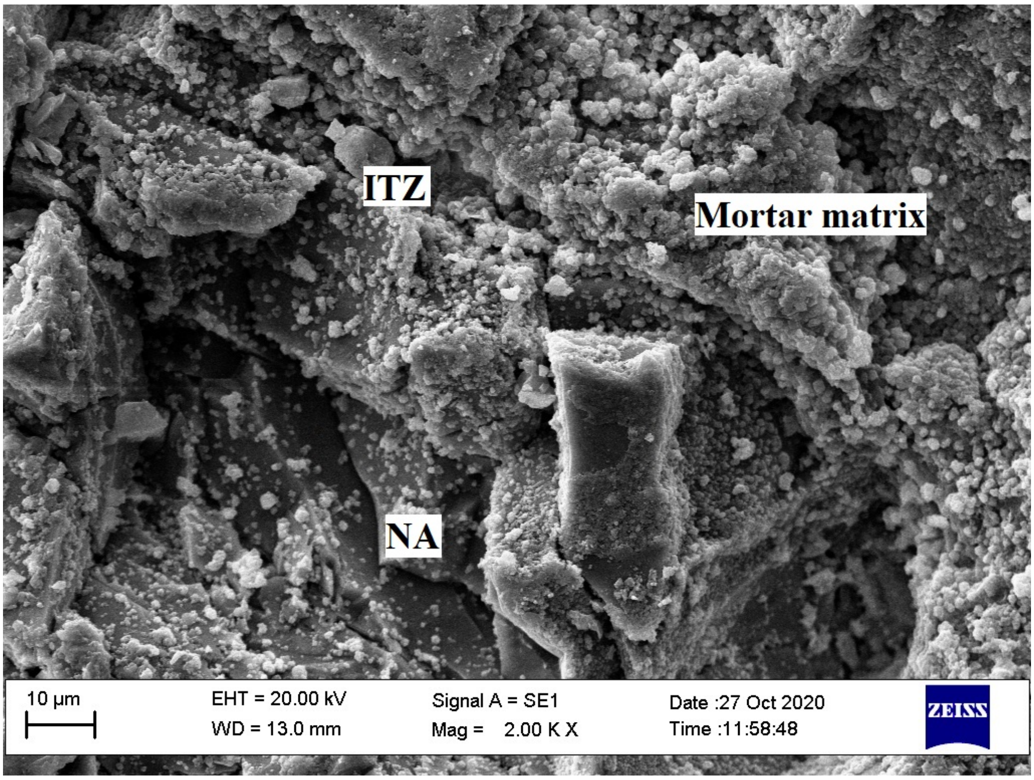


Figure 5.21: SEM micrographs of NA-concrete showing strong ITZ bond between coarse-NA and cement paste, at 90 days

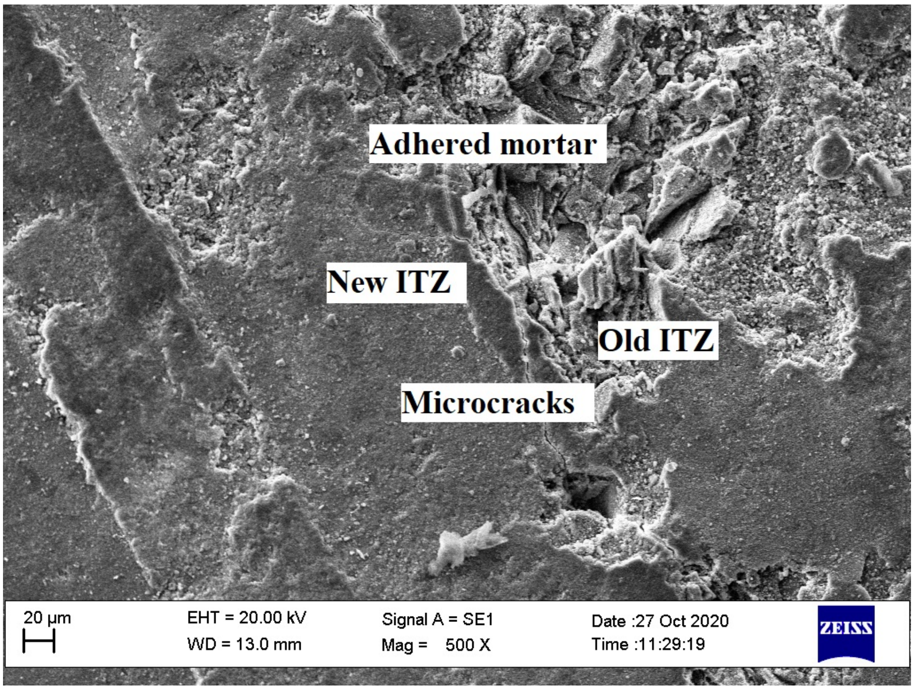


Figure 5.22: SEM micrographs of RCAH-concrete showing the presence of adhered mortar, two ITZ and micro-cracks between the coarse-RCA and cement paste at 90 days

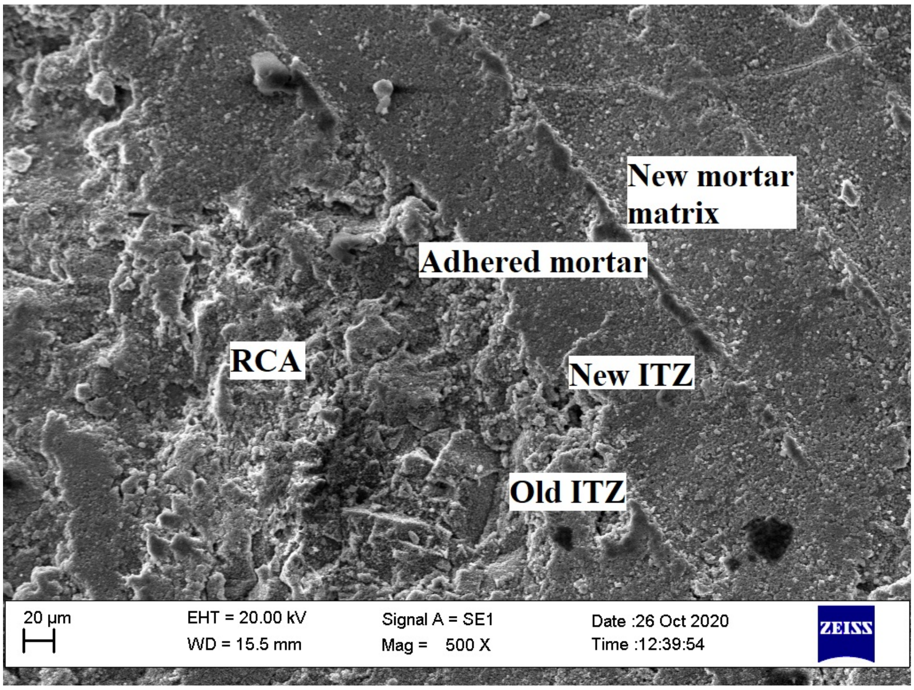


Figure 5.23: SEM micrographs of RCAL-concrete show adhered mortar's presence; therefore, the two ITZ but no micro-cracks between the coarse-RCA and cement paste at 90 days

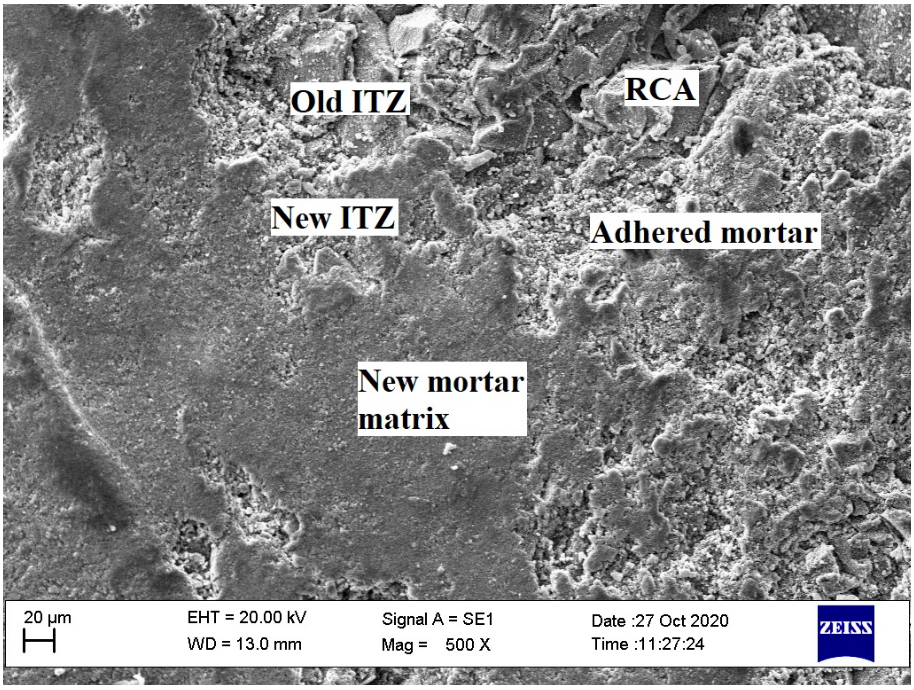


Figure 5.24: SEM micrographs of RCAM1-concrete show adhered mortar's presence; therefore, the two ITZ but no micro-cracks between the coarse-RCA and cement paste at 90 days

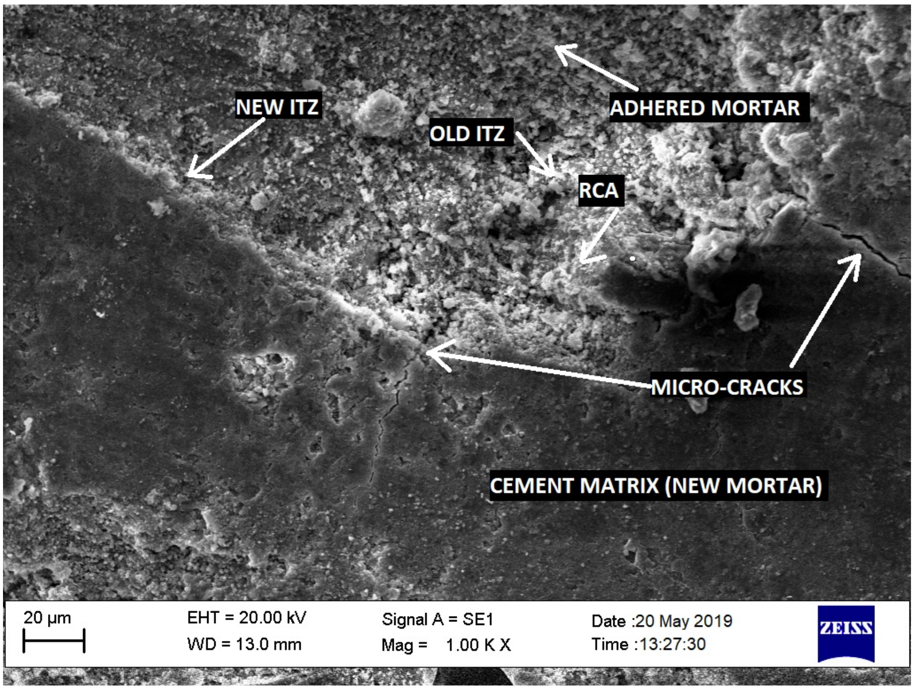


Figure 5.25: SEM micrographs of RCAM2-concrete show adhered mortar's presence; therefore, the two ITZ and micro-cracks between the coarse-RCA and cement paste at 90 days

5.6 Summary

For reducing adhered mortar, the quenching and abrasion (QA) method removed the highest amount of adhered mortar, followed by the heating and abrasion (HA)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-concrete, the compressive strength of RCA-concrete samples was lower at an early age, equivalent at 28-days, and higher after 90-days. RCAM1-C mix prepared with QA treated RCA obtained from a mix of old concrete containing different mineral admixture showed highest compressive strength (>4% than NA-concrete). RCAM2-C mix with DA treated RCA resulted lowest among all RCA-concrete samples but equivalent to the NA-concrete. Splitting tensile strength of RCA-concrete was lower than NA-concrete by a more significant margin at 28-days but less than 10% at 90-days. Mix RCAM1-C performed best among RCA-concrete samples and also equivalent to that NA-concrete. The impact of RCA was negligible for flexural strength; all RCA-concrete samples performed better than NA-concrete. Although mechanical properties of concrete with DA treated, RCA is equivalent to that of NA-concrete.

The application of the re-modified two-stage mixing approach (R-TSMA) in the production of RCA-concrete has very high significance. A new combined approach that includes the recycling process, primary and secondary crushing, treatment, and R-TSMA, concrete with 100% C-RCA, shows similar properties equivalent to NA-concrete.