

Chapter 6

Study on the percentage replacement of RCA in concrete

6.1 General

This chapter deals with the study on the effect of percentage replacement of C-NA and F-NA with C-RCA and F-RCA respectively on the properties of concrete produced from it. Major objective towards this experimental study is to study the interaction between natural aggregates and recycled aggregates (both coarse and fine); interaction between C-RCA with C-NA, F-NA and F-RCA; interaction between F-RCA with C-NA, F-NA and C-RCA. F-RCA was used directly for production of concrete, whereas C-RCA was passed through simple dry abrasion (SDA) treatment method and the adhered mortar reducing capacity of SDA treatment method was lower than other treatment methods but the overall performance of concrete produced with C-RCA treated with this method was satisfactory, the experimental results of both the methods are in discussed in chapter 4. Using two stage mixing approach for the production of concrete reduces the negative effect of adhered mortar on the performance of resulting concrete [77]. Similarly, the remodified two-stage mixing approach (R-TSMA) discussed in chapter 3 helped in producing RCA-concrete with equivalent performance as NA-concrete. For the analysis of fresh concrete, properties like workability and density were studied. Hardened concrete properties like compressive, splitting tensile and flexural, for durability, coefficient of permeability and carbonation was analysed. Scanning electron microscope (SEM) was used to study the micro structural differences between the different concrete mixes in hardened

Table 6.1: CxRC: Only C-RCA was varied from 0 to 100% in place of C-NA.

Group	Sample	Description
CxRC	CC	0% Coarse-RCA and 0% Fine-RCA
	C30RC	30% Coarse-RCA and 0% Fine-RCA
	C60RC	60% Coarse-RCA and 0% Fine-RCA
	C100RC	100% Coarse-RCA and 0% Fine-RCA

Table 6.2: FxRC: Only F-RCA was varied from 0 to 100% in place of F-NA

Group	Sample	Description
FxRC	CC	0% Coarse-RCA and 0% Fine-RCA
	F30RC	0% Coarse-RCA and 30% Fine-RCA
	F60RC	0% Coarse-RCA and 60% Fine-RCA
	F100RC	0% Coarse-RCA and 100% Fine-RCA

state. The test mechanism, monitoring of data during the test, test results, and summary of observation are discussed below.

6.2 Test Procedure and Conditions

In this part of study, C-RCA is the treated RCA by SDA treatment method. Different mixtures of coarse aggregates such as ‘100% C-NA’, ‘30% C-RCA+70% C-NA’, ‘60% C-RCA+40% C-NA’ and ‘100% C-RCA’ are referred to as C-NA, C-RCA30, C-RCA60 and C-RCA100, respectively. Similarly, mixtures of fine aggregates such as ‘100% FNA’,

Table 6.3: CxFxRC: Both C-RCA and F-RCA were varied from 0 to 100% in place of C-NA and F-NA respectively.

Group	Sample	Description
CxFxRC	CC	0% Coarse-RCA and 0% Fine-RCA
	C30F30RC	30% Coarse-RCA and 30% Fine-RCA
	C60F60RC	60% Coarse-RCA and 60% Fine-RCA
	C100F100RC	100% Coarse-RCA and 100% Fine-RCA

Table 6.4: C100FxRC: F-RCA was varied from 0 to 100% in place of F-NA, with 100% C-RCA.

Group	Sample	Description
C100FxRC	CC	0% Coarse-RCA and 0% Fine-RCA
	C100F0RC	100% Coarse-RCA and 0% Fine-RCA
	C100F30RC	100% Coarse-RCA and 30% Fine-RCA
	C100F60RC	100% Coarse-RCA and 60% Fine-RCA
	C100F100RC	100% Coarse-RCA and 100% Fine-RCA

‘30% F-RCA+70% FNA’, ‘60% F-RCA+40% FNA’ and ‘100% F-RCA’ are referred to as FNA, F-RCA30, F-RCA60 and F-RCA100, respectively. RCA sampling for this of study is given in chapter 4. For the convenience in analysis and discussion concrete samples were divided into four groups; ‘CxRC’, ‘FxRC’, ‘CxFxRC’ and ‘C100FxRC’, where x signifies the respective percentage replacement of C-NA and F-NA by C-RCA and F-RCA respectively by volume. Details of all four group are shown from table 6.1 to table 6.4.

All the concrete samples were designed for the mix design for 0.5 w/c and M30 grade as per the specification IS 10262 [24]. The quantity of cement per cubic metre of concrete was constant in each mix, i.e. 350 kg, while the amount of aggregates in each concrete mix is given in table 6.5. The combined gradation of aggregates is shown in Fig. 6.1. Sika® ViscoCrete®-5207 NS, based on modified polycarboxylate and a specific gravity of 1.12, was used as a high performance superplasticizing admixture to maintain the slump of each concrete mix between 50 to 100 mm. Its dosage (by weight of cement) was fixed to 1% in CxFxRC and C100FxRC, and 0.6% in CxRC and FxRC. F-RCA was treated by the ‘water compensation method’ to compensate for its high water absorption [140]. The conventional mixing technique was used in CC, while the re-modified two-stage mixing approach (a modified version of approach developed by [77] was used in recycled concrete mixes.

Table 6.5: Mix design of concrete samples.

Concrete mix	Water (l)	Cement (Kg)	Natural aggregates		Fine aggregates (FNA)	Recycled concrete aggregates		Fine aggregates (F-RCA)
			Coarse aggregates (C-NA)			Coarse aggregates (C-RCA)		
			20 mm size	10 mm size		20 mm size	10 mm size	
0C0F-C	175	350	730	469	755	0	0	0
30C0F-C	175	350	510	325	755	210	130	0
60C0F-C	175	350	295	190	755	415	260	0
100C0F-C	175	350	0	0	755	684	430	0
0C30F-C	175	350	730	469	497	0	0	213
0C60F-C	175	350	730	469	271	0	0	407
0C100F-C	175	350	730	469	0	0	0	641
100C30F-C	175	350	0	0	496	684	430	213
100C60F-C	175	350	0	0	271	684	430	407
100C100F-C	175	350	0	0	0	684	430	640
30C30F-C	175	350	510	325	497	210	130	213
60C60F-C	175	350	295	190	271	415	260	407

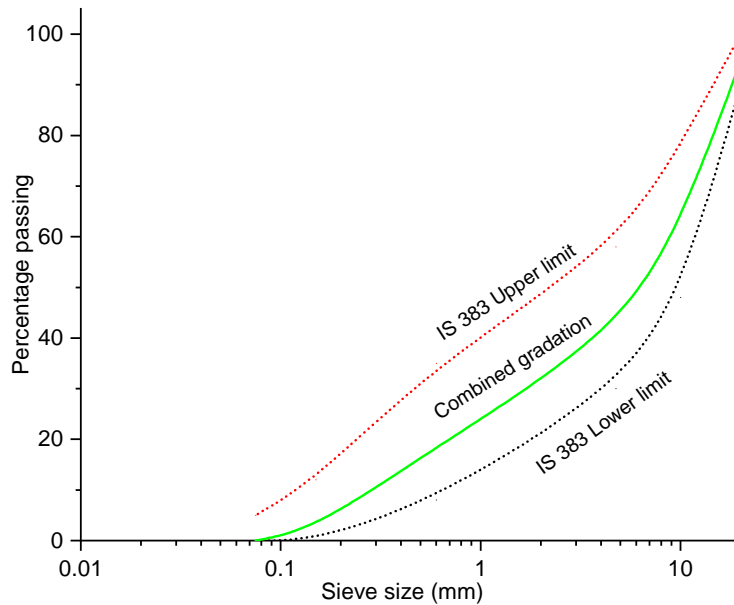


Figure 6.1: Combined aggregate gradation.

6.3 Comparison between different types of aggregates

6.3.1 Aggregate properties

The properties of different aggregates and grain size analysis are compared in table 6.5 and Fig. 6.2, respectively. The gradation of 10 mm and 20 mm nominal size C-NA were comparatively on the finer and coarser side, respectively, while the gradation of FNA was within the limits of Grading Zone II of IS 383 [20]. 20 mm nominal size untreated C-RCA

Table 6.6: Mechanical and physical properties of aggregates

Concrete mix	Water (l)	Cement (Kg)	Natural aggregates		Recycled concrete aggregates			
			Coarse aggregates (C-NA)		Fine aggregates (FNA)	Coarse aggregates (C-RCA)		Fine aggregates (F-RCA)
			20 mm size	10 mm size		20 mm size	10 mm size	
0C0F-C	175	350	730	469	755	0	0	0
30C0F-C	175	350	510	325	755	210	130	0
60C0F-C	175	350	295	190	755	415	260	0
100C0F-C	175	350	0	0	755	684	430	0
0C30F-C	175	350	730	469	497	0	0	213
0C60F-C	175	350	730	469	271	0	0	407
0C100F-C	175	350	730	469	0	0	0	641
100C30F-C	175	350	0	0	496	684	430	213
100C60F-C	175	350	0	0	271	684	430	407
100C100F-C	175	350	0	0	0	684	430	640
30C30F-C	175	350	510	325	497	210	130	213
60C60F-C	175	350	295	190	271	415	260	407

and C-NA had similar gradation Fig. 6.2 . On comparing their gradation curve with that of treated C-RCA, it was found that they had a higher content of particles of size greater than 10 mm. Also, the fineness modulus of treated C-RCA was minutely lower than the other two table 6.3, which contradicts the argument that the RCA will be coarser than natural aggregate due to the presence of adhered mortar. treated C-RCA was produced by the combination of sieving and abrasion, which resulted in higher amounts of fines than C-NA, which was obtained directly from the supplier. Contrarily, 10 mm nominal size C-NA was finer than treated C-RCA and untreated C-RCA as expected Fig. 6.2 . table 6.3 also shows that the fineness modulus of fine aggregate mixture decreases with an increase in its F-RCA content. But, particles of F-RCA30 and F-RCA60 were finer than that of FNA when only size range 4.75-2.36 mm was considered Fig. 6.2.

There were minimal differences between the specific gravities of natural aggregate and RCA table 6.3. The specific gravity of 20 mm and 10 mm nominal size untreated C-RCA was 12.72% and 15.8% lower than C-NA's. In the case of treated C-RCA, these values were 6% and 7.72%, respectively. Similarly, the specific gravity of F-RCA30, F-RCA60 and F-RCA100 was reduced by 5.7%, 9.89% and 14.83%, respectively, in comparison with FNA. It indicates that incorporating RCA produced from lab-tested concrete in place of natural aggregate (by volume) will affect the concrete weight but very little.

It is recommended that water absorption of aggregates should not be more than 2% [33]. In this study, only C-NA and FNA had water absorption less than 2%, as shown in table 6.3, while RCA absorbed more water due to the presence of highly porous adhered mortar. Moreover, the water absorption of F-RCA may have been underestimated because

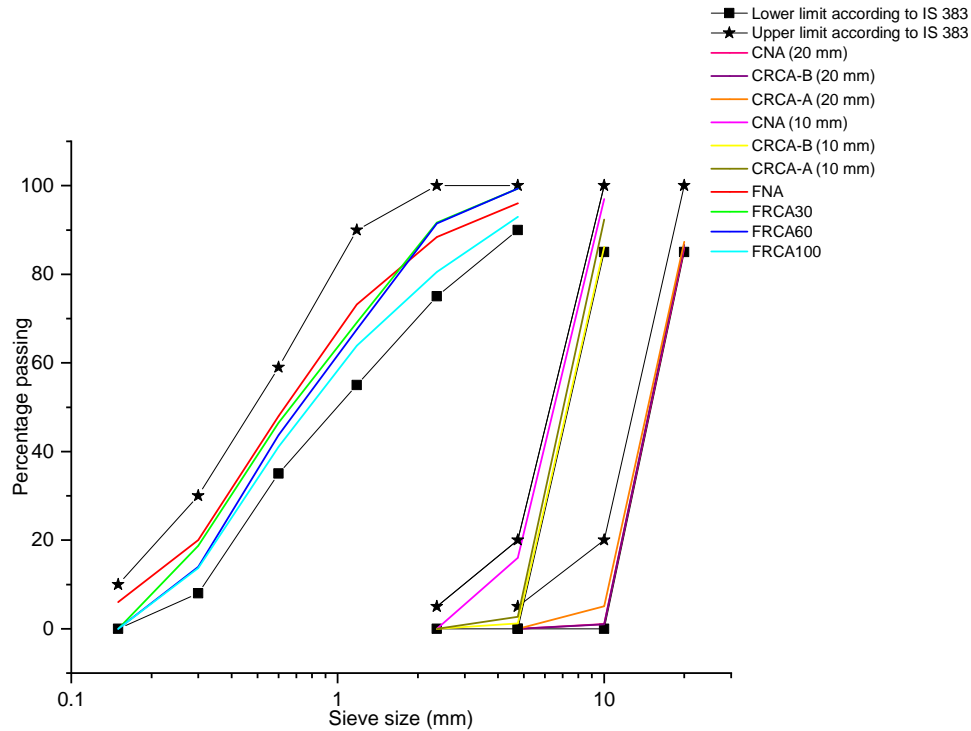


Figure 6.2: Gradation curves of different types of aggregates

before the water absorption test, F-RCA was washed with water and then surface-dried. Had it not been washed with water, a significant amount of foreign or loose particles would have been present (which were otherwise absent), and therefore, the water absorption capacity of unwashed F-RCA would have been comparatively higher. In C-RCA, the water absorption of 20 mm and 10 mm size treated C-RCA was reduced by 44% and 40% compared with untreated C-RCA. Still, it was well above the specified limit by 25% and 86%, respectively. Also, abrasion reduced the percentage of voids in 20 mm and 10 mm size C-RCA by 7% and 6.5%, respectively.

The mechanical properties of aggregates were determined by performing various tests such as abrasion, impact, crushing, elongation and flakiness index. According to IS 383 [20], their maximum value when aggregates are used in the wearable surface of concrete is 30% (35% for elongation index). For non-wearable surfaces, the maximum permitted abrasion and impact values are 50% and 45%, respectively. It can be seen in table 6.3 that untreated C-RCA did not fulfil some of these criteria for usage in the wearing course. However, treated C-RCA was well within the specified limit. On the other hand, the results suggest that untreated C-RCA may be utilised in the non-wearing course.

6.3.2 XRD analysis

The XRD analysis of different types of aggregates is shown in Fig. 6.3. The XRD diffractogram of FNA indicates predominance of quartz (SiO_2) which was expected since SiO_2 is the principal constituent of river sand [141]. Also, it can be seen that with an increase in the F-RCA content, the intensities of quartz and microcline peaks reduced and were minimum in F-RCA100. It suggests that a high amount of hydrated cement paste was adhered to F-RCA, although XRD analysis was qualitative. Similarly, on reducing the FNA content, the belite and portlandite peak's intensities continuously increased, reflecting a few unhydrated cement particles in adhered mortar. However, no portlandite peaks were observed in C-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 RCA [120]. [142] observed that grinding of RCA to powdered form for XRD analysis releases portlandite from the hydrated cement paste, which undergoes accelerated carbonation on being exposed to atmospheric carbon dioxide and results in the formation of calcite. In general, the presence of calcite is due to these reasons: (1) limestone aggregates utilised in the production of original concrete (from which RCA are produced) [143]; (2) carbonation of hydrated cement phases in original concrete [144]; (3) utilisation of limestone filler as supplementary cementitious material or raw material during cement production [145, 146]. XRD of untreated C-RCA and treated C-RCA reveal a minor dolomite phase due to the geological origin of most natural aggregates. As a result of cement hydration reactions, a minor secondary peak of crystalline C-S-H gel (tobermorite) was also observed in C-RCA.

6.4 Fresh concrete properties

6.4.1 Workability

The effects of F-RCA on the slump of CxRC, FxRC, C100FxRC and CxFxRC can be seen in Fig. 6.5, Fig. 6.6, Fig. 6.7, and Fig. 6.8 respectively. Fig. 6.4 shows the slump value comparison of all the samples used in the study. It also shows the compatibility of different percentages of C-RCA and F-RCA with C-NA and F-NA respectively based on the workability. It was observed that the concrete slump reduces with the increase in RCA

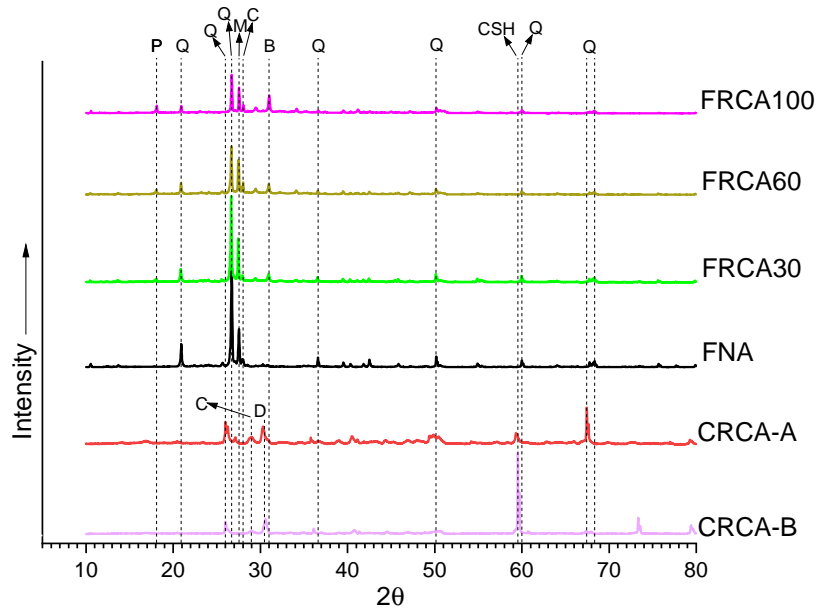


Figure 6.3: XRD of aggregates (C - Calcite; B - Belite; P - Portlandite; Q - Quartz; CSH - Calcium Silicate Hydrate; M - Microcline; D - Dolomite)

percentage. Slump reduction was higher in FxRC mix as compared to CxRC mix. When only coarse aggregate was replaced, loss in slump value was 1.08% for C30RC, 2.17% for C60RC, and 5.43% for C100RC in comparison of CC (NA-concrete). The reduction in slump (FxRC) of F30RC, F60RC and F100RC (in comparison with CC/F0RC) was 7.6%, 20.7% and 34.8%, respectively. When both coarse and fine aggregates were replaced simultaneously (CxFxRC), the reduction in slump value of fresh concrete increases, but concrete mix with 100% F-RCA (F100RC) showed more reduction than the C100F100RC mix. C30F30RC, C60F60RC and C100F100RC showed 11.95%, 26.087% and 28.26% lower slump value as compared to NA-C (CC). Similarly, when 100% C-RCA was kept constant for coarse aggregate and F-RCA was replaced with increasing percentage (C100FxRC) the slump value also reduced but the intensity was lower than FxRC and CxFxRC. In comparison to CC the slump value of concrete mix C100F30RC was 11.95% lower than CC, similar to C30F30RC, for C100F60RC reduction was 17.39%, and the highest reduction was in C100F100RC as stated earlier. The reduction in slump of C100F30RC, C100F60RC and C100F100RC (in comparison with C100F0RC) was 6.9%, 12.6% and 24.1%, respectively. Results show that the slump reduction is more for the concrete mix FxRC (containing F-RCA with 100% C-NA) as compared to C100FxRC (F-

RCA with 100% C-RCA). In FxRC, CxFxRC and C100FxRC, more water was required to maintain pre-specified workability even though F-RCA was coarser than FNA and coarser particles require less amount of water than finer particles to wet their surface [147]. It was because F-RCA had a higher water absorption capacity than FNA (5.2 times) due to its rougher surface texture, higher void content and more open pores. Another reason for the slump reduction could be the constant w/c in all the concrete mixes. The F-RCA concrete requires more cement [148] and water [149] than CC to achieve similar workability.

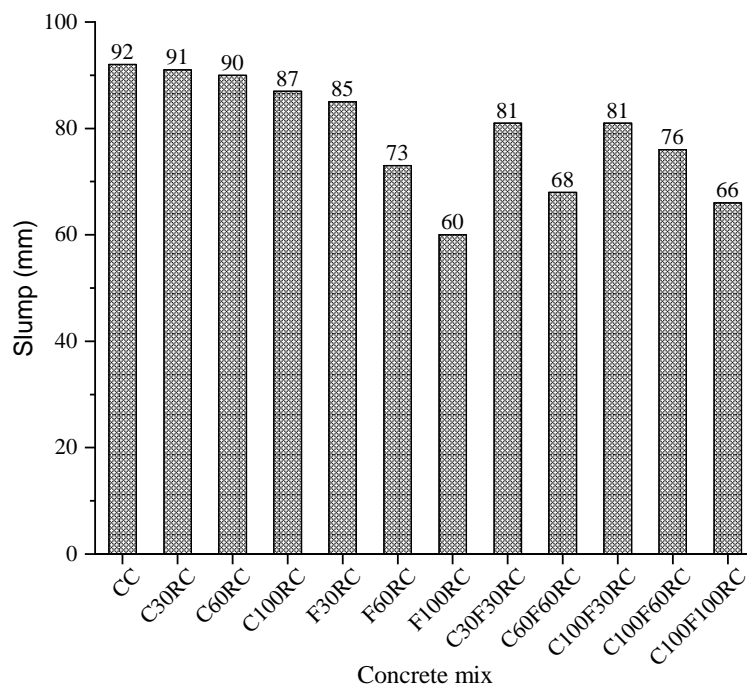


Figure 6.4: Comparison between slumps of different concrete mix.

In this study, additional water to the tune of 100% water absorption capacity of F-RCA30, F-RCA60 and F-RCA100 was added to the respective concrete mix at the time of mixing. Therefore, when compatibility between F-RCA and C-NA/ C-RCA (group 2/group 4) was examined (based on the slump of C100FxRC and FxRC nearest to that of CC), it was found that at 30% replacement, F-RCA was more compatible with C-NA than treated C-RCA and vice-versa at 60% and 100% replacement. In addition to being coarser, 20 mm size C-NA also had a lower water absorption capacity than treated C-RCA. Also, the difference between the water absorption of F-RCA30 and FNA was lower as compared to between treated C-RCA and C-NA (20 mm size). Therefore, due to these properties of C-NA and F-RCA30, F30RC had a higher slump than C100F30RC (even

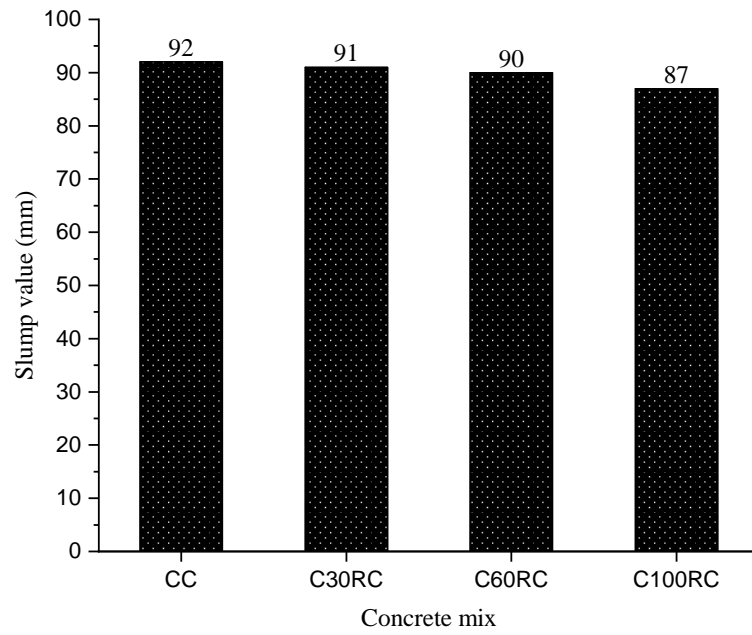


Figure 6.5: Slump value of series 1 concrete (CxRC).

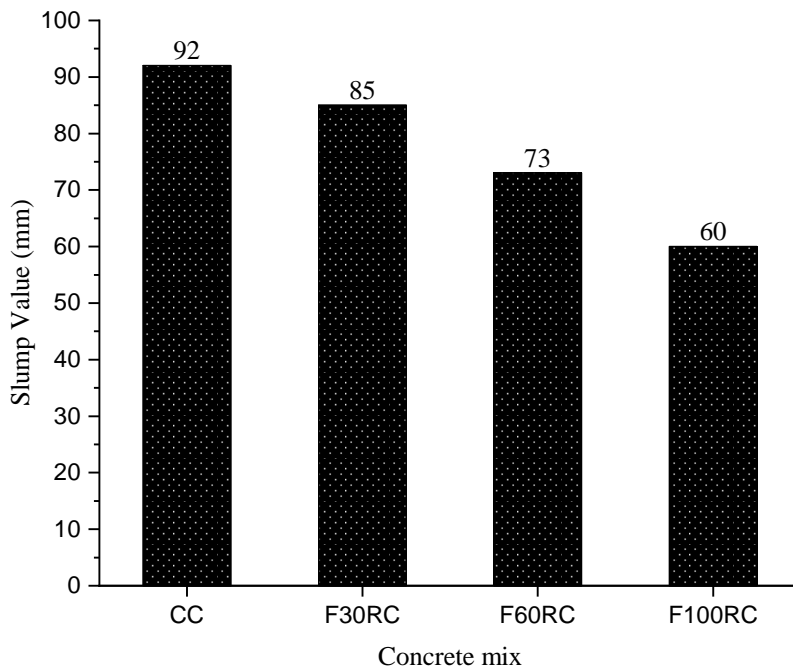


Figure 6.6: Slump value of series 2 concrete (FxRC).

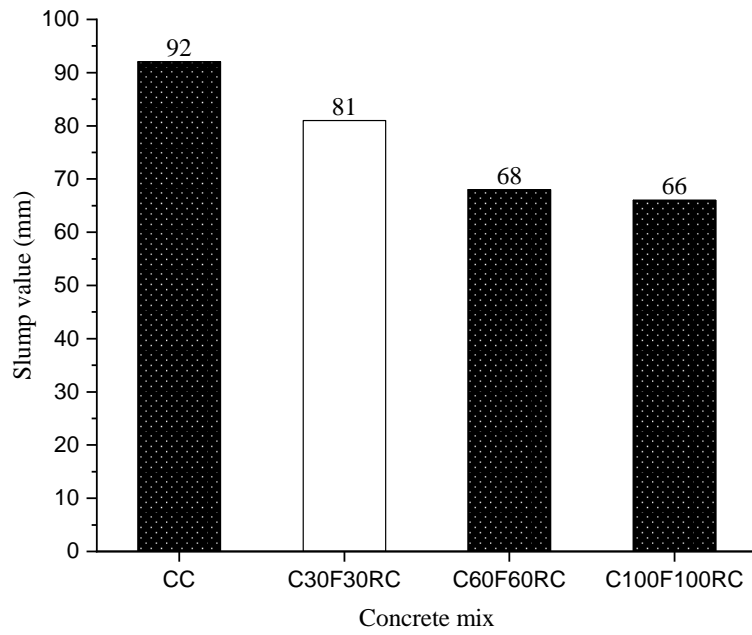


Figure 6.7: Slump value of series 3 concrete (CxFxRC).

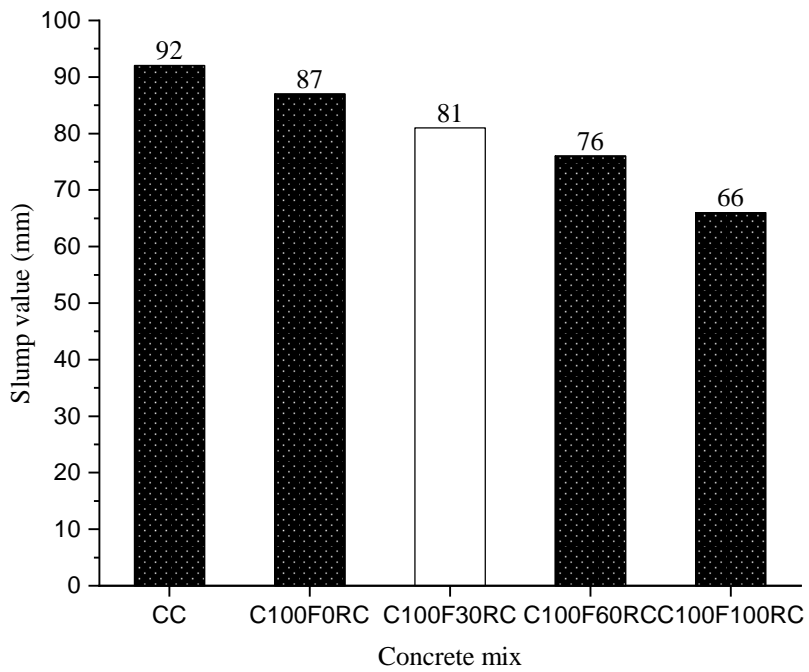


Figure 6.8: Slump value of series 2 concrete (C100FxRC).

when 1% superplasticiser by weight of cement was used in C100FxRC in comparison to 0.6% in FxRC). On the other hand, C100F60RC or C100F100RC had a higher slump than F60RC or F100RC, respectively. In general, an extra amount of water is required in concrete with RCA to compensate for its high water absorption capacity, which is done either by pre-saturating RCA with water or adding additional water (equivalent to water absorption of RCA) during concrete mixing up until its completion. The main issues associated with the pre-saturation of RCA are to estimate the amount of water needed in this method and to define ways to achieve it. According to [150], the amount of water absorbed by RCA in 15 min accounts for more than 90% of the water absorbed in 24 h. In the absence of any corrective measures, this rapid rate of water absorption by RCA reduces effective w/c of concrete mix; thereby, affecting its workability [140]. Therefore, to achieve workability in RAC similar to that in conventional concrete, [150] suggested pre-soaking RCA with only 50% of the amount of water absorbed by RCA in 15 minutes. In the water compensation method, the level of compensation depends on the workability requirements and size of RCA (extra water is required in F-RCA compared to C-RCA) [151]. The extra water added during concrete mixing should not be equivalent to the 100% water absorption capacity of F-RCA, as excess water may cause bleeding in concrete [152]. In addition, F-RCA may not absorb this excess water quickly due to the short duration of mixing of concrete [153]. Also, excess water gets deposited near the interfacial transition zone, thereby reducing the bond of aggregates with the surrounding paste matrix [154]. Therefore, [155] and [75] recommended utilising F-RCA in a dry condition to enhance the bond between cement matrix and aggregates. The complications associated with the addition of extra water during concrete mixing can be mitigated by autoclave curing [156], hot curing [157] or adding polycarboxylate-based high range water reducer [158]. The reasonable and satisfactory explanation regarding complex phenomena, such as flow behaviour or workability of concrete with F-RCA, differs universally and should be backed by experiments.

6.4.2 Fresh density

The density of fresh concrete depends on the type of aggregates, w/c and void content [159]. 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-concrete is lower than that of natural aggregate concrete due to the presence of low-density adhered mortar [121, 122]. Fig. 6.9 shows the effects of C-RCA and F-RCA on the density of fresh CxRC, FxRC, CxFxRC and C100FxRC and compatibility between F-RCA, C-RCA, F-NA and C-NA (based on the density of CxRC, CxFxRC, C100FxRC and FxRC nearest to that of CC).

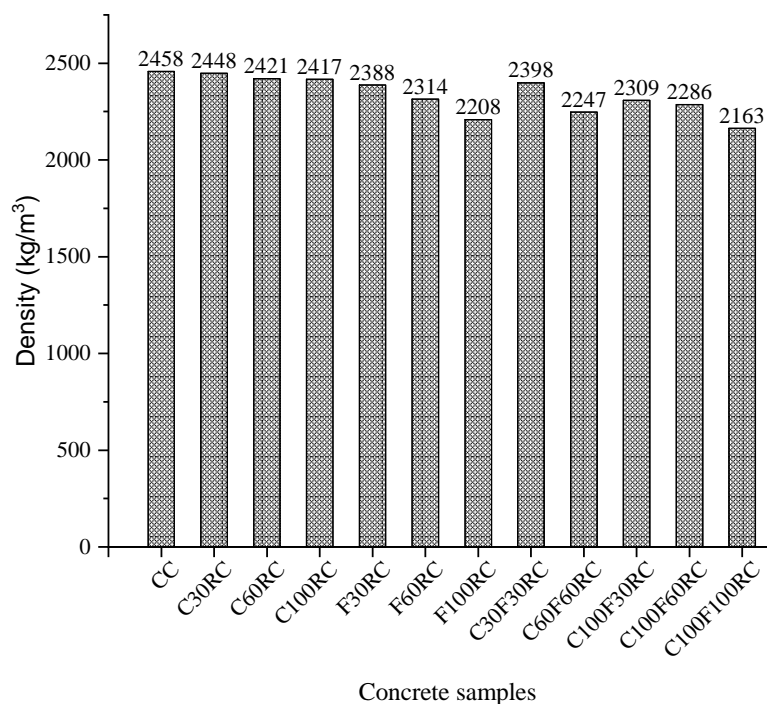


Figure 6.9: Effect of F-RCA and C-RCA on the density of fresh concrete.

The fresh concrete density reduces with the increase in RCA percentage. The density of F-RCA and C-RCA was about 15% and 6% lower than that of FNA and C-NA, respectively. Therefore, slump reduction was higher in FxRC mix as compared to CxRC mix. Compared to the density of CC, F100RC had higher reduction in density (10.2%) than C100F0RC (1.7%), the reduction increased to 12% in C100F100RC. When only coarse aggregate was replaced (CxRC), loss in concrete density was 0.4% for C30RC, 1.50% for C60RC, and 1.69% for C100RC in comparison of CC (NA-concrete). Variation of fresh density with percentage replacement in series CxRC is shown in Fig. 6.10. The reduction in density of F30RC, F60RC and F100RC (FxRC) (in comparison with CC/F0RC) was 2.84%, 5.85% and 10.17%, respectively. Fig. 6.11 shows the density variation in series FxRC. When both coarse and fine aggregates were replaced simulta-

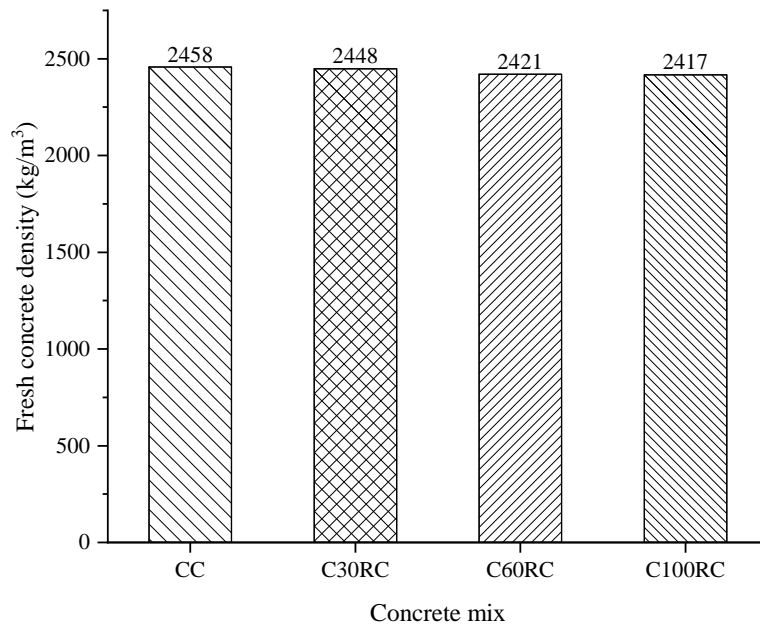


Figure 6.10: Fresh concrete density of CxRC (series 1)

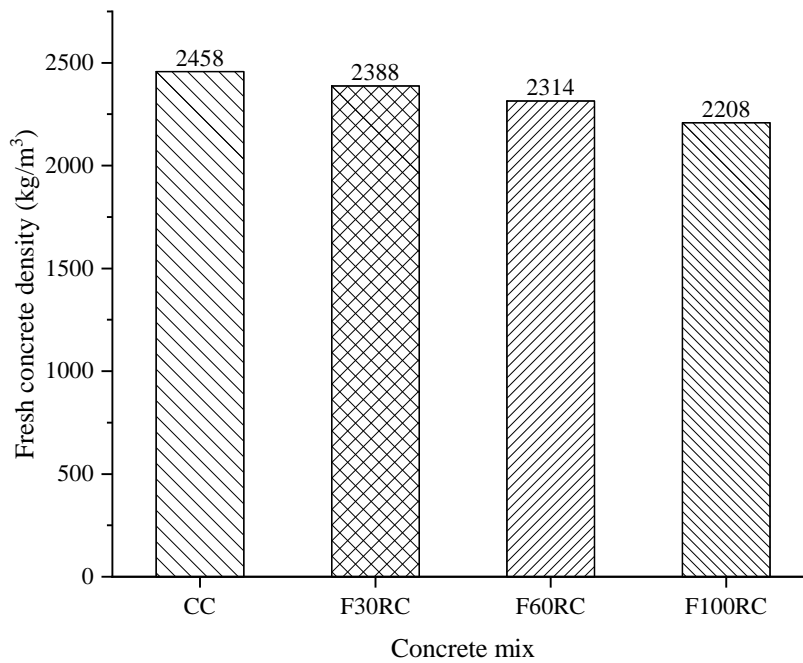


Figure 6.11: Fresh concrete density of FxRC (series 2)

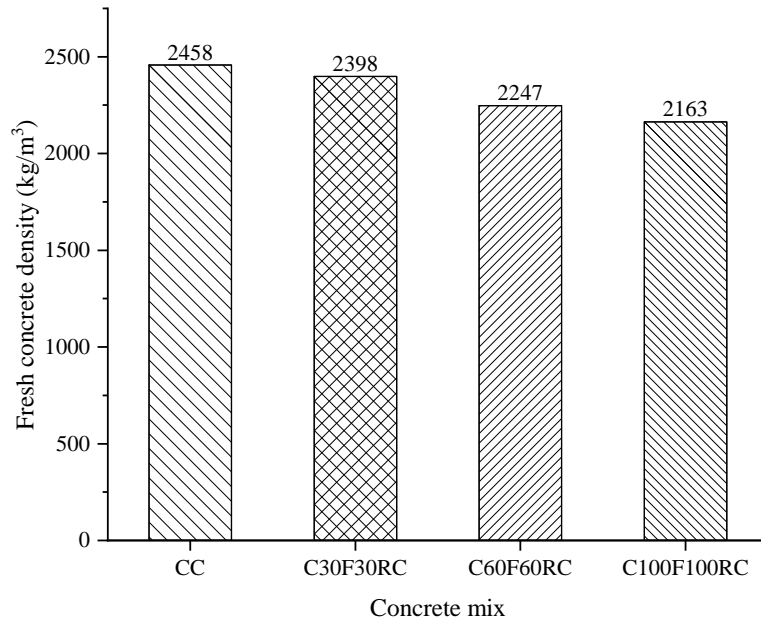


Figure 6.12: Fresh concrete density of CxFxRC (series 3)

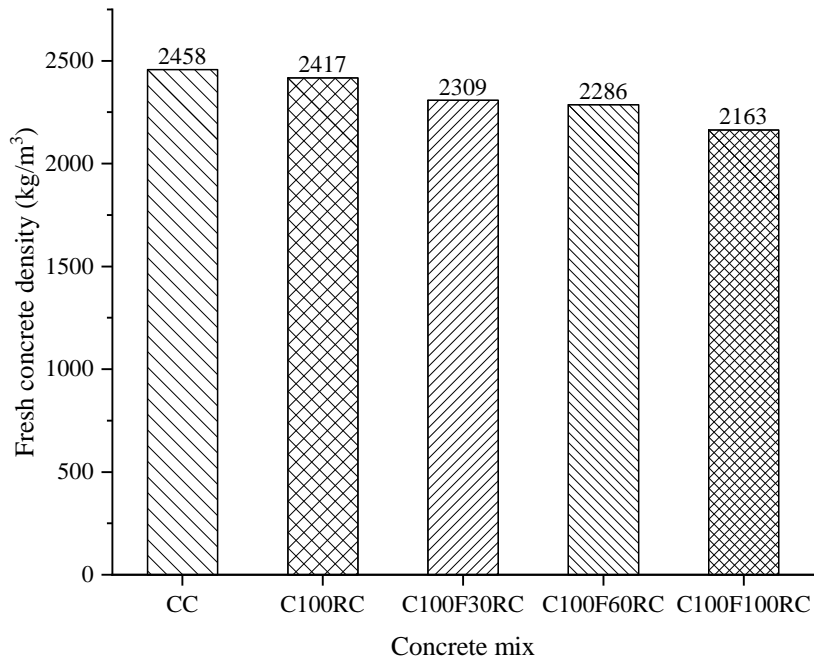


Figure 6.13: Fresh concrete density of C100FxRC (series 4)

neously (CxFxRC), the reduction in density value of fresh concrete increases as shown in Fig. 6.12. C30F30RC, C60F60RC and C100F100RC showed 2.44%, 8.58% and 12% lower fresh density as compared to NA-C (CC). Similarly, in series C100FxRC shown in Fig. 6.13, the density of concrete mix C100F30RC was 6.05% and 4.46%, for C100F60RC it was 6.99% and 5.33%, and in C100F100RC it was 12% and 10.50% lower than CC and C100RC respectively. Reduction in fresh concrete density was higher in CxRxRC series as compared to FxRC and C100FxRC, with exception of C30F30RC in which density reduction was lower than F30RC. Comparison of Fig. 6.11, Fig. 6.12 and Fig. 6.13 shows that F-RCA was more compatible with 100% C-NA at all the replacement percentages. At various replacement percentages of F-RCA (30%, 60%, 100%), the difference between the density of fresh FxRC and C100FxRC was 3.3%, 1.2% and 2%, respectively. It indicates that in relation to the fresh density of CC, the concrete series FxRC had lower density reduction than concrete series C100FxRC. The relationship between F-RCA content and concrete density was more linear in FxRC series than in C100FxRC series. The density of ordinary concrete and semi-lightweight concrete varies between 2240-2400 kg/m³ [160] and 1840-2240 kg/m³ [158], respectively. Therefore, all the concrete mixes can be termed as ordinary concrete except F100RC and C100F100RC, which come into the category of semi-lightweight concrete. These types of concrete may reduce the overall dead load of the structure, thereby reducing the required amount of reinforcement and foundation.

6.5 Hardened concrete properties

6.5.1 Compressive strength

Fig. 6.14, Fig. 6.15, Fig. 6.16 and Fig. 6.17 shows the variation in compressive strength of CxRC, FxRC, C100FxRC and CxRxRC, respectively. The test results indicate that the addition of F-RCA resulted in reduction of compressive strength irrespective of curing age and concrete series. However, the general trend in performance of FxRC, C100FxRC and FxCxRC indicates that their sensitivity to F-RCA reduces with an increase in curing age, i.e., the difference between the compressive strength of CC and recycled concrete was higher at early curing age (7, 14 and 28 days) than at later curing age (56 and 90 days). Considering each FNA/F-RCA replacement ratio, the percentage difference between compressive strength of CC and CxRC varied between 1.71% to 4.11% at 28

days, 2.23 to 2.34 at 56 days, and 0.71 to - 1.20% ('-' denotes the higher strength than CC) at 90 days. FxRC series varied between 3.4% to 31.4% at 28 days, 2.1% to 19.6% at 56 days and 11.92% to -0.49% at 90 days. Similarly, in the case of the C100FxRC series, it varied between 11.8% to 29.4% at 28 days, 7% to 17.7% at 56 days, and 3.11% to 10.63% at 90 days. CxFxRC series varied between 4.71% to 29.37% at 28 days, 3.12% to 17.72% at 56 days, and 0.33% to 10.63% at 90 days. [149] reviewed more than 30 past studies related to F-RCA incorporation in concrete and reported that at an F-RCA replacement ratio greater than or equal to 30%, the maximum reduction in 28 days compressive strength varies between 11.1% to 50%, which was inferior to the results obtained in this study. Most likely, it could be associated with the high-quality original concrete rather than that of F-RCA. However, according to [12], FxRC performance does not depend on the source of laboratory-produced F-RCA.

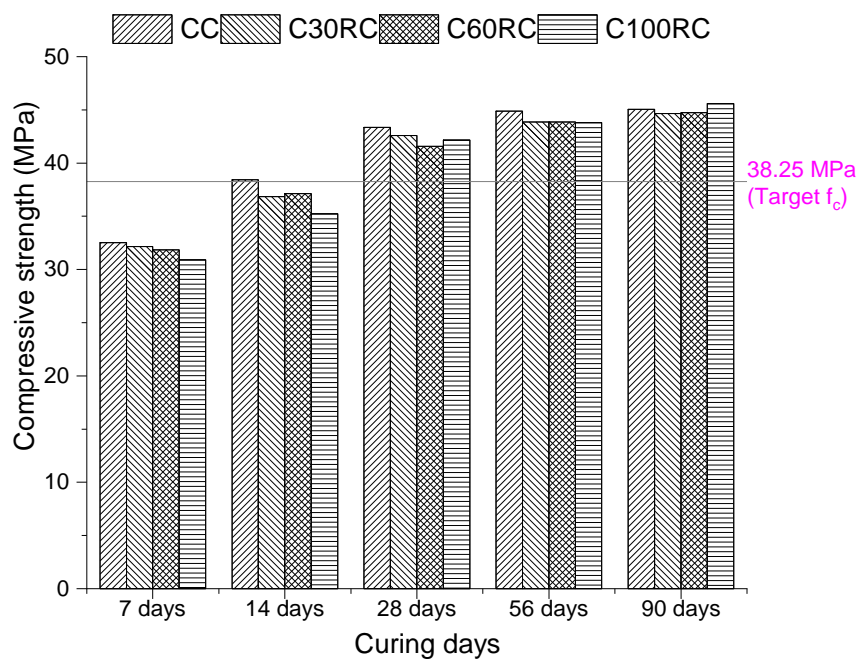


Figure 6.14: (Compressive strength of CC and CxRC

Two concrete mixes viz. F30RC (Fig. 6.15) and C100RC Fig. 6.14) exhibited slightly higher compressive strength than CC at 90 days (by 0.5% and 1.2%, respectively), also the compressive strength of C30F30RC mix was only 0.33% lower than CC (almost equal) . These concrete mixes benefitted from high water absorption of F-RCA and C-RCA, which facilitated internal curing at a later age. In C100F0RC and F30RC, the

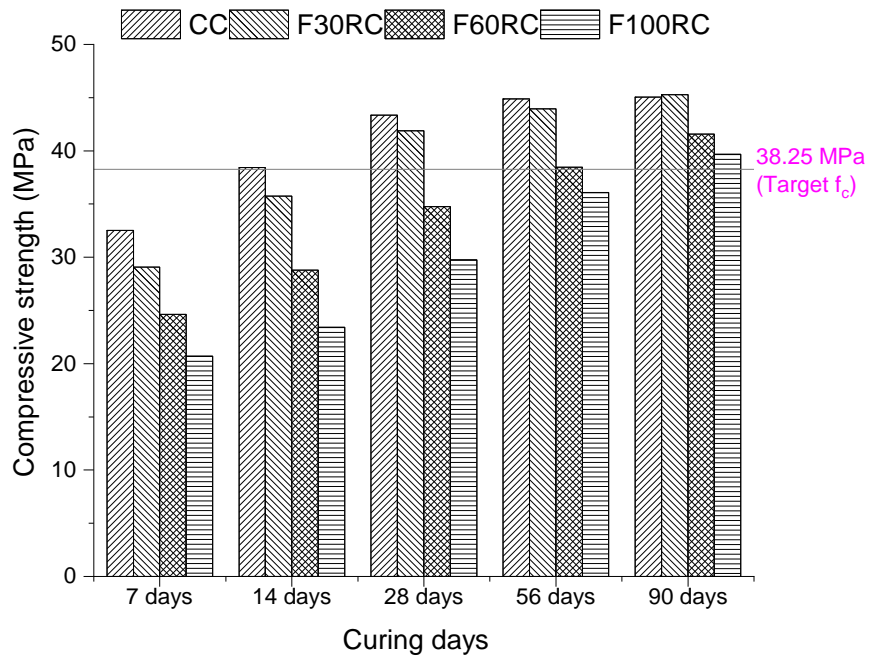


Figure 6.15: (Compressive strength of CC and FxRC)

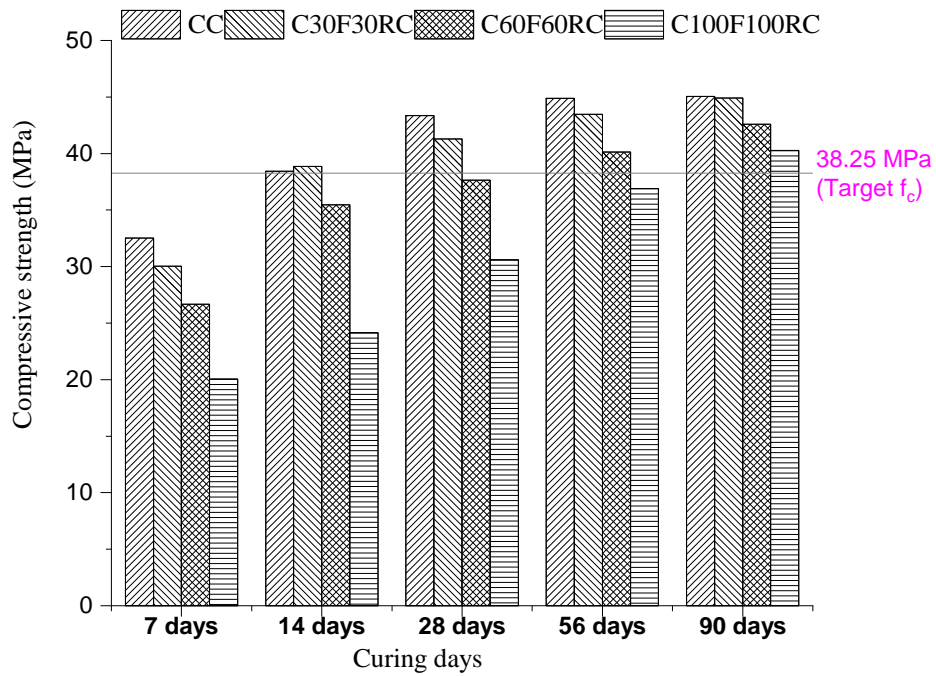


Figure 6.16: (Compressive strength of CC and CxFxRC)

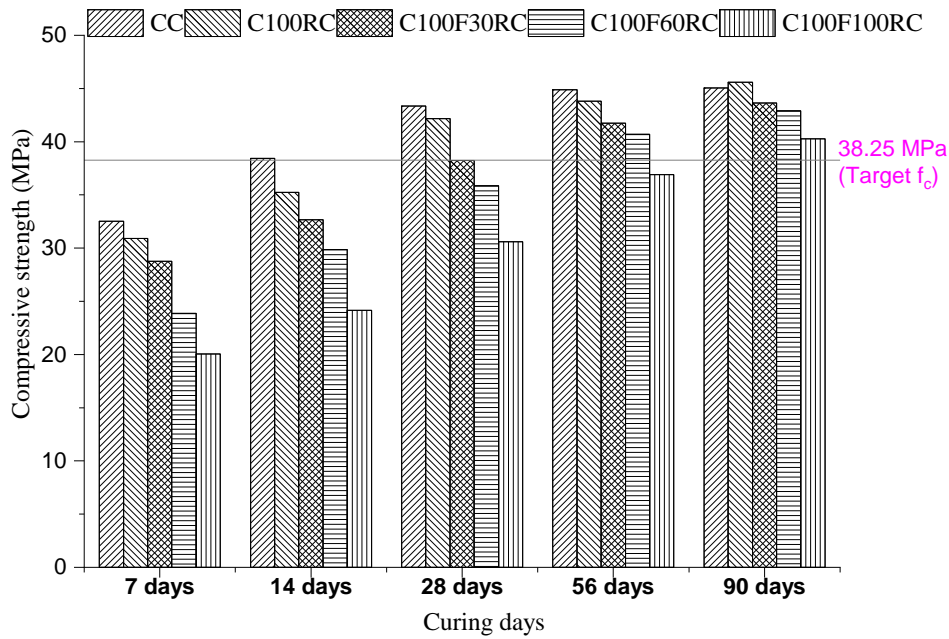


Figure 6.17: (Compressive strength of CC and C100F_xRC)

internal curing by recycled aggregates was far more efficient and dominant than their mediocre mechanical and physical properties. However, when F-RCA content was further increased, the negative influence of its properties overcame the positive effect of internal curing. Hence, recycled concrete mixes (other than C100F0RC and F30RC) had lower compressive strength than CC, irrespective of the curing age. It is widely recognised that the high water absorption capacity of F-RCA and C-RCA emanates lower compressive strength at an early age but acts as an internal curing agent and assists in strength gain at a later age [118]. When the effects of replacing 100% natural aggregates by either F-RCA or C-RCA on the compressive strength of concrete were compared, it was found that C-RCA was a better performer than F-RCA, i.e. C100F0RC had higher compressive strength than F100RC, irrespective of curing age. The compressive strength of C100F0RC and F100RC was 1.2% higher and 12% lower than that of CC at 90 days, respectively. The better performance of C100F0RC than F100RC was due to the lower fineness modulus of C-RCA than C-NA (20 mm size) and higher fineness modulus of F-RCA than F-NA. It was also because the difference between the water absorption capacity of F-RCA and F-NA was more significant than the difference between C-RCA and C-NA [12]. Moreover, the difference between the compressive strength of C100F0RC and F100RC was 10.22

MPa, 11.83 MPa, 12.42 MPa, 7.73 MPa and 5.91 MPa at 7, 14, 28, 60 and 90 days, respectively. The difference was increasing up to 28 days and after that decreasing. It means that the gain in compressive strength was higher in C100F0RC up to 28 days. But, beyond 28 days, it was higher in F100RC. It could be attributed to the unhydrated cement particles (in the form of belite) found in the adhered mortar of F-RCA (presence of belite was confirmed in the XRD analysis of F-RCA (C100F0RC, while its compressive strength was still lower. Like the slump test results, F-RCA was also more compatible with C-NA at the 30% F-NA replacement and C-RCA at 60% and 100% FNA replacement. According to IS 10262 [24], the target compressive strength of M30 grade concrete is 38.25 MPa. Only two concrete mixes, viz. C30RC, C60RC, C100RC, F30RC, C30F30RC could attain higher strength than 38.25 MPa at 28 days, while the difference was insignificant for C100F30RC (0.03% lower). Therefore, by compressive strength test results, it can be assumed that C-NA replacement by C-RCA, 30% FNA replacement by F-RCA or simultaneous utilisation of both are the feasible options for producing concrete of M30 grade. Moreover, concrete of similar quality can also be made by 60% and 100% F-RCA content; however, they have to be cured for a minimum of 56 and 90 days, respectively, to attain the specified target compressive strength. Therefore, it can be concluded that as the F-RCA content in concrete increases, the curing time required for achieving M30 grade concrete's target compressive strength also increases. Various studies have utilised F-RCA in different types of concrete such as self-compacting concrete [161], foam concrete [162], geopolymer concrete [163], etc. and obtained mixed results. The reduction in compressive strength of concrete due to the addition of F-RCA is mainly because of an increase in the water requirement of concrete for achieving workability similar to CC. On the other hand, the increase in compressive strength is because of F-RCA's filler effect (when finer than FNA), internal curing effect, rough surface texture and angular shape [164]. Conclusively, it would not be wrong to assume that the compressive strength of F-RCA concrete is mainly affected by three factors (i) FNA/F-RCA replacement ratio; (ii) w/c of concrete; (iii) saturation state of F-RCA.

6.5.2 Flexural strength

Fig. 6.18 to Fig. 6.21 shows the results for flexural strength of concrete. The flexural strength of CxRC, FxRC, C100FxRC and CxFxRC was lower than that of CC (irrespec-

tive of the curing age and replacement ratio), likely due to the characteristics of F-RCA and C-RCA such as low angularity and surface roughness, the weak layer of old mortar, high water absorption capacity etc. which adversely affected the mechanical interlocking between these aggregates and weakened the interfacial transition zone [165].

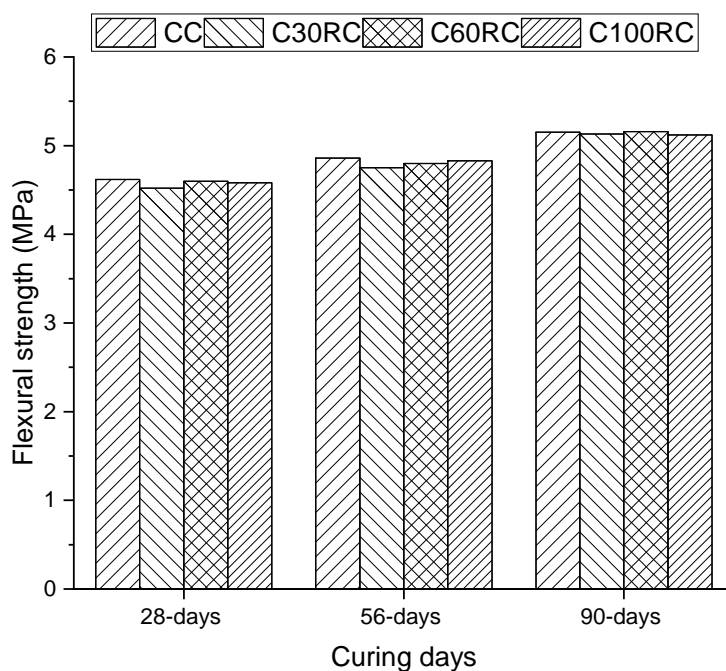


Figure 6.18: (Flexural strength of CC and CxRC)

The flexural strength loss in CxRC, FxRC, C100FxRC and CxFxRC (with respect to CC) was maximum at 28 days (more pronounced in compressive strength than the flexural strength), except C30RC and C60RC whose maximum loss was at 56-days of curing. At 28 days, the compressive strength losses in C30RC, C60RC, F30RC, F60RC, F100RC, C100F0RC, C100F30RC, C100F60RC, C30F30RC, C60F60RC and C100F100RC were 1.71%, 4.11%, 3.4%, 19.8%, 31.4%, 2.7%, 11.8%, 17.2%, 4.71%, 13.17% and 29.4%, respectively while the flexural strength losses were 2.26%, 1.23%, 1.5%, 6.1%, 6.9%, 0.9%, 2.2%, 4.3%, 2.06%, 3.09% and 5.4%, respectively. The recycled concrete performed better in terms of flexural strength as the loss in flexural strength of recycled concrete was lower than the loss in its compressive strength. In general, the orientation/position of the larger dimension of coarse aggregates is along the prism length, thereby increasing the effectiveness of the interfacial bond [166]. It compensates for the adverse effects of RCA on the flexural strength of recycled concrete by offering greater resistance to the bending.

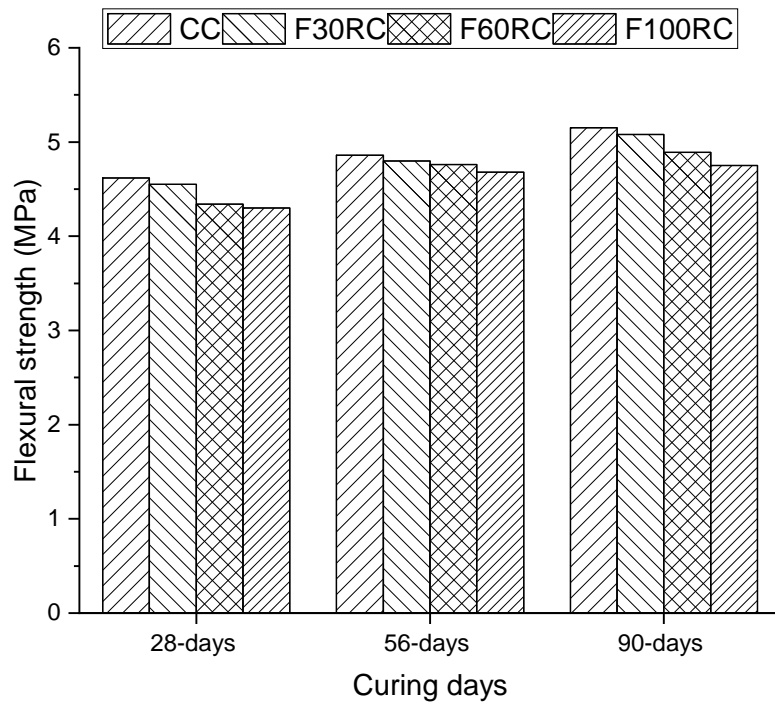


Figure 6.19: (Flexural strength of CC and FxRC)

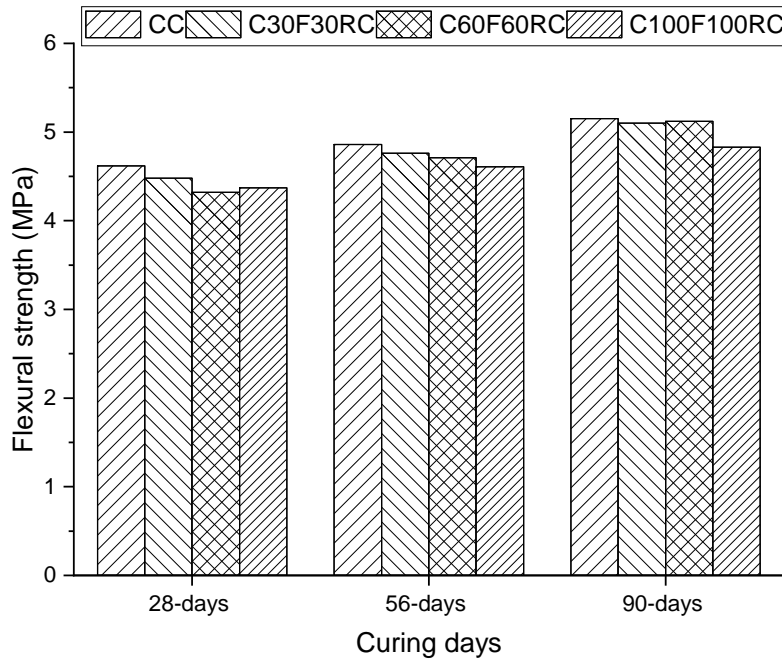


Figure 6.20: (Flexural strength of CC and CxFxRC)

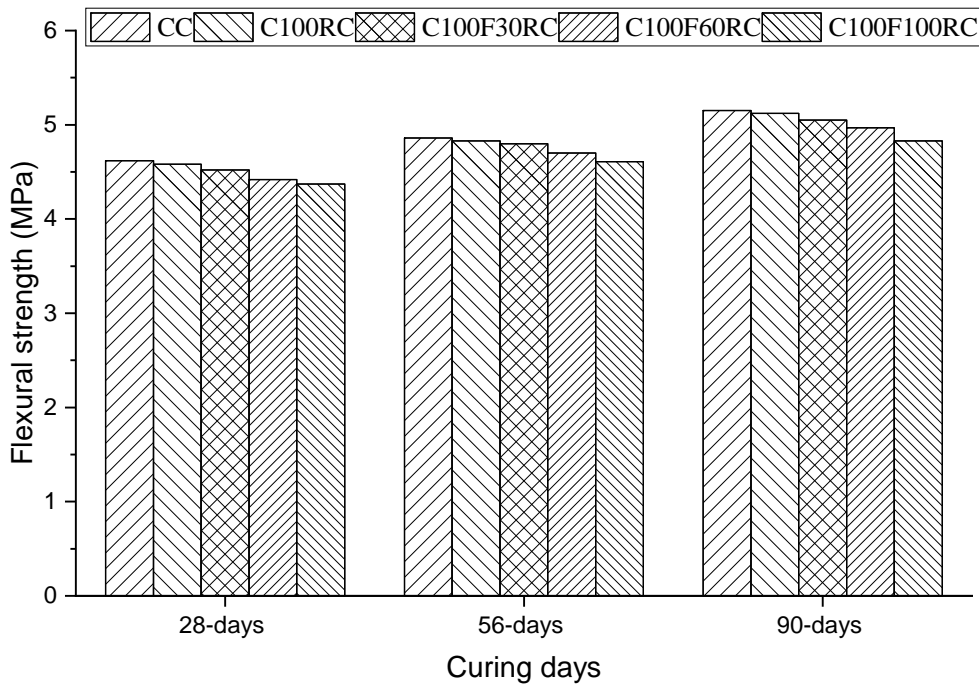


Figure 6.21: (Flexural strength of CC and C100FxRC)

That is why the flexural strength of recycled concrete was less affected as compared to its compressive strength. At each F-RCA content, the flexural strength of FxRC, CxFxRC and C100FxRC was equivalently affected (irrespective of the curing age) (Fig. 6.19 to Fig. 6.21). The difference between their flexural strength ranged from 0 to 0.03 MPa, 0.06 to 0.08 MPa and 0.07 to 0.08 MPa at 30%, 60% and 100% FNA replacement, respectively. Moreover, C100F0RC performed better as compared to F100RC. Hardly any reduction ($\leq 1\%$) was observed in the strength of C100F0RC with respect to CC, while the decrease in strength ranged from 3 to 8% in F100RC. The difference between flexural strength of C100F0RC and F100RC was 0.28 MPa, 0.15 MPa and 0.37 MPa at 28, 56 and 90 days, respectively. The internal curing effect was minimal in the flexural strength test.

6.5.3 Split tensile strength

Fig. 6.22, Fig. 6.23, Fig. 6.24 and Fig. 6.25 shows the results of split tensile strength test. The pattern was similar to the results of compressive and flexural strength test, i.e. reduction in strength with increase in F-RCA and C-RCA content, irrespective of the curing age. This was likely due to the weaker fracture plane of recycled concrete

because of its highly porous microstructure in the presence of F-RCA and C-RCA [166]. As the curing age was increased, the adverse effects of F-RCA, and C-RCA became less detrimental. Considering F0RC/CC as the reference concrete for CxRC, FxRC, CxFxRC and C100FxRC, it was observed that the strength loss at 28 days was lowest in CxRC, then in CxFxRC and C100FxRC and highest in FxRC. The split tensile strength loss in CxRC, FxRC, C100FxRC and CxFxRC (with respect to CC) was maximum at 28 days (more pronounced in compressive strength than the flexural strength), except C30RC, C60RC, C30F30RC, and C60F60RC whose maximum loss was at 56-days of curing. At 28 days, the strength loss in C30RC, C60RC and C100RC with respect to CC was 1.72%, 2.07% and 3.45%, while the strength loss in F30RC, F60RC and F100RC (with respect to F0RC) was 5.5%, 12.8% and 16.9%, respectively. Strength loss in C30F30RC, C60F600RC, C100F30RC, C100F60RC and C100F100RC, with respect to C100F0RC was 5.52%, 8.62%, 5.4%, 7.9% and 12.5%, respectively and with respect to CC was 8.62%, 11.03% and 15.52%. The maximum 28 days split tensile strength was observed in C30RC followed by C60RC and C100RC (apart from CC). While, the maximum reduction in strength with respect to the strength of CC was observed in mix C100F100RC (18%), which was a little higher when compared with the results of past studies (8% [45] and 15% [167]).

In the past, the relationship between the split tensile strength and compressive strength of recycled concrete has not been well represented, likely due to the considerable variation in results of split tensile strength tests in different studies [168]. Similarly, in this study, on comparing losses in all three types of strength (compressive, flexural and split tensile), no distinctive patterns were observed, i.e., for some samples, the loss was maximum in split tensile strength. In contrast, others had a maximum loss in their compressive strength. However, according to [169], the strength loss is more pronounced in compressive strength and less in split tensile strength. According to [47], the interface between RCA and new cement paste has low w/c (indicating a good bond between them) than both bulk-paste as well as old mortar (attached to RCA). Consequently, in recycled aggregate concrete, failure happens through old mortar (attached to RCA) and not through interfacial transition zone between the new mortar and RCA (unlike conventional concrete where interfacial transition zone is the strength controlling link) [28]. This old mortar is prone to failure in compression; however, if present in limited quantities, it

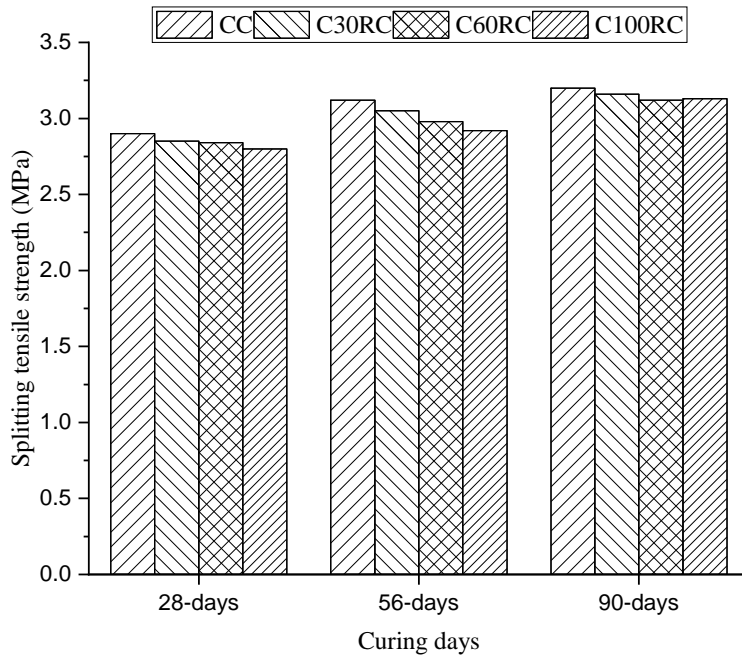


Figure 6.22: (Split tensile strength of CC and CxRC)

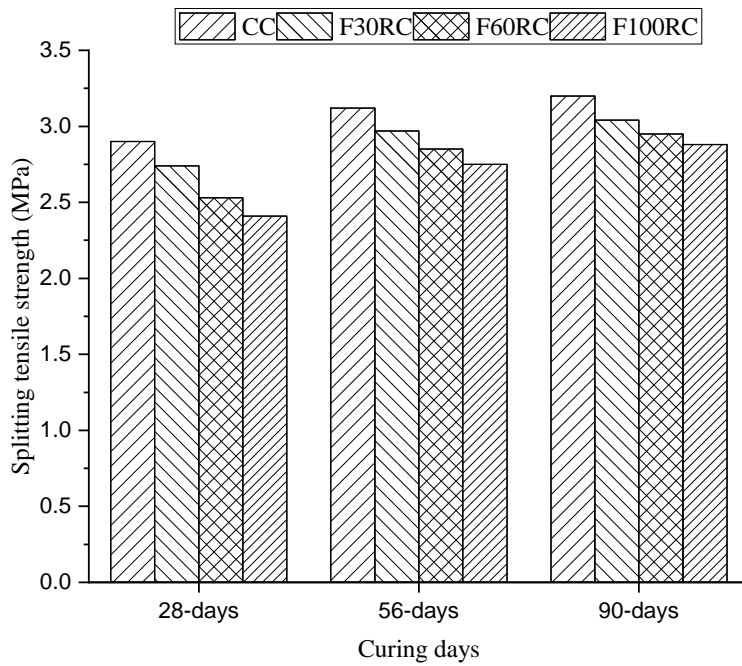


Figure 6.23: (Split tensile strength of CC and FxRC)

enhances the performance of recycled aggregate concrete against tension by providing a smoother transition between RCA and new mortar [168].

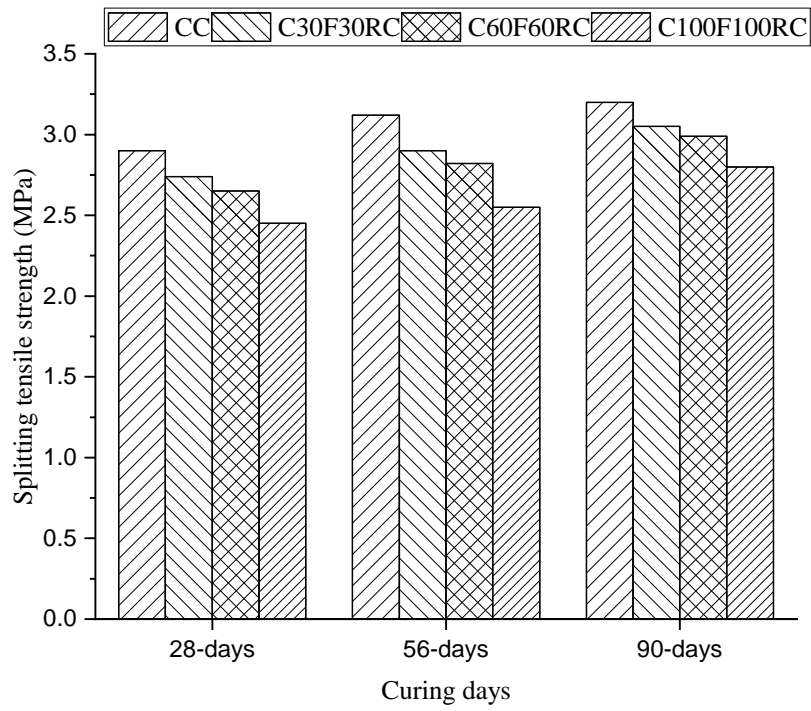


Figure 6.24: (Split tensile strength of CC and CxFxRC)

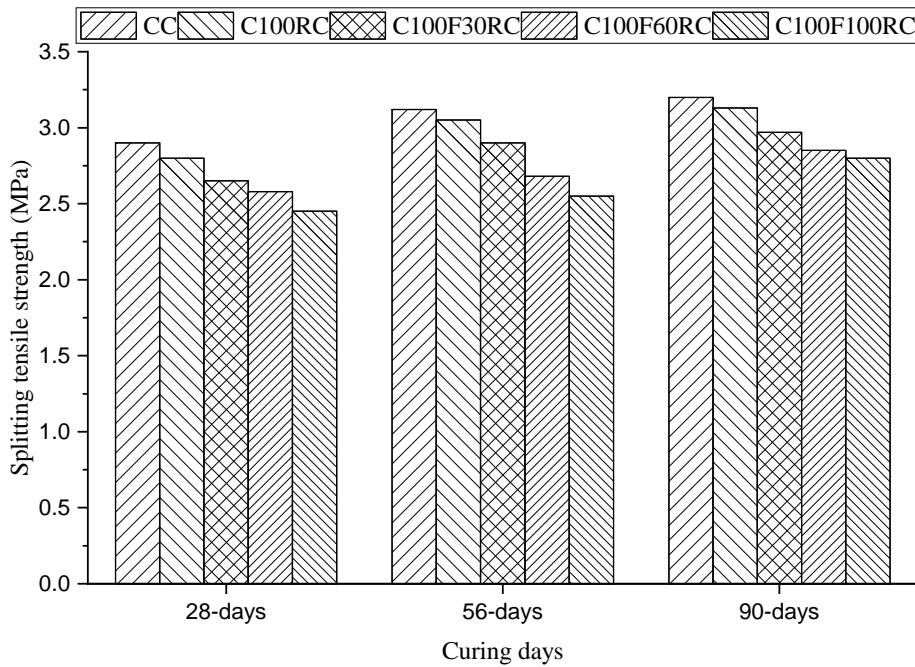


Figure 6.25: (Split tensile strength of CC and C100FxFRC)

6.6 Durability properties

6.6.1 Water permeability

Primarily, concrete durability is measured in terms of its resistance to water permeability. In the past, the water absorption capacity of concrete has been measured in many ways, such as water sorptivity test (water absorption by capillary action), saturated water absorption test (water absorption by complete immersion), etc [37,126,127]. In this study, the coefficient of permeability ('k') of concrete (shown in Fig. 6.26) was determined as per the procedure laid out in specification IS 3085 [30].

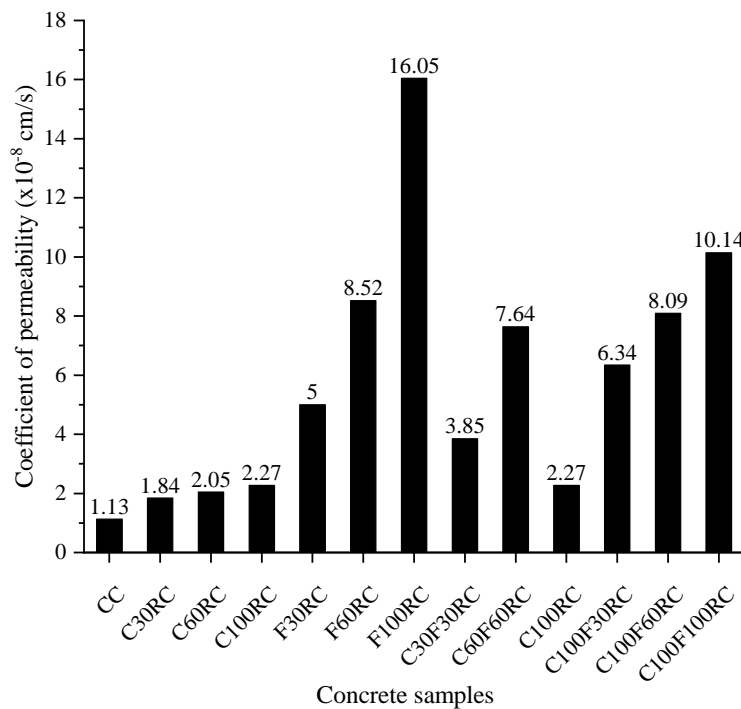


Figure 6.26: Coefficient of permeability of different concrete samples.

It can be seen that concrete permeability increases with an increase in the replacement ratio of F-RCA (higher the 'k' value, more will be the permeability). The 'k' value of CxRC, FxRC CxFxRC and C100FxRC after 28 days of curing was approximately 1.63 to 2.01 times, 4.4 to 14.2 times, 3.41 to 9, and 2 to 9 times higher than that of the conventional concrete (F0RC), respectively. In this study, F-RCA increased the permeability of concrete (at 28 days of curing) because of its ability to absorb additional water during mixing. If the curing age of concrete is equivalent to or less than 28 days, this additional water damages the paste matrix and the interfacial transition zone by influencing the

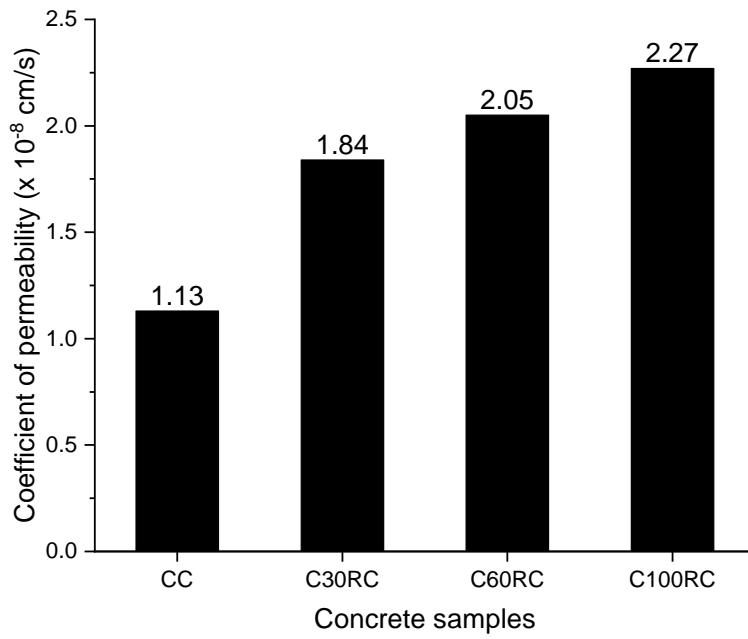


Figure 6.27: Coefficient of permeability of concrete of CxRC (series 1)

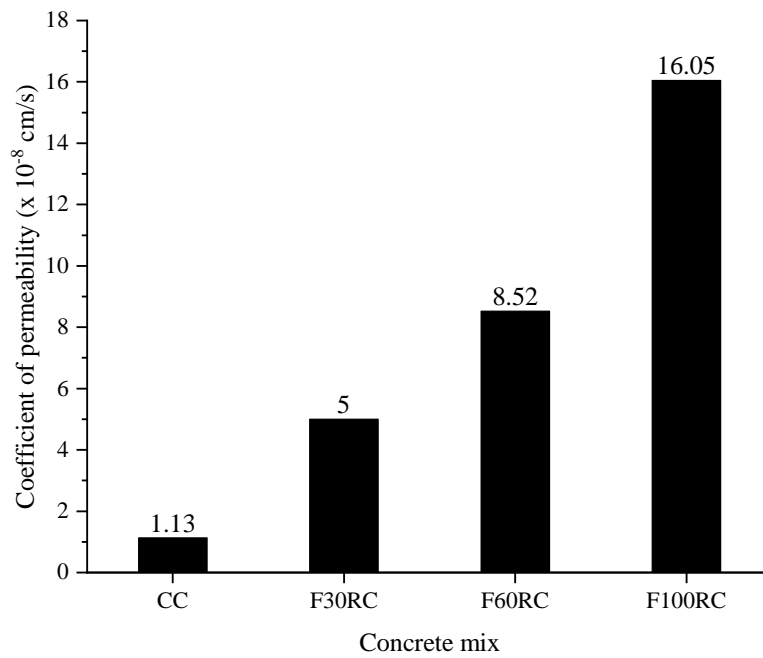


Figure 6.28: Coefficient of permeability of concrete FxRC (series 2)

number of pores and volume of water in the mix. But, if the curing age is more than 28

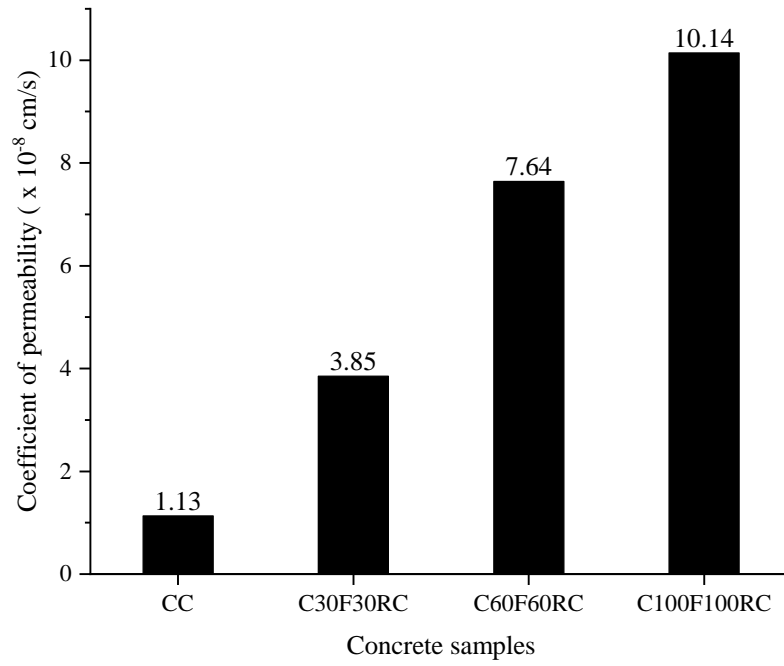


Figure 6.29: Coefficient of permeability of concrete CxFxRC (series 3)

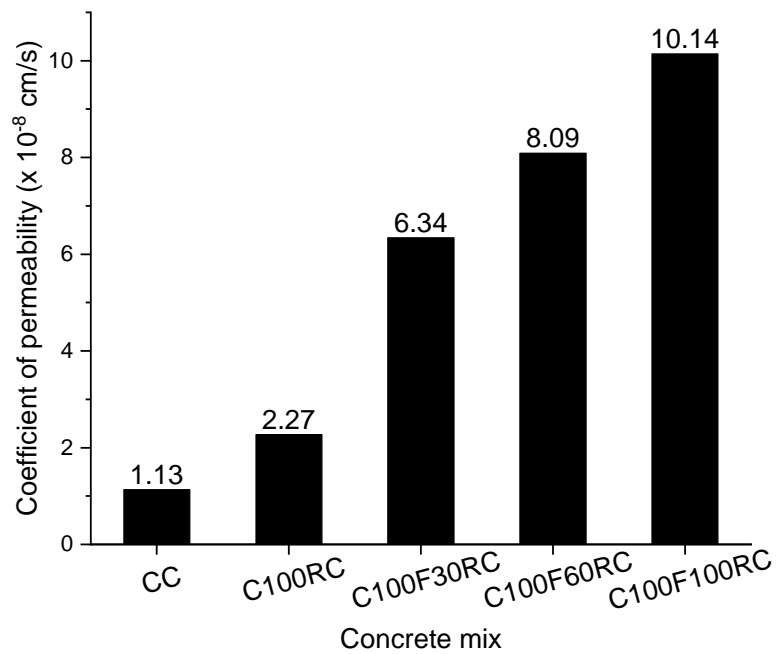


Figure 6.30: Coefficient of permeability of concrete C100FxRC (series 4)

days, the same additional water facilitates the internal curing effect of RCA (it was also observed in the results of compressive strength tests).

When only C-RCA was used the water permeability did not vary much as can be seen in Fig. 6.27. For determining whether F-RCA performed well in combination with C-NA or C-RCA, the water permeability of FxRC (Fig. 6.28 series) was compared with that of the corresponding CxFxRC (Fig. 6.29) and C100FxRC series (Fig. 6.30). At 30% F-RCA content, the water permeability in the FxRC series was 21.13% lower than that of the C100FxRC series and 30% higher in comparison to CxFxRC. On the contrary, the water permeability in FxRC series was 5.31% and 10.32% higher than that of the C100FxRC and CxFxRC series, respectively, at 60% F-RCA content. At 100% F-RCA content the water permeability in FxRC series was 58.28% higher than C100FxRC and CxFxRC. The water absorption and fineness of C-RCA were higher than that of C-NA because the C100FxRC series absorbed more water to fulfil the water deficit and therefore had higher water permeability than FxRC and CxFxRC at 0% and 30% F-RCA content. However, at 60% and 100% F-RCA content, its combination with C-RCA performed better than with C-NA because F-RCA and C-RCA were produced from the same source; therefore, the synergistic effect of F-RCA and C-RCA became more dominant than the harmful properties of C-RCA. 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 RAC reduces the volume of capillary pores and results in pore refinement, thereby reducing water permeability of RAC, bringing it at par with that of control concrete.

6.6.2 Carbonation

The reaction in which cement hydration products react with CO_2 in the atmosphere and in the presence of moisture to form CaCO_3 is known as weathering carbonation. In comparison, the accelerated carbonation reactions ($\text{C}_3\text{S}/\text{C}_2\text{S}$ reaction with CO_2) occur alongside the early cement hydration when concrete is intentionally exposed to CO_2 . Both types of carbonation result in the formation of CaCO_3 and contribute to strength development as CaCO_3 occupies more space than $\text{Ca}(\text{OH})_2$ leading to a denser concrete matrix [129]. Nevertheless, the passivity of reinforcement's protective layer is destroyed due to a reduc-

tion in the pH value of the concrete by carbonation. Anyways, the weathering carbonation reaches the level of reinforcement after several years, while accelerated carbonation could be applied to unreinforced/plain concrete so that there is no concern about reinforcement corrosion in concrete [131, 132]. In this study, the compressive strength of concrete submerged in water for 56 days was compared to that of concrete submerged in water for 28 days and further subjected to accelerated carbonation curing for another 28 days (referred to as ‘carbonated concrete’) (Fig. 6.32).

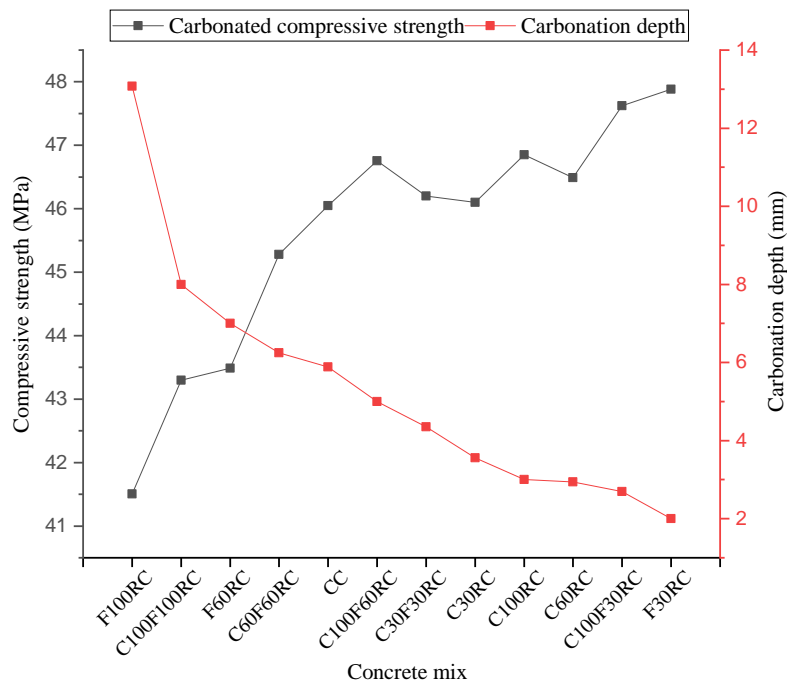


Figure 6.31: Carbonated compressive strength vs Carbonation depth

The compressive strength of carbonated concrete was higher than that of concrete cured in water, albeit the difference varied from one concrete mix to another. For concrete mix CC, C30RC, C60RC, C100RC, F30RC, F60RC, F100RC, C30F30RC, C60F60RC, C100F30RC, C100F60RC and C100F100RC, the carbonated concrete had 2.63%, 5.08%, 6.02%, 7%, 9%, 13.1%, 15%, 6.28%, 12.83%, 14.06%, 14.9%, and 17.27% higher compressive strength than concrete cured in water, respectively. Fig 6.32 shows the variation in compressive strength samples at 56 days of water curing and after combined curing of water and ACC (accelerated carbonation curing). The strength gain in C100FxRC series was higher than in the FxRC and CxFxRC series. Moreover, in water curing, each concrete mix had lower compressive strength than CC at 56 days; however, in carbonated

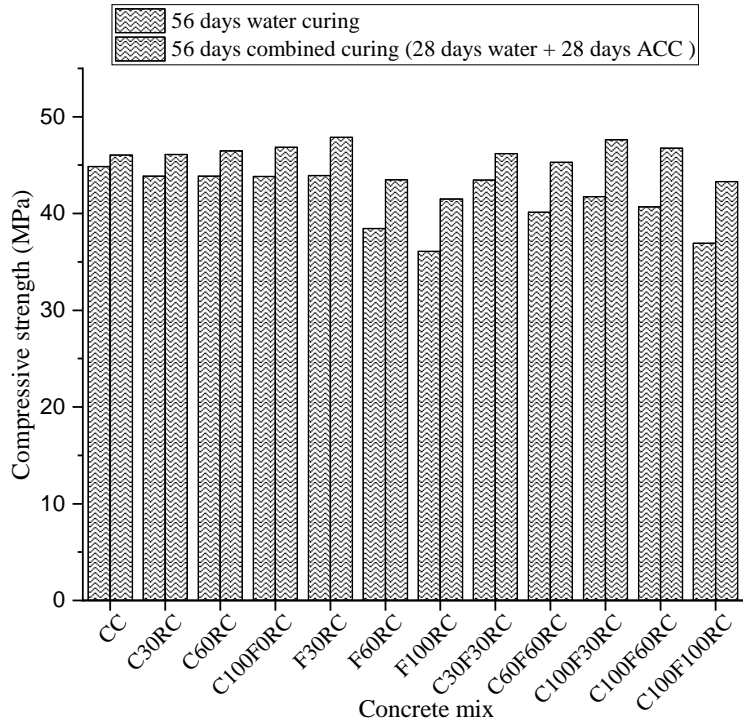


Figure 6.32: Carbonated compressive strength vs Compressive strength after water curing



Figure 6.33: Carbonation depth of CC



Figure 6.34: Carbonation depth of C30RC



Figure 6.35: Carbonation depth of C60RC



Figure 6.36: Carbonation depth of C100RC

concrete, C30RC, C60RC, C100RC, F30RC, C30F30RC, C100F30RC and C100F60RC had higher compressive strength than CC. It could be attributed to additional hydration products ($\text{Ca}(\text{OH})_2$ and C-S-H gel) present in the adhered mortar, which in contact with CO_2 may have resulted in additional CaCO_3 formation, thereby increasing the compactness of concrete. However, the positive effects of CaCO_3 formation were overshadowed by mediocre mechanical and physical properties of F-RCA and C-RCA at higher replacement ratios, resulting in lower compressive strength of F60RC, F100RC, C60F60RC and C100F100RC than that of CC. Fig. 6.33 to Fig. 6.44 shows the depth of carbonation in each concrete mix, while the carbonation depth vs carbonated compressive strength of each concrete mix is shown in Fig. 6.31. It can be seen that the carbonation depth was inversely proportional to the carbonated compressive strength, similar to a study by [126]. The more the compressive strength was, the lower was carbonation depth and vice versa. Generally, the increase in compressive strength is associated with the reduced pore volume and compact microstructure. As a result, the water present in the pores becomes inaccessible to CO_2 from the atmosphere; thereby, carbonation of concrete reduces [133].

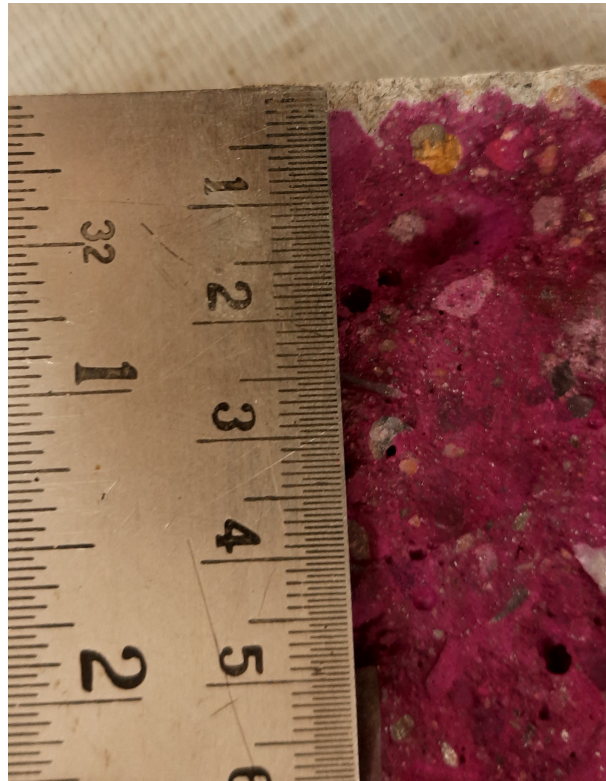


Figure 6.37: Carbonation depth of F30RC



Figure 6.38: Carbonation depth of F60RC

At 30% F-RCA content, the carbonation depth was higher in C100FxRC, and at 60% or 100% F-RCA content, it was higher in FxRC. In relative terms, F-RCA was more



Figure 6.39: Carbonation depth of F100RC



Figure 6.40: Carbonation depth of C30F30RC



Figure 6.41: Carbonation depth of C60F60RC

compatible with C-NA at 30% and with treated C-RCA at 60% and 100%. The effects of F-RCA on the carbonation of concrete can easily be compensated by: (1) utilising a high range water reducer [149]; (2) maintaining low (effective) w/c [170]; (3) limiting the minimum size of F-RCA particles [171].

6.7 Relationship between properties of concrete and aggregates

In this section, correlations between weighted properties of aggregate mixtures (density and water absorption) and properties of concrete (compressive strength, water permeability and carbonation depth at 28 days) were established. The methodology adopted



Figure 6.42: Carbonation depth of C100F30RC

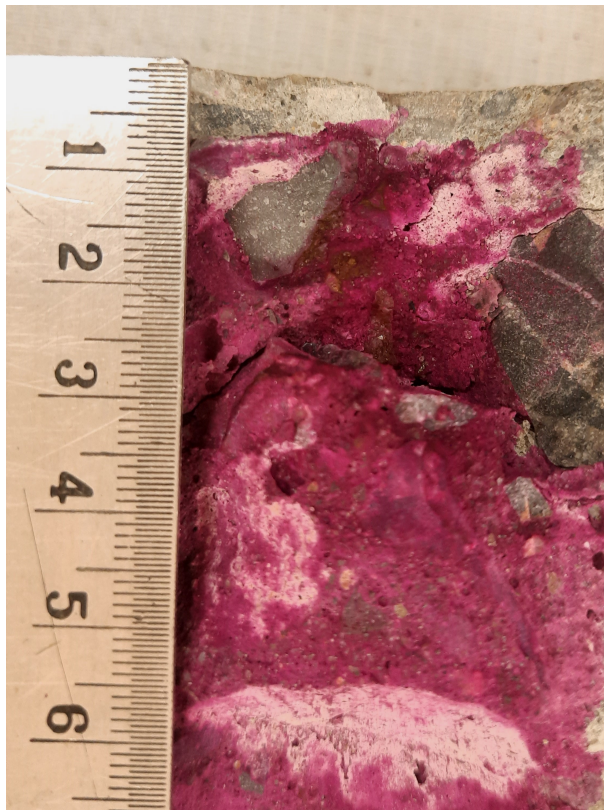


Figure 6.43: Carbonation depth of C100F60RC

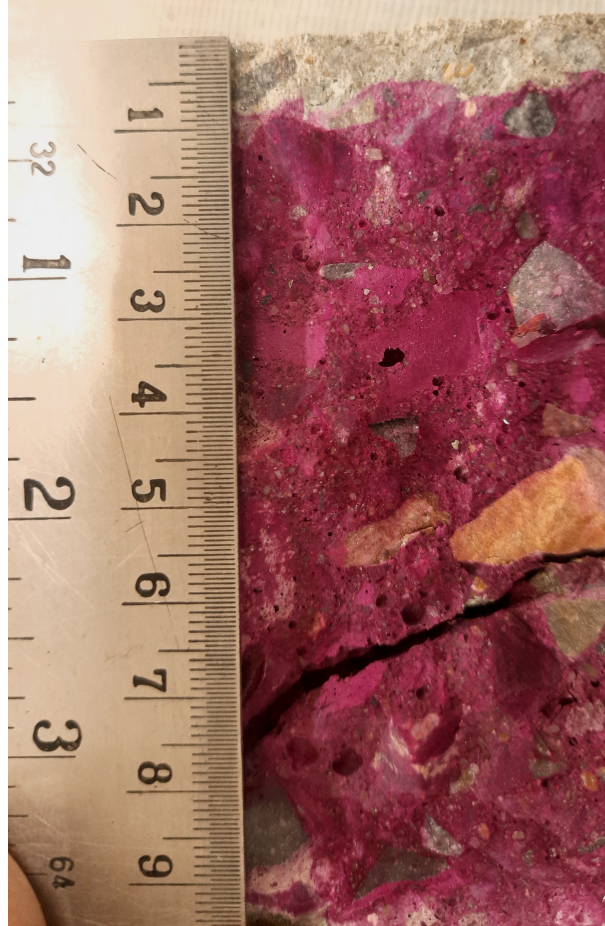


Figure 6.44: Carbonation depth of C100F100RC

to find these correlations was loosely based on a data processing technique published in a study by Brito and Robles [172]. The concise description and framework of this technique are given below. In the graphical analysis, the ratio between absolute values of RCA-concrete and reference concrete properties was used as the ordinates, while the ratio between weighted densities of aggregate mixtures in these concrete mixes was used as the abscissas. For this study, concrete mic FxRC and F100xRC was used. F0RC and C100F0RC were considered the reference concrete for FxRC and C100FxRC series, respectively, to determine whether FRCA is more compatible with CNA or CRCA-A. Eq. (6.1) was used to calculate the weighted density of aggregate mixtures in different concrete mixes. In this equation, different replacement ratios of CNA and FNA with CRCA

and FRCA and their densities were also considered proportionally.

$$\rho = \frac{FA}{100} \times \left[\frac{(FRCA \times \rho_{FRCA}) + (FNA \times \rho_{FNA})}{100} \right] + \frac{CA_{20}}{100} \times \left[\frac{(CRCA_{20} \rho_{CRCA_{20}}) + ((CNA_{20} \rho_{CNA_{20}}))}{100} \right] + \frac{CA_{10}}{100} \times \left[\frac{(CRCA_{10} \rho_{CRCA_{10}}) + ((CNA_{10} \rho_{CNA_{10}}))}{100} \right] \quad (6.1)$$

where,

ρ = weighted density of mixture of aggregates in a concrete mix; FA / CA20 / CA10 = % of fine aggregates / 20 mm / 10 mm nominal size coarse aggregates in a aggregate mix = 38.64% / 37.36% / 24%; FRCA = % of FRCA in a concrete mix = 0%, 30%, 60% or 100%; CRCA20 / CRCA10 = % of 20 mm / 10 mm nominal size CRCA-A in a concrete mix = 0% or 100%; FNA/ CNA20 / CNA10 = % of FNA / 20 mm / 10 mm nominal size CNA in a concrete mix = (100 – FRCA)/(100 – CRCA₂₀)/(100 – CRCA₁₀); $\rho_{FRCA}/\rho_{CRCA20}/\rho_{CRCA10}$ = density of FRCA/20mm/10mm nominal size CRCA – A = 2240kg/m³/2660kg/m³/2510kg/m³; $\rho_{FNA}/\rho_{CNA20}/\rho_{CNA10}$ = density of FNA / 20 mm / 10 mm nominal size CNA = 2630 kg/m³ / 2830 kg/m³ / 2720 kg/m³.

Further, graphs between ordinates and abscissas were plotted, and equations between them were derived in the form of Eq. (6.2). The constant ‘c’ was kept equal to 1 so that the linear regression lines can be forced to represent the actual behaviour of concrete by passing them via point representative of reference concrete, i.e., x=0, y=1. However, by doing so, the coefficient of determination (‘R²’) was lowered as compared to it would have been if the value of ‘c’ was kept as obtained in the graphical analysis. The slope of the linear regression lines (‘m’) helped in computing, comparing and differentiating the effects of aggregates properties on FxRC and C100FxRC.

$$y = mx + c \quad (6.2)$$

where, m = slope of the linear regression line, c = constant = 1

The same equation (Eq. (6.2)) was also adopted in the case of water absorption, where water absorption values replaced the corresponding densities of aggregates mixtures. The degree of confidence in linear regression lines was indirectly measured by qualitatively classifying their ‘R²’ into four categories as shown in Table 6.7.

Table 6.7: Qualitative classification of R^2

Range of R^2	Grading
$R^2 \leq 0.65$	Unacceptable
$0.65 \leq R^2 \leq 0.80$	Acceptable
$0.80 \leq R^2 \leq 0.95$	Good
$R^2 \geq 0.95$	Very good

Fig. 6.45 & Fig. 6.46 indicates that the compressive strength of concrete at 28 days (f_c) reduces with the decrease in density (ρ) and increase in water absorption ('WA') of the aggregate mixtures. Both CRCA-A and FRCA had lower density and higher water absorption than natural aggregate due to adhered mortar. Therefore, it can be assumed that for obtaining the positive effects of RCA on concrete compressive strength, it should be characterised such that its density and water absorption are better or similar to that of NA.

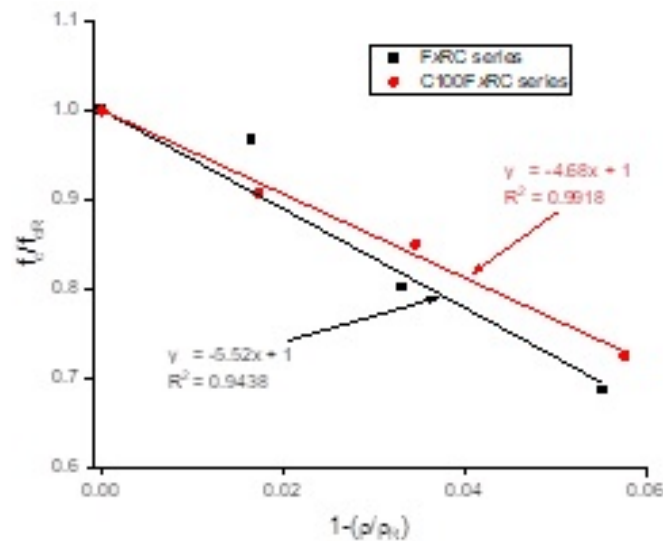


Figure 6.45: Ratio of 28 days compressive strength of FxRC and C100FxRC (f_c) with that of reference concrete (f'_{cR}) versus Ratio between weighted density of aggregate mixtures in FxRC and C100FxRC (ρ) and reference concrete (ρ_R);

' R^2 ' of the linear regression line of C100FxRC (0.9918) was better than FxRC (0.9438). As per Table 4, they can be classified into 'very good' and 'good' categories, respectively. Similarly, based on the slope of linear regression lines, it can be concluded that the effect of aggregates' density is higher than their water absorption on the compressive

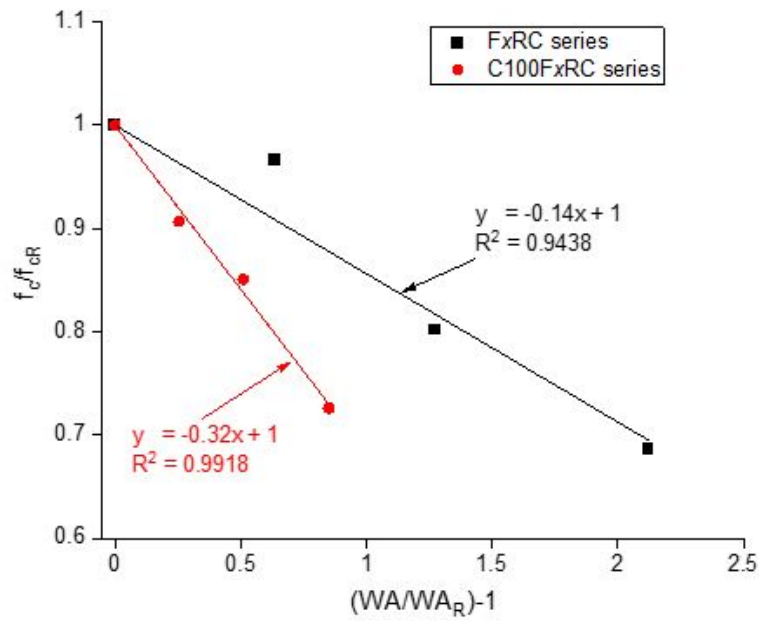


Figure 6.46: Ratio of 28 days compressive strength of FxRC and C100FxRC (f'_c) with that of reference concrete (f'_{cR}) versus Ratio between weighted water absorption of aggregate mixtures in FxRC and C100FxRC (WA) and reference concrete (WA_R).

strength of concrete at 28 days. Moreover, the 28 days compressive strength of FxRC series was more adversely affected than C100FxRC series due to the decrease in density of aggregate mixtures (Fig. 6.47). This particular behaviour was contradictory because FRCA should have performed better with CNA than with CRCA-A. However, as both FRCA and CRCA-A were derived from the same original concrete, their combination was better than FRCA and CNA. On the contrary, FxRC series performed better than C100FxRC series when there was an increase in weighted water absorption of aggregate mixtures (Fig. 6.48) because the difference between water absorption of RCA and natural aggregate was significantly higher than the difference between their densities. The difference between the maximum and minimum weighted density of aggregate mixtures was less than 10%, while it was more than 350% in the case of weighted water absorption of aggregate mixtures.

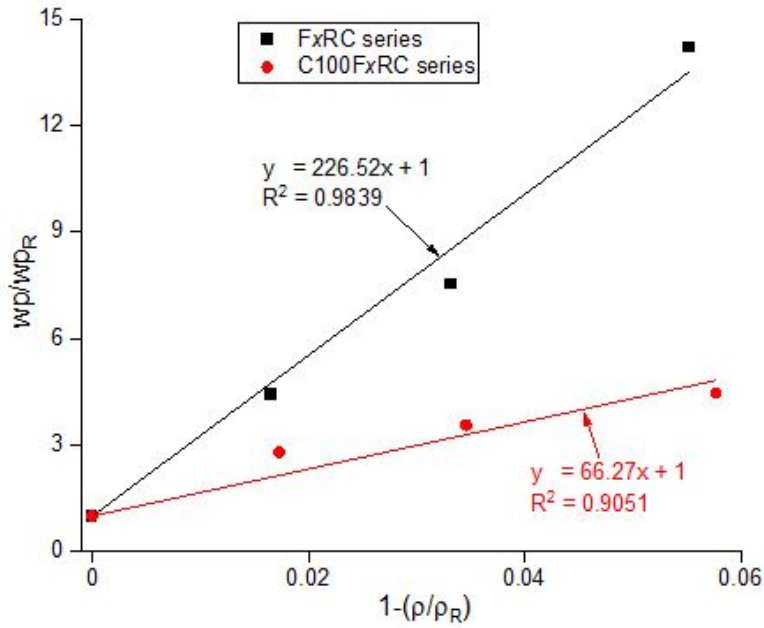


Figure 6.47: Ratio between water permeability of FxRC and C100FxRC (w_p) and reference concrete (w_{pR}) versus (a) Ratio between weighted density of aggregate mixtures in FxRC and C100FxRC (ρ') and reference concrete (ρ'_R);

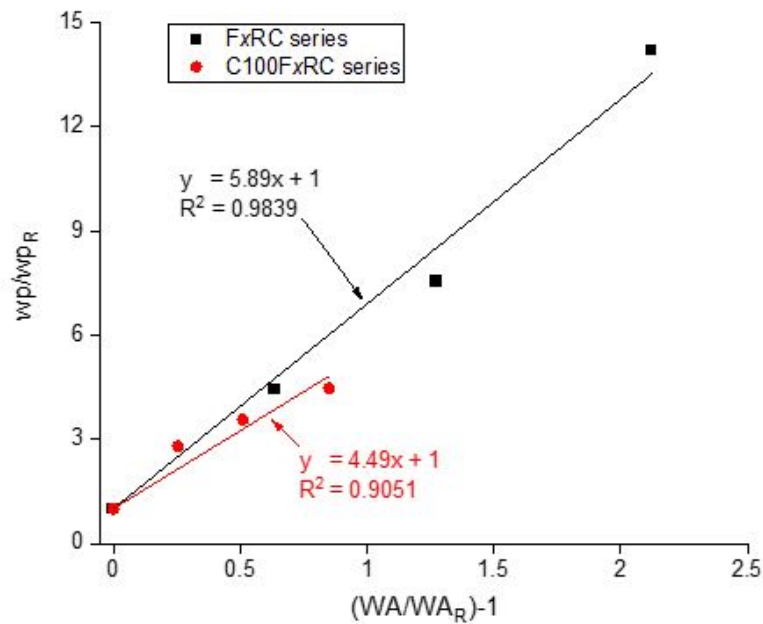


Figure 6.48: Ratio between water permeability of FxRC and C100FxRC (w_p) and reference concrete (w_{pR}) versus Ratio between weighted water absorption of aggregate mixtures in FxRC and C100FxRC (WA) and reference concrete (WA'_R).

6.7.1 Water permeability vs density and water absorption of aggregates

Fig. 6.49 shows the graphs between ratio of water permeability of RAC ('wp') and reference concrete (wp_R) versus the ratio of aggregate mixtures properties. The pattern of coefficient of determination (R^2) was similar to that obtained in the case of 28 days compressive strength. The water permeability of FxRC and C100FxRC can be strongly linked with weighted density and water absorption of aggregate mixtures. These aggregate properties had a higher impact on 'wp' of FxRC than on 'wp' of C100FxRC (the correlation lines of FxRC had higher slopes than the correlation lines of C100FxRC). Also, it can be deduced from the slope of correlation lines in Fig. 6.49 and Fig. 6.50 that 'wp' of concrete (compared to f_c) was more affected by FRCA.

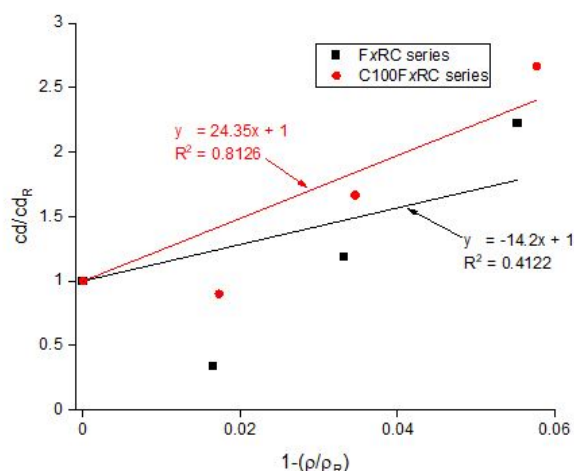


Figure 6.49: Ratio between carbonation depth of FxRC and C100FxRC ('cd') and reference concrete (cd'_R) versus Ratio between weighted density of aggregate mixtures in FxRC and C100FxRC (ρ') and reference concrete (ρ'_R);

6.7.1.1 Carbonation depth vs density and water absorption of aggregates

It can be seen in Fig. 6.48 that the coefficient of determination (R^2) for carbonation depth ('cd') versus weighted densities/water absorption of aggregate mixtures was 'good' in C100FxRC series and 'unacceptable' in FxRC series. This behaviour is justified because F30RC and C100F30RC performed better (lower carbonation depth) than their reference concrete F0RC and C100F0RC, respectively. Moreover, the difference between the car-

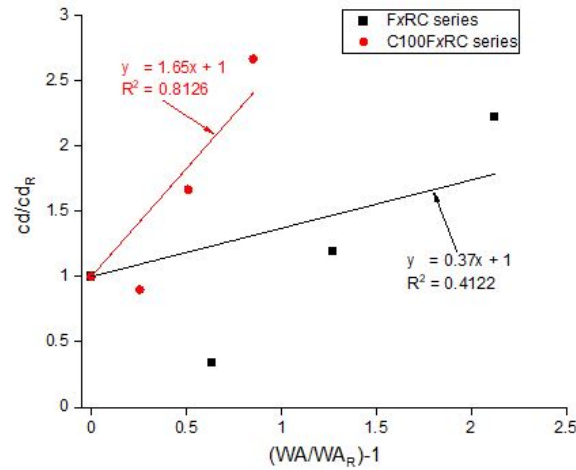


Figure 6.50: Ratio between carbonation depth of FxRC and C100FxRC ('cd') and reference concrete (' cd'_R ') versus Ratio between weighted water absorption of aggregate mixtures in FxRC and C100FxRC ('WA') and reference concrete (' WA'_R ').

bonation depth of F0RC and F30RC was significantly higher than the difference between that of C100F0RC and C100F30RC. By comparing the correlation lines' slopes in Fig. 6.45, Fig. 6.46 and Fig. 6.47, it can be concluded that the water permeability of concrete, followed by its carbonation depth and compressive strength, was most susceptible to the degradation mechanism of RCA

6.8 Microstructural analysis

6.8.1 Scanning Electron Microscopic (SEM) analysis

Fig. 6.52 to Fig. 6.62 shows the SEM micrographs of CxRC, FxRC, CxFxRC and C100FxRC at different magnification levels and after 90 days of curing. Various phases in SEM micrographs of concrete microstructure were identified based on the extensive findings of past studies. The conventional concrete mix F0RC (Fig. 6.51) had a dense microstructure with no sign of micro-cracks in the cement paste matrix or interfacial transition zone. Few macro-pores with a pore size of $4.6\mu\text{m}$ were, however, observed. When only C-RCA was incorporated in the concrete (mix CxRC), few micro-cracks (avg. width $3\mu\text{m}$) and macro-pores (pore size $40\mu\text{m}$) were observed in C100RC (Fig. 6.54). The cracks could have occurred as a result of the shrinkage of cement paste [138]. Few of them were visible only at higher magnification. Nevertheless, the CxRC microstructure was

more compact and had better characteristics (compared to other mixes), such as a good bond between C-RCA and cement paste, which justifies its highest compressive strength amongst all the concrete mixes at 90 days [139]. When the microstructures of F30RC and C100F30RC were compared (Fig. 6.55 and Fig. 6.60), it was found that C100F30RC had a higher amount of loose particles and micro-cracks (avg. width 1.5 μ m, practically undetectable at low magnification). Similarly, a close inspection and comparison of the microstructure of F60RC (Fig. 6.56) and C100F60RC (Fig. 6.61) reveal that the former had inferior interfacial transition zone characteristics, which can be attributed to the presence of micro-crack (avg. width 2.5 μ m) in the interfacial transition zone between C-NA and cement paste (formation of wall effect). C100F60RC showed higher strength than F60RC at 90 days due to better morphometrical and morphological attributes of F-RCA when combined with treated C-RCA compared to its combination with C-NA. F100RC Fig. 6.57 had lower number of pores and micro-cracks than C100F100RC (and Fig. 6.62). According to this phenomenon, F100RC's compressive strength should have been higher than C100F100RC, but the opposite was seen due to the synergistic effect of F-RCA and C-RCA [173].

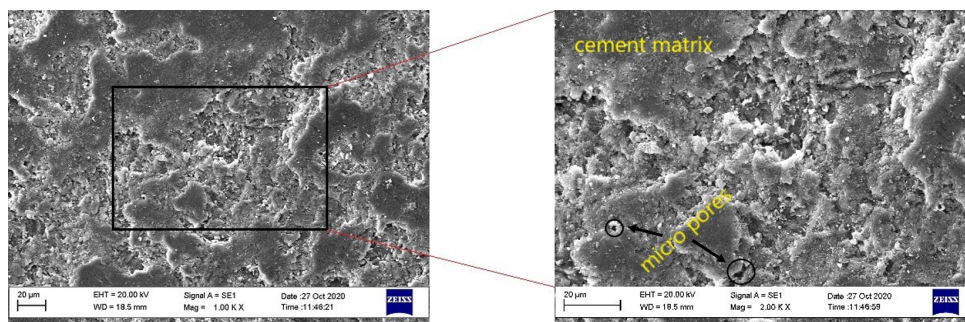


Figure 6.51: SEM image of CC

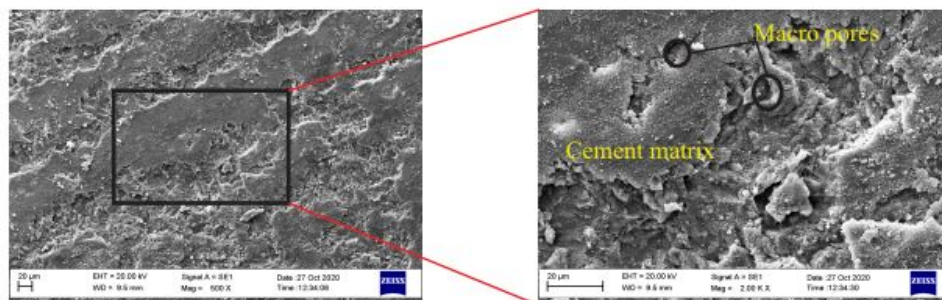


Figure 6.52: SEM image of C30RC

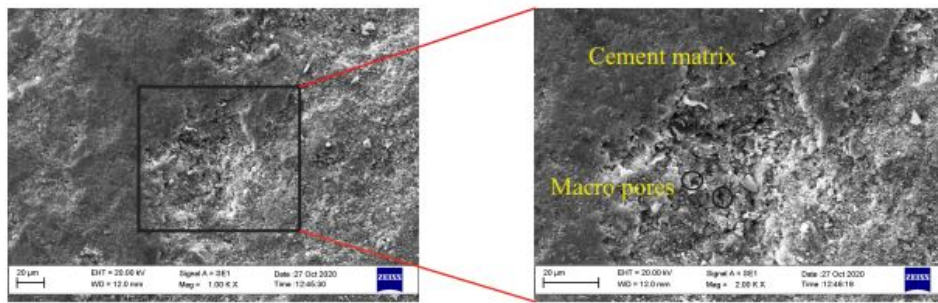


Figure 6.53: SEM image of C60RC

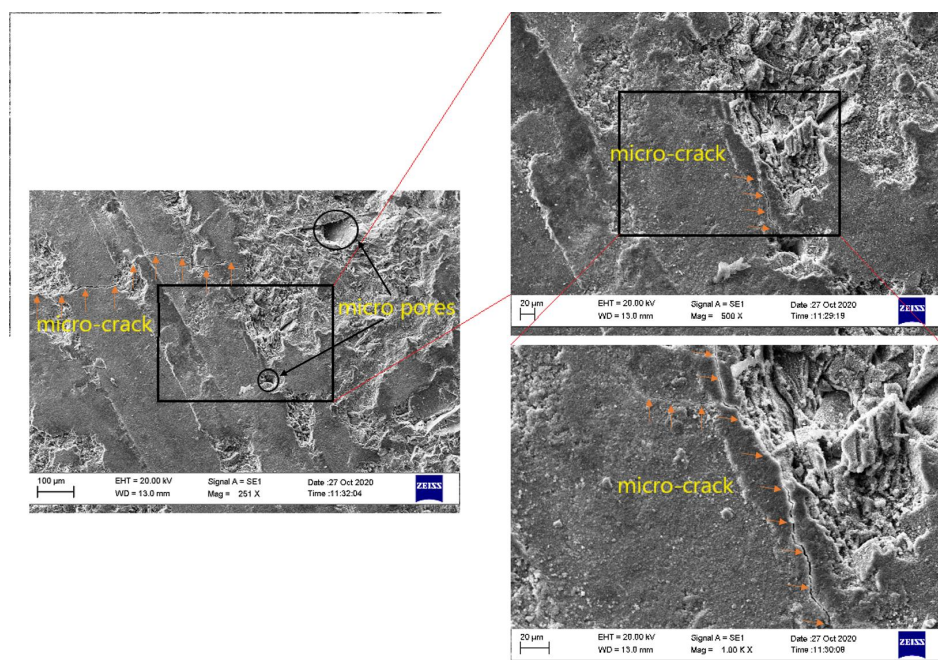


Figure 6.54: SEM image of C100RC

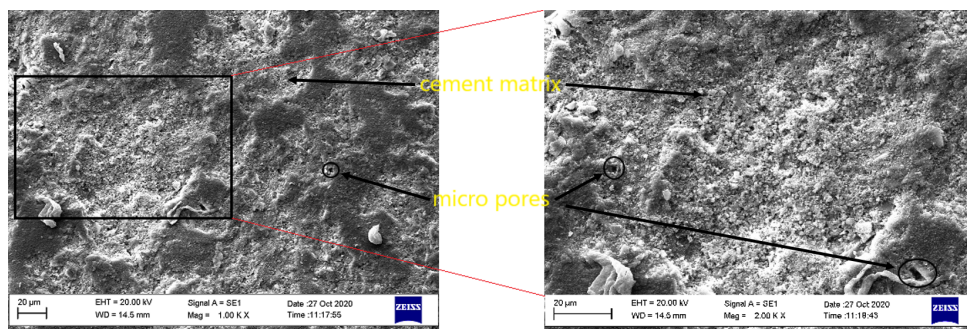


Figure 6.55: SEM image of F30RC

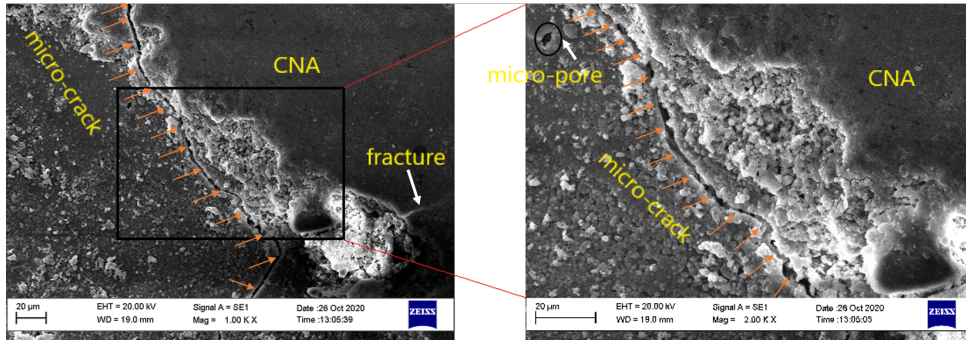


Figure 6.56: SEM image of F60RC

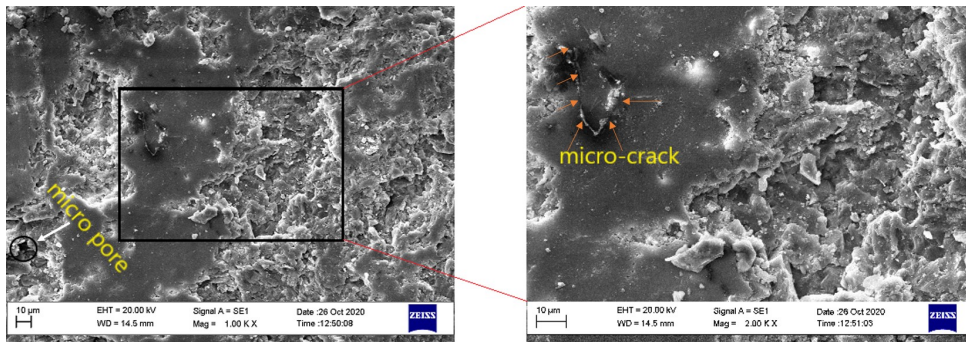


Figure 6.57: SEM image of F100RC

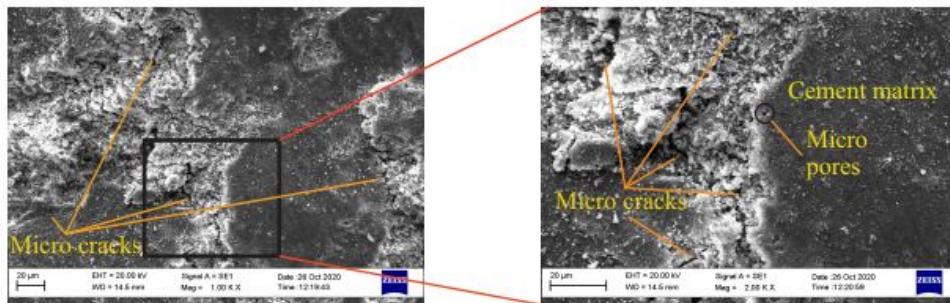


Figure 6.58: SEM image of C30F30RC

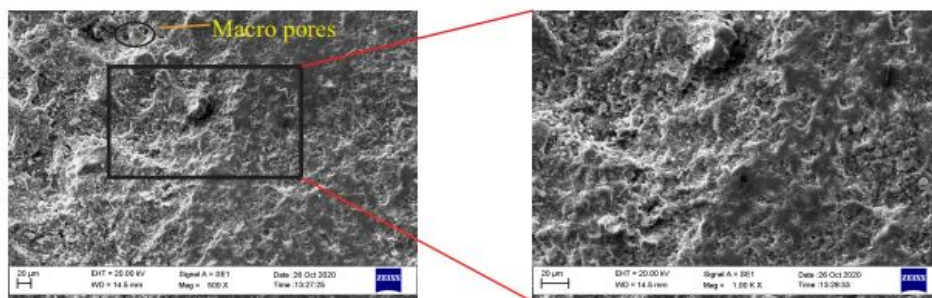


Figure 6.59: SEM image of C60F60RC

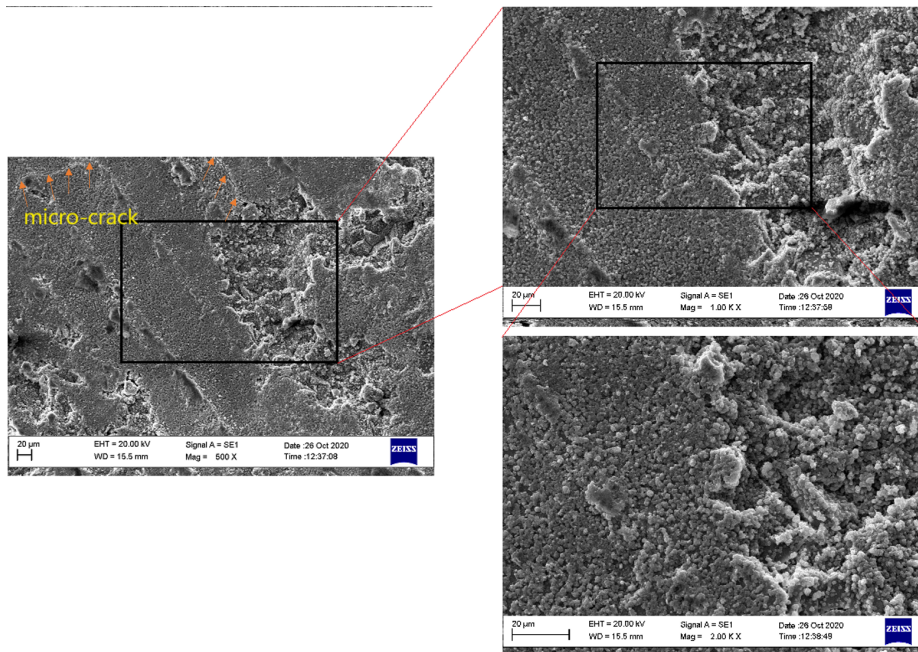


Figure 6.60: SEM image of C100F30RC

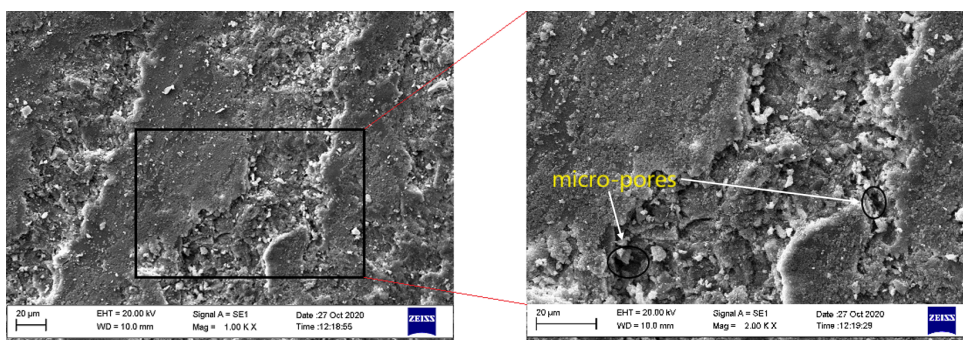


Figure 6.61: SEM image of C100F60RC

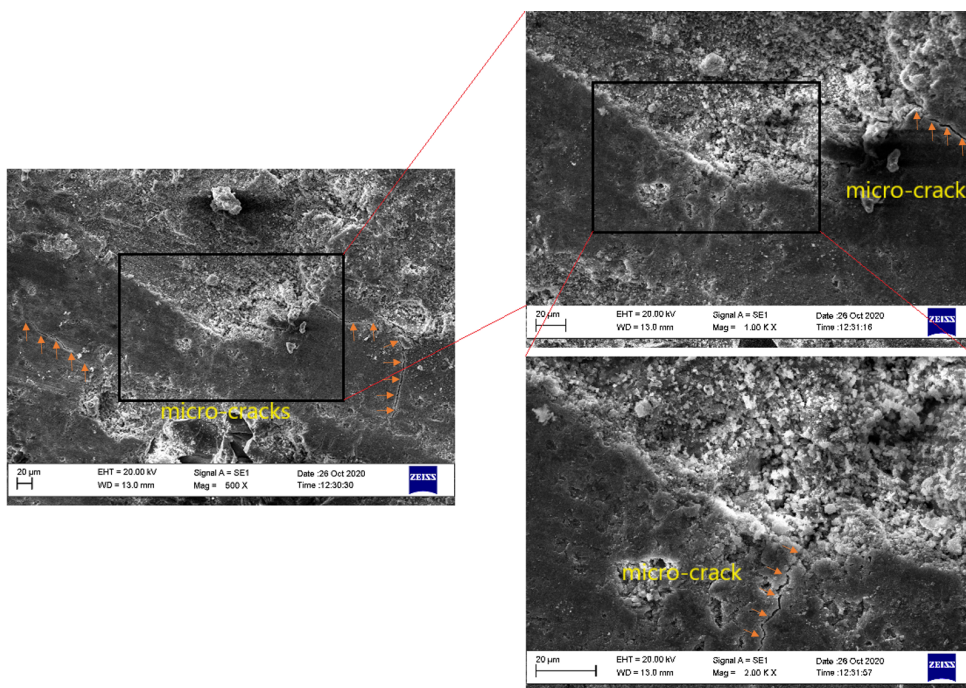


Figure 6.62: SEM image of C100F100RC

6.9 Summary

Most of the past studies observed the effects of only C-RCA on the properties of concrete, while F-RCA was ignored due to the complexities associated with its usage. It compelled the authors to assess the effects of different ratios of F-RCA on properties of concrete containing either 100% treated C-RCA or C-NA. The mechanical and physical properties of C-RCA are significantly strengthened by abrasion (against each other) but are still lower than that of C-NA. Similarly, F-RCA has higher water absorption than FNA. Both workability and fresh density reduce with an increase in F-RCA content. Nevertheless, all concrete mixes can be categorised into ‘ordinary concrete’ (except mix C100F100RC and F100RC, which can be categorised into ‘semi-lightweight concrete’) as per the past studies’ classification of concrete based on fresh density. Concrete containing only F-RCA and F-RCA with 100% C-RCA have lower strength than CC, irrespective of curing age. Amongst these strengths, flexural strength is least affected due to the addition of recycled aggregates. As the curing time increases, the adverse effects of F-RCA on concrete strength begin to diminish. The water permeability of increases with an increase in the replacement ratio of F-RCA. Also, their carbonated compressive strength is higher than their water-cured compressive strength. Moreover, few concrete samples (F30RC, C100F0RC, C100F30RC and C100F60RC) have higher carbonated compressive strength than CC. Mostly, F-RCA is more compatible with C-NA at 30% replacement level and treated C-RCA at 60% and 100% replacement level.

