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Evaluating the Carbonation Resistance of Self Compacting Concrete made with Recycled Concrete Aggregates

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ABSTRACT

The paper presents the results of an investigation conducted to examine carbonation resistance of Self Compacting Concrete (SCC) made with coarse Recycled Concrete Aggregates (RCA). In total, five SCC mixes were prepared by systematically replacing coarse Natural Aggregates (NA) by RCA at 0, 25, 50, 75 and 100%. In order to measure the carbonation resistance of SCC made with RCA, accelerated carbonation tests were performed for 4 and 12 weeks of exposure to carbon dioxide. The carbonation resistance has been evaluated after curing periods of 28 and 90 days. In addition to this, the compressive strength of all the mixes was also obtained after 7, 28 and 90 days of curing and ultra-sonic pulse velocity tests (UPV) were also conducted. The results indicate that with the increase in the content of RCA as replacement of NA, decrease in the carbonation resistance, compressive strength and UPV was observed for all SCC mixes. It has been observed that the SCC mixes containing low percentages of RCA (i.e. 25%) as replacement of NA do not impart detrimental behaviour in the overall performance but higher replacement levels (>50%) have been found to deteriorate the performance in terms of carbonation resistance, compressive strength and UPV.

1 Introduction

Modern structures having up to date facilities/techniques have over-taken the existing structures which give rise to huge amount of demolition wastes which is particularly related to construction industry. The problem of huge generation of construction and demolition (C&D) waste came into focus since last two decades. Recycled aggregates are considered as the materials for the future for construction industry, though many countries have already implemented its use in the field of infrastructure development. Some countries of Europe, America and Asia have already started using coarse Recycled Concrete Aggregates (RCA) as construction materials since past decade [1-2]. India also generates 23.75 million tons of demolition waste annually out of which only 3% waste is utilized as construction material [3].

In the past, attempts have been made to study the use of recycled concrete as coarse aggregates in concrete [4-9]. Coarse recycled concrete aggregates are nowadays considered as the future or non-conventional material for construction industry [10-12]. The C&D waste in the form of coarse RCA has already been used in Normally Vibrated Concrete (NVC) as well as Self Compacting Concrete (SCC). Self compacting concrete has gained its popularity world-wide because it has

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advantages to offer owing to its relatively dense, homogeneous and uniform nature with better engineering and durability properties compared to NVC [13].

The most inevitableaspect of RCA is its old adhered mortar which is responsible for its poor behavior. This highly porous nature of attached mortar on the surface of RCA makes it less dense compared to coarse Natural Aggregates (NA) [14]. The old or adhered mortar/aggregate is attached to new mortar/aggregate through boundary which is known as Interfacial Transition Zone (ITZ). The RCA comprises of two ITZs i.e. one between the RCA and new mortar, and the other between the RCA and the old mortar attached to it (old ITZ). The clinging old mortar forms the weak link in whole RCA structure, thus making a complex micro-structure than that of NA [15]. Due to above fact, the RCA has proved to be poor performer in terms of mechanical and durability properties [16-19].

It is well known that carbonation is an important durability property which affects the long term performance of any concrete structure. Carbonation is a major risk for reinforced concrete because it lowers alkalinity of concrete to such an extent, that the reinforcement present in concrete gets corroded and spalling of cover takes place. The prolonged behavior consequently reduces the bond between steel and concrete, making it an unwanted process in total service life of the concrete structure. Significant amount of research has been carried out to study the carbonation resistance of NVC made with NA. The carbonation depth has been found to depend on many factors such as water/cement ratio, water/binder ratio, curing conditions, concrete cover, super plasticizers, type of aggregates, grade of concrete, porosity etc. In a similar manner, the carbonation resistance of NVC made with RCA has been examined and it has been reported that, with increase in replacement of NA with RCA, the carbonation resistance has been found to decrease [20-23].

The carbonation depths of concrete made with RCA were found to be 1.3-2.5 times than that of concrete made with NA [15, 24-25]. A diminutive literature of SCC made with NA is available, in which carbonation depths have been examined and it was concluded that SCC mixes were found to be more durable than NVC mixes in association with carbonation coefficients [26-29].The durability of any concrete can additionally be judged by knowing Ultrasonic Pulse Velocity (UPV) test which is a non-destructive in nature, as it provides estimation of compressive strength. The technique (UPV test) has gained popularity worldwide due to its many advantages such as simplicity in use, its application both in the laboratory and on site, small portable size, inexpensive and easy to use [30]. Ultrasonic pulse velocity is a function of density and ITZ characteristics and it increases with decreasing total porosity of the concrete [31, 32].

However, to the best of knowledge of the authors, diminutive information on the carbonation resistance of SCC made with RCA is available. Thus the main purpose of this paper is to evaluate the carbonation resistance and UPV of SCC containing RCA, considering the possible applications of SCC made with RCA in the field of civil engineering and construction. In addition to this, the compressive strength of each SCC mix has been found and has been further related to above stated parameters. In this investigation, a total of five SCC mixes were cast and tested for various parameters. A fixed percentage of Portland cement (PC) and fly ash (FA) was used in all the mixes. The reference mix contained 100% NA and the remaining mixes were cast using different replacement levels of NA with RCA.

2 Experimental program

2.1 Materials

Ordinary portland cement of grade 43 confirming IS 8112: 1989 (having a specific gravity of 3.11 and a Blaine specific surface of 3362 cm^2/g), natural sand, natural and recycled crushed gravel of maximum size 10 mm were used while preparation of 5 different mixes of SCC. Coarse recycled concrete aggregates were obtained by crushing the old concrete specimens available in the Structures Testing Laboratory of the Department of Civil Engineering of the author's Institute. A poly-carboxylic ether based superplasticizer (SP), having a specific gravity of 1.063 was used. In order to achieve adequate workability, viscosity modifying agent (VMA) of specific gravity 1.103 (as reported by its manufacturer) was incorporated. The VMA assisted in attaining bleed free concrete mixes. The particle size gradation of materials, obtained through the sieve analysis of PC, FA and NA, RCA has been presented in Fig.-1 & Fig.-2 respectively.

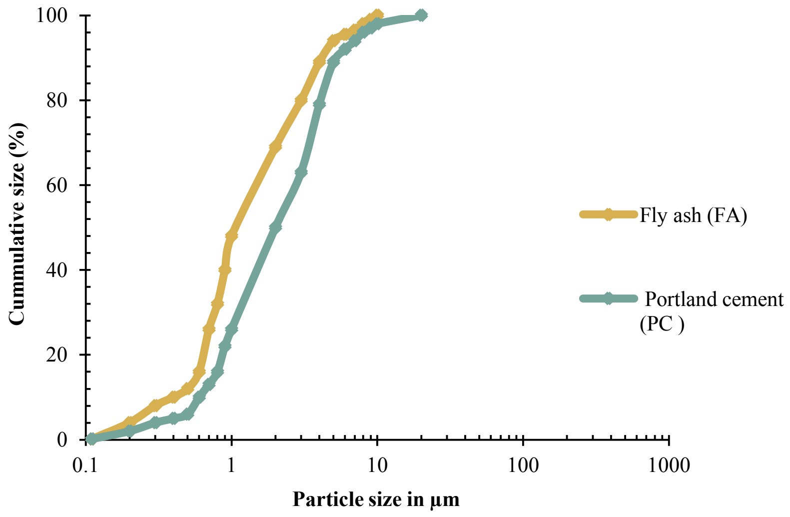


Fig. 1 Particle size distribution of cement and cement additions used in experimental program

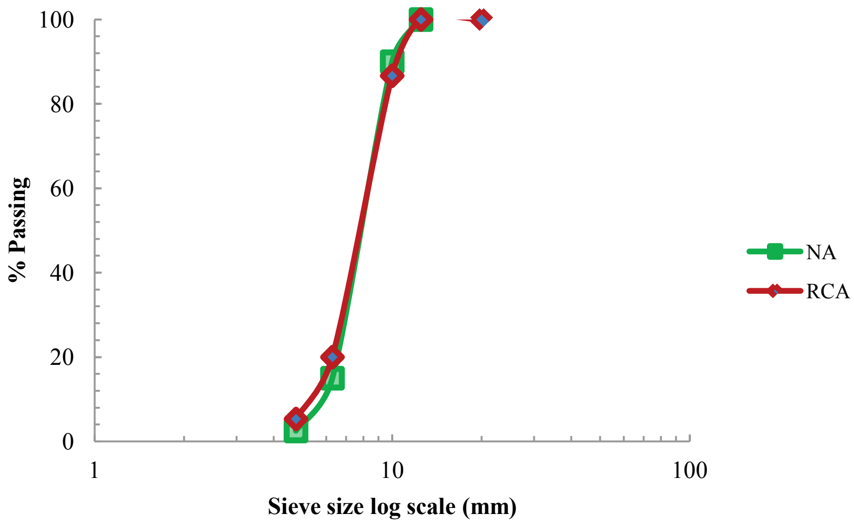


Fig. 2 Particle size distributions of NA and RCA

2.2 Mix proportions, tests and curing regime

A total number of 5 mixes of SCC were cast with a constant water/binder (w/b) ratio of 0.45 and total binder content of 615 kg/m^3. The mixes were prepared by replacing 30% of PC by weight to form 5 mixes namely; Control mix as binary blended having 70% PC + 30% FA and designated as ‘CF’. Further the coarse NA were replaced with coarse RCA in all the remaining mixes; the binary blended control mix was designated as CF-RCA0 while, other mixes with different percentage replacement of RCA are designated as ‘CF-RCA25’, ‘CF-RCA50’, ‘CF-RCA75’ and ‘CF-RCA100’ for 25%, 50%, 75% and 100% replacement levels of RCA respectively. The detail of the control mix is shown in Table 1. In order to satisfy the workability tests and other requirements given by EFNARC for producing SCC, the quantities for SP and VMA have been adjusted in the range of 1.72-2.80 kg/m^3.

Table 1 - Mix proportioning for SCC control mix

Mix no.	Mix description	Water (kg/ m^3)	PC (kg/ m^3)	FA (kg/ m^3)	Natural sand (kg/ m^3)	NA (kg/ m^3)
M 1	CF-RCA0 (Control)	277	430	185	820	652

2.3 Fresh concrete tests

Slump flow, T_{50} cm and V-funnel flow time tests were performed in accordance with SCC Specifications and Guidelines [33]. All the tests were done within 15 minutes after making the mixes to avoid any loss of workability with time. The results have been summarised in Table 2. The quantity of SP and VMA were chosen in such a manner that all the mixes should satisfy all the guidelines given by EFNARC for SCC.

Table 2 - Results for the fresh properties of CF-RCA mixes

Mix no.	Mix description	Slump flow		V - funnel (s)	Whether conforms EFNARC guidelines
		T50 (s)	D (mm)		
M 1	CF-RCA0 (Control)	1.8	690	6	Yes
M 2	CF-RCA25	2	688	5.8	Yes
M 3	CF-RCA50	2.2	685	6	Yes
M 4	CF-RCA75	2.5	685	6.1	Yes
M 5	CF-RCA100	2.5	680	7	Yes

2.4 Hardened concrete tests

For checking mechanical properties, compressive strength and UPV tests were performed. For durability determination, accelerated carbonation test was conducted.

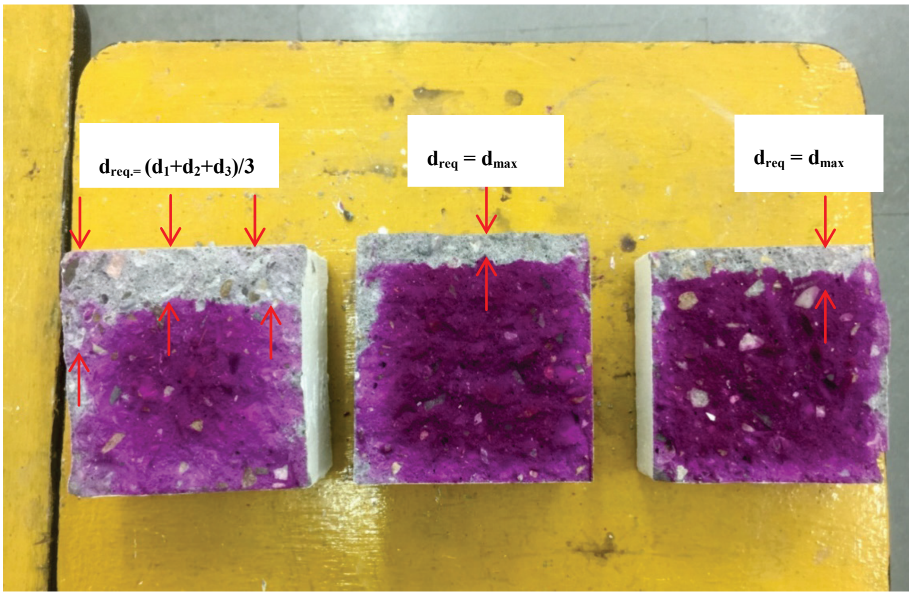
2.4.1 Compressive strength test

Compressive strength of all the specimens was obtained testing 100mm x 100mm x 100mm size cubes in accordance with Indian standards, “Methods of tests for strength of concrete – IS 516-1959 (Reaffirmed 2004)”. Compressive strength tests were performed after curing period of 7, 28 and 90 days.

2.4.2 Accelerated carbonation test

For accelerated carbonation test, prisms of size 100mm × 100mm × 500mm were cast. The specimens were cured for a period of 28 and 90 days. Each specimen was cut into two pieces of 100mm x 100mm x 250mm to facilitate handling and placing in the carbonation chamber. Oven drying process was followed for conditioning of specimens [34-36]. While exposing the specimens in the carbonation chamber, carbon dioxide (CO_2) concentration was maintained at 4% with relative humidity between 40-70% and temperature between 25 ± 2^0C. All the specimens were exposed to CO_2 for a period of 4 and 12 weeks. The depth of carbonation was measured in accordance with RILEM recommendations, “CPC-18; Measurement of hardened concrete carbonation depth”. After the required exposure period to CO_2, two portions of the specimen measuring approximately 50 mm were split from the specimen. The faces of the split specimens were cleaned and sprayed with a phenolphthalein pH indicator. The indicator used was a phenolphthalein 1% ethanol solution with 1 g phenolphthalein and 90 ml 95.0 V/V% ethanol diluted in water to 100 ml. The carbonation depths were measured using normal ruler (geometric scale). Carbonation depth readings were taken immediately after spraying the indicator and after 24 hours later also. The colourless portion left on the specimens provided the required carbonated depths. The accelerated carbonation test set up and carbonated regions of split specimens have been shown in Fig.-3 (a) and Fig.-3(b) respectively.

Fig. 3(a) Accelerated environment controlled carbonation chamber



*** $d_{required} = (d_1+d_2+d_3)/3$ mm** **** $d_{req} = d_{max}$**

Fig. 3(b) Specimens showing carbonated regions

2.4.3 Ultra-sonic pulse velocity test

The test was performed in accordance with Indian standards, "Non-destructive testing of concrete – Methods of test, IS 13311 (Part-1): 1992. The test was done after curing period of 28 and 90 days.

3 Results and Discussion

3.1 Workability tests

The results for workability tests are summed up in Table 2. The slump values were found in range of 680mm – 690mm and the T_{50} cm time varied from 1.8sec- 2.5sec. With increase in percentage content of RCA in the SCC mixes, the viscosity was also found to increase. The flow times, which were measured during V-funnel test and slump flow test; have been found to be highly associated with the viscosity of SCC mixes. The reason behind this kind of behaviour depends on the physical nature of RCA, as reported in previous studies [31, 37-38]. The increase in the percentage of coarse RCA, used as replacement of coarse NA also leads to reduction of the basing ability [39].

3.2 Compressive strength results

The average of three compressive strength results for the five SCC mixes, designated as CF-RCA containing 100% NA (0% RCA), 25%, 50%, 75% and 100% RCA after curing periods of 7, 28 and 90 days respectively have been shown in Fig.-4. From the results obtained, it has been noticed that with the increase in the percentage of RCA in regular intervals (25%), the compressive strength has been to decrease at all the three curing ages, however as expected, the compressive strength increases as the curing period increases.

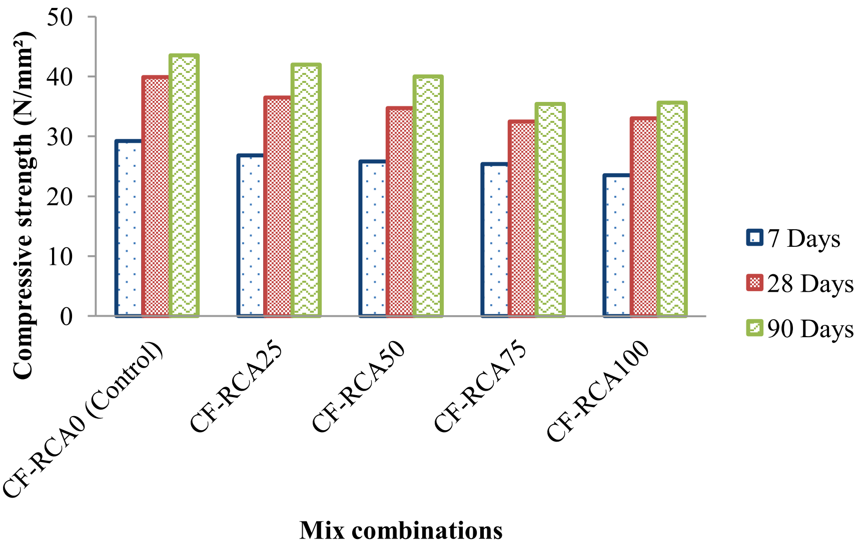


Fig. 4 Compressive strength results for CF-RCA mixes for different curing periods

Self compacting concrete mix having 25% (CF-RCA25) replacement is treated as low level replaced mix, whereas, 50% (CF-RCA50) replacement is treated as intermediate level and beyond 50%, the mixes have been considered as high level replacement mixes. The maximum decrease in compressive strength for CF-RCA25 was found to be 8.5% after curing period of 28 days in comparison to the control mix (CF-RCA0). Likewise, for CF-RCA50 the maximum decrease in compressive strength is up to 13% after 28 days of curing. The decrease reached to a significant level of around 19% after 90 days of curing period for both CF-RCA75 and CF-RCA100 mixes compared to control SCC mix. Based on the fall in strength up to 90 days of curing among all mixes, CF-RCA25 has performed the best. The microstructure of the RCA-bearing concrete mix is quite complex than that of the conventional concrete due to presence of old and new ITZ as discussed in preceding section. Also it is well known that the mechanical properties especially, the compressive strength is directly dependent on the ITZ's characteristics of RCA [31]. Hence, the weak mutual bonding between the new ITZ and the old ITZ probably seemed to be responsible for the observed higher reductions in strength [40-41]. Moreover, the strength of any concrete depends on the strength of the aggregates, source of collection of concrete debris, cement matrix, etc., hence, concretes made with RCA from weak and unknown strength resulted in lower strength. In addition to this, the presence of higher porosity and lower density of RCA also contribute in the reduction of strength. The continuous gain in strength was mainly attributed to curing age may be due to completion of the pozzolanic reactions between cement and FA. The results obtained are in agreement with the one reported in literature [37-38, 42-43]. The above behaviour of higher variation in compressive strength in SCC mixes made with coarse RCA can be understood very easily from the scanning electron microscopic images (SEM) Fig.-5(a) & Fig.-5(b) which show the presence of **1)** NA **2)** RCA **3)** old and new ITZ of RCA **4)** micro and macro pores and **5)** loosely bonded adhered mortar with cracks/joints in RCA which are mainly responsible for its poor performance.

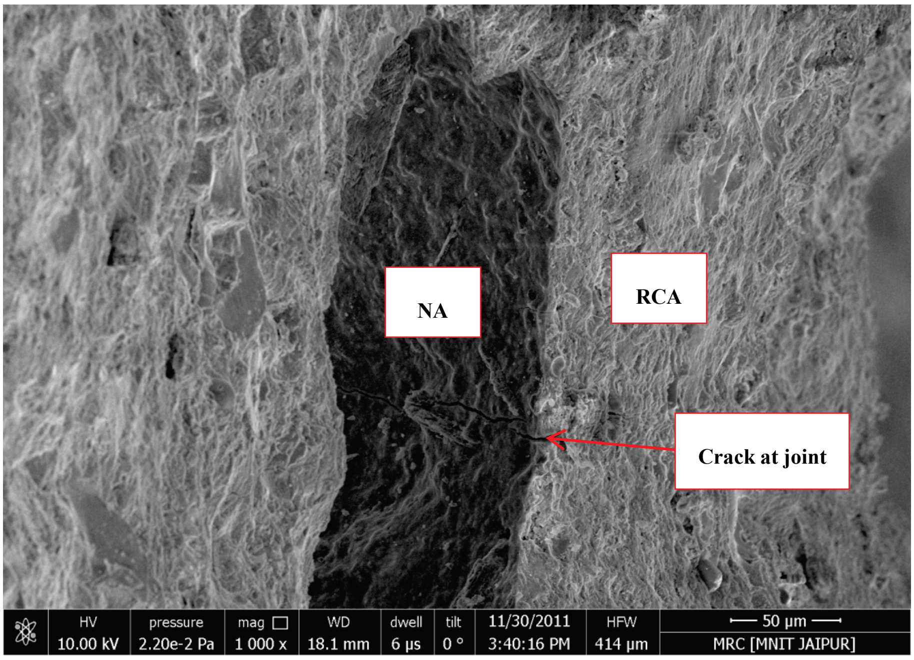


Fig. 5(a) SEM image showing NA and RCA

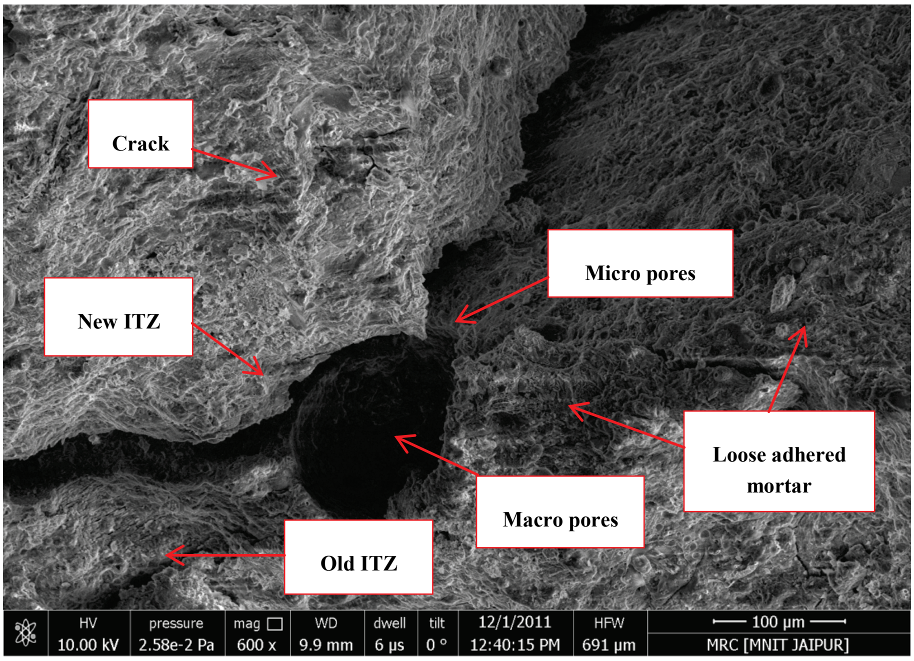


Fig. 5(b) SEM image showing characteristics of RCA

3.3 Accelerated carbonation test results

The change in carbonation depths of all SCC mixes containing RCA with exposure period of 4 and 12 weeks, for curing regime of 28 days, have been shown in Fig.-6. A significant increase in the depth of carbonation has been observed with the increase in content of RCA as replacement of NA. The depth of carbonation seems to be directly proportional to the exposure period i.e. higher the exposure period, higher is the depth of carbonation. From Fig.-6, it can be noticed that, the maximum increase in values of carbonation depths for CF-RCA25, CF-RCA50, CF-RCA75 and CF-RCA100 mixes with respect to the control mix CF-RCA0 has been found after 12 weeks of exposure period. The tendency of decreasing carbonation resistance is similar to the pattern of compressive strength obtained for the SCC mixes containing higher percentages of RCA replacements.

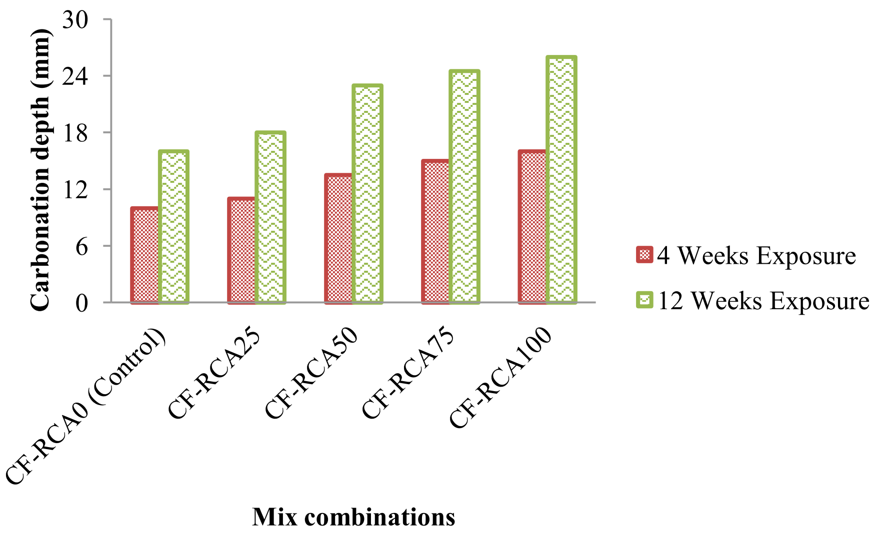


Fig. 6 Accelerated carbonation test results for 28 days curing period with exposure periods of 4 and 12 weeks

The growth in carbonation depths appears to be less significant in mixes having low (CF-RCA25) and intermediate (CF-RCA50) replacement levels of RCA rather than in higher replacement levels (CF-RCA75 and CF-RCA100) of RCA. Results represented in figures revealed that the gap between the CF-RCA0 and CF-RCA25 seems to be accommodating, as percentage increase in carbonation depth limits to 12.5%. The increase moves to significant level when RCA replacement level crossed 25%, as maximum increment in case of CF-RCA50 mix goes up to 43.8% which is quite high. The worst behaviour has apparently be seen in case of CF-RCA75 and CF-RCA100 mixes, in which carbonation depth increases maximum up to 53.1% and 62.5% respectively, when compared to CF-RCA0 mix. This undoubtedly implies that the increasing percentage of RCA in all the mixes decreases the carbonation resistance in comparison to control concrete mix made with NA. The trend of results has been witnessed in agreement with previous literature related to NVC made with RCA [44-46].

The observed behaviour of carbonation can be explained by two main reasons: **1)** the carbonation depth has been seen to be dependent on the microstructure and pozzolanic reactions, which happens between cement and FA. During these reactions, calcium hydroxides (CH) which are produced along with other hydration products are consumed at faster rates, which consequentially reduces the alkalinity and initiating higher chances of carbonation process [45-47] and **2)** the type of aggregates and the pore structure of RCA also plays an important role in decreasing the carbonation resistance. Moreover, it is well known that pore structure of coarse RCA is different from that of coarse NA and higher porosity of RCA leads to higher probabilities of CO_2 ingression [23, 48]. The negative effect of RCA has been quite evident from the above facts which have been justified from SEM images presented in Fig.-5(a) & Fig.-5(b).

In a similar manner as in previous case, possessing exactly the same conditions the carbonation depths have been calculated after curing period of 90 days for an exposure period of 4 and 12 weeks. The results are presented in Fig.-7.

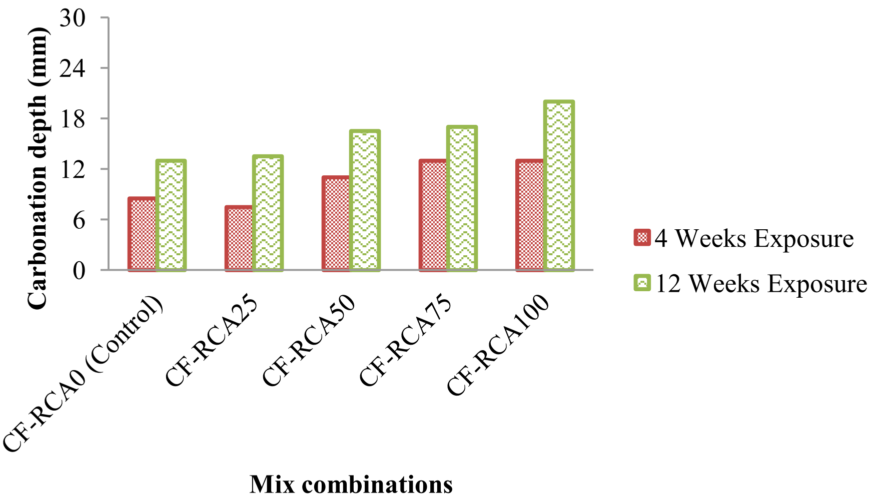


Fig. 7 Accelerated carbonation test results for 90 days curing period with exposure periods of 4 and 12 weeks

An increase in the depth of carbonation has also been observed in this case with the increase in content of RCA incorporation but the results have been found to be quite less compared to 28 days of curing period. The maximum change in carbonation depths for CF-RCA25 has been found to be -11.7% after 4 weeks of exposure. Similarly, an increase to an extent of 29.4%, 52.9% and 58.8% has been examined after 4 weeks of exposure period for CF-RCA50, CF-RCA75 and CF-RCA100 mixes respectively. On carefully observation, it can be seen that prolonged water curing certainly helps in decreasing the carbonation depths for all the SCC-RCA mixes. For example, in mix CF-RCA25 the percentage increase in carbonation depth which was initially 10% and 12.5% after 28 days curing has been reduced to -11.7% and 3.8% after 90 days of curing. In the same way, for CF-RCA100 mix the increase of 60% and 62.5% has come down to 58.8% and 53.8% for 4 and 12 weeks of exposure period respectively.

The improved performance can be judged clearly from the reduction in percentage increase for all the SCC-RCA mixes. Thus, from the results it is clear that low content of RCA mix (CF-RCA25) has performed better amongst all other SCC-RCA mixes. In addition to this, a satisfactory performance has also been achieved in case of intermediate content of CF-RCA mix (CF-RCA50).

The reason behind this change is obvious due to prolonged age of curing which helped in more or less completing the hydration process. The statement becomes more favourable from the obtained SEM images Fig.-8 & Fig.-9, in which change in formation of calcium silicate hydrate (CSH) gel can be clearly observed, as quite denser CSH gel can be seen in comparison to scattered lumps, which have been visible after 28 days of curing. This dense phase of CSH gel helps in filling the micro and macro pores, cracks and loose joints in SCC mixes, which certainly results in resisting the ingression of CO_2. Also the overall performance of any concrete depends on two main factors: **1)** on the completion of hydration process and **2)** prolonged water curing which helps in improving the short as well as long term properties.

The steadiness of curing phenomenon supports in dropping the porosity of concrete as concluded in the previous literature studies [49-50]. Based on the achieved results, the prolonged water curing adopted in this investigation certainly backs in nullifying the negative effects of poor RCA structure to some extent, as the carbonation depths have been reduced to a significant level which ultimately yields to quite durable RCA based SCC mixes.

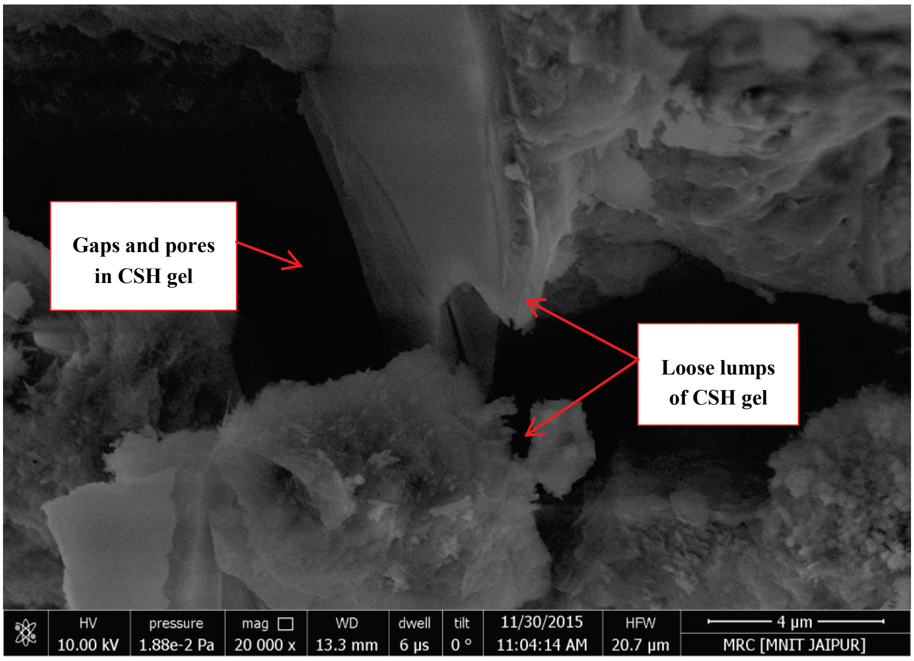


Fig. 8 SEM photograph showing loose lumps of CSH gel after 28 days of curing

Fig. 9 SEM photograph showing dense formation of CSH gel after 90 days of curing

3.3.1 Relation between compressive strength and carbonation coefficient

The process of CO_2 ingression can be demonstrated according to Fick's first law. According to Fick's law the carbonation rate is proportional to the square root of the time of exposure to CO_2:

$$X = K\sqrt{t} \tag{1}$$

Where X is the carbonation depth (mm); K the carbonation coefficient (mm/ weeks½) and t the exposure time (weeks). Typical values of compressive strength ranges from 33 MPa -39.9 MPa with carbonation coefficients (CC) stretching between 4.6-8 mm/weeks½ for curing period of 28 days after an exposure period of 4 and 12 weeks have been observed. In the similar way, the CCs' vary from 3.8-6.8 mm/weeks½ after curing period of 90 days for the same exposure periods of 4 and 12 weeks with compressive strengths varying from 35.6 MPa to 43.5 MPa have been noticed respectively. On the basis of the investigation, a linear relationship having regression coefficients R^2 equals to 0.9046 and 0.8901 have been obtained for curing period of 28 days. Likewise, R^2 to be equal to 0.8051 and 0.8905 have been noted for curing period of 90 days after an exposure periods of 4 and 12 weeks respectively. In general, the potential of any concrete can be umpired very well by relating compressive strength and the carbonation resistance. The prior speech has been justified undoubtedly from Fig.-10 & Fig.-11, as all correlation coefficients of all mixes used in this investigation have found to be more than 80%, which consequently verifying an overall agreeable performance [48].

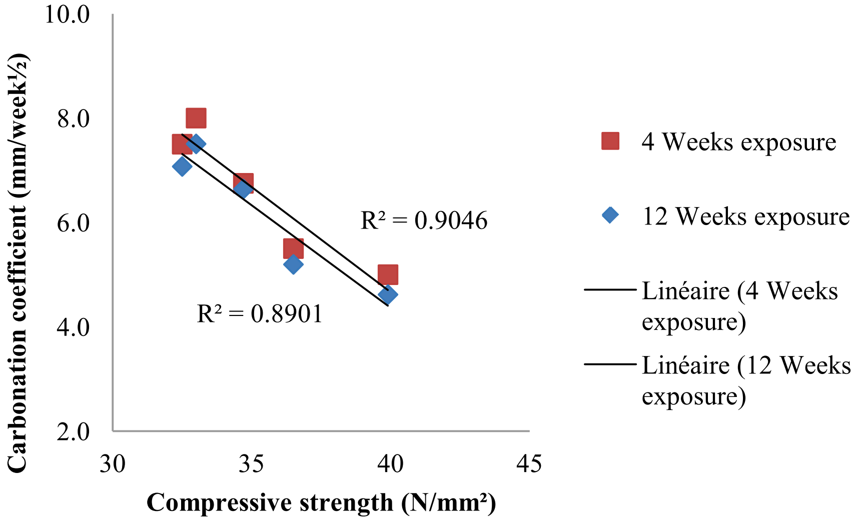


Fig. 10 Relation between carbonation coefficients with compressive strength for 28 days curing

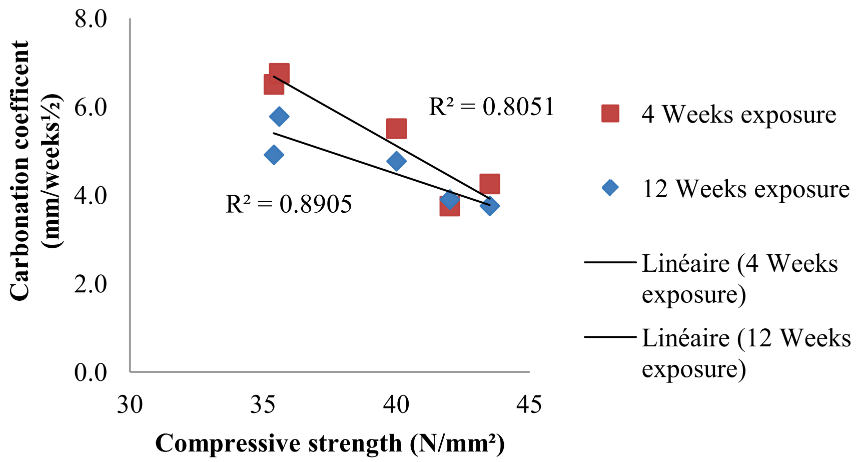


Fig. 11 Relation between carbonation coefficients with compressive strength for 90 days curing

3.4 Ultra-sonic pulse velocity test

Non-destructive testing is used to investigate the material integrity of the concrete structures. 'Direct testing method' was adopted for measuring UPV values for all the SCC mixes. Any reduction in UPV in a given region indicates the defective or deteriorated concrete in that region. The obtained values have been ranged from 3905 to 4618 m/s after curing periods of 28 and 90 days. The values are presented graphically in Fig.-12. The results indicate that UPV values decreased with increasing RCA content at all the ages. The minimum value of UPV has been observed for CF-RCA100 and highest value is noticed for CF-RCA0 mix. Ultrasonic Pulse Velocity values also depend on factors such as density of aggregates, ITZ characteristics and porosity [51-52]. The obtained UPV values have been found to be in agreement with previous studies, which proved that UPV figures have been highly influenced by presence of cracks (joints) or cavities [53].

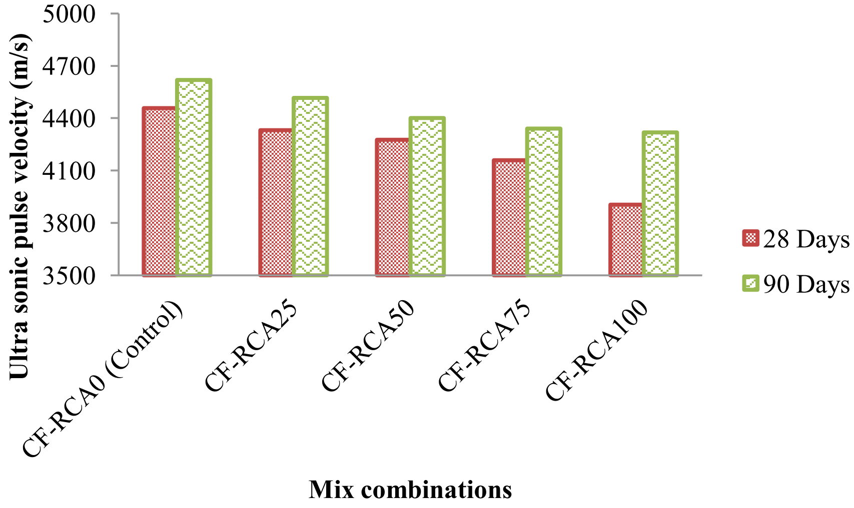


Fig. 12 Results of ultra-sonic pulse velocity test (m/s) for 28 and 90 days curing period

IS 13311(Part-1): 1992 classified the concretes as excellent, good, medium and doubtful for UPV values of 4500m/s and above, 3500-4500m/s, 3000-3500m/s and below 3000m/s respectively. From the obtained results it is clear that SCC mixes containing RCA as replacement behaves satisfactorily as the UPV values fall under the excellent and good categories which clearly indicates the good quality of concrete. A unique correlation between UPV and the compressive strength exists, as the nature of the aggregates highly influences the correlation between these two [54-55]. It has been revealed that the increasing rate of UPV figures has been seemed to be sufficiently higher in the early ages; correspondingly on the other hand, the increase becomes gradual with increase in time (slower rate from 28 to 90 days). The matter is consistent with the function of the compressive strength of SCC-RCA mixes with higher ages.

4 Conclusions

Based on the experimental results in the present study, it has been noticed that the compressive strength of all the RCA-SCC mixes has found to be decreased with increasing RCA content. The low level of replacement of RCA with NA (i.e. CF-RCA25) does not impart any negative effect, as observed percentage reduction for compressive strength has been quite comparable. Moreover, the prolonged curing for all the SCC-RCA mixes has proved to be beneficial, as satisfactory performance has been achieved not only in low level of replacement of RCA but also for the intermediate replacement level (i.e. CF-RCA50).

Anti –carbonation property for all the SCC mixes completely deteriorates with increase in percentage of RCA. Carbonation depths of CF-RCA100 is approximately 1.6-1.63 times higher than that of SCC mix made purely with NA after curing period of 28 days. Likewise, the carbonation depths after curing period of 90 days has been found to be increased by 1.53-1.58 times. A reliable linear relationship between carbonation coefficient and compressive strength has been observed for both at early and higher curing ages.

It has also been witnessed that UPV values decreases with increase in RCA extent in all the mixes. Results clearly proved that a replacement of RCA with NA for lower percentages does not impart any negative behavior despite the poor properties of RCA. Based on the observations and relationships presented in this research, it is confirmed that lower and intermediate content of RCA based SCC mixes meet the recommended limiting values for SCC based on NA which unveils compressive strength, carbonation resistance and UPV performances adequate to accomplish the target service life. Hence, use of RCA is a suitable material for reinforced concrete structures in future. Further, SCC designed with concrete industry products like RCA could certainly promote in achieving low cost for concrete production besides maintaining the sustainability and conservation of the natural resources for future generation.

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