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Fresh, Mechanical and Permeability Properties of Self Compacting Concrete with Recycled Concrete Aggregate

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Abstract: *The objective of this research is to evaluate the effect of the incorporation of coarse recycled concrete aggregate, on the properties of self compacting concrete. The effects of such incorporation on fresh, mechanical and permeability properties were investigated and are discussed. Two different series of concrete mixes (i.e. 30 Mpa and 40 Mpa) were prepared to test these properties. In each series, six concrete mixes with replacement ratios of 0%, 20%, 40%, 60%, 80% and 100% of natural coarse aggregate by recycled concrete aggregates were adopted. Results obtained show that self compacting concrete with recycled concrete aggregate exhibits adequate performance. However with increasing replacement of NCA the performance of concrete decreased but at higher strengths it shows improvement in all properties.*

Keywords: *recycled aggregate, self compacting concrete, permeablity, strength*

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I. Introduction

The 10.5 billion tonnes a year concrete industry is a largest consumer of natural resources in the world. It is estimated that the demand for concrete is expected to grow to 18 billion tons a year by 2050 (Mehta, 2001). According to Berkeley, Ordinary concrete typically contains 12% cement, 8% water and 80% aggregates by mass. This means that, in addition to 1.5 billion tons of cement, the concrete industry is consuming annually 9 billion tones of aggregates putting enormous pressure on the environment. On the other hand, the amount of construction waste has been dramatically increased in the last decades, and social and environmental concerns on the recycling of the waste have been consequently increased. Non- biodegradable construction and demolition waste is creating lots of problem in the environment and its disposal is becoming a great concern. In India presently construction and demolition waste accounts for 23.75 million tons annually and these figures are likely to double fold up to 2016[Vaishali et al, 2012].

The recycling of demolished concrete, which comprises roughly two third of the total construction waste in India, has been emerging as a sustainable solution to warrant the reduction of construction wastes, as well as to prevent the depletion of natural resources from growing construction demand. The use of coarse recycled concrete aggregate (RCA) in the concrete industry could lead to a situation much closer to that of sustainable development. The suitability of RCA for use in different applications with a low or moderate degree of requirement has been extensively tested and proved by many authors (Etxeberria et al2007; Tam et al 2005; Ravindrajah1988; Tabsh & Abdelfatah 2009 and Poon et al 2004). Some authors (Ravindrajah1988; Tabsh & Abdelfatah 2009) suggested that the use of coarse RCA could be extended to high performance concrete (HPC), offering additional value to RCA. Following on from previous research work, Limbachiya et al. (2000) examined the influence of coarse RCA in high-strength concrete, 50 MPa or more. The concrete performance was assessed, while practical issues and durability properties were also tackled. The results obtained showed that concrete containing up to 30% of coarse RCA could be used in a wide range of applications in high performance concreting and the durability properties were similar to those of natural aggregate concrete. Recycled aggregate have been found to have low density, low specific gravity, high water absorption and high porosity (Padmini et al 2009). Also the recycled aggregate obtained from crushing of old concrete can exhibit inconsistent properties depending on the composition, particularly the W/C ratio and cement content of original concrete (Dhir and Paine 2010). Recycled aggregate contains not only the original aggregate, but also hydrated cement paste and mortar, adhered to the surface of the aggregate. This paste makes them more porous which leads to higher porosity and water absorption in concrete. Also recycled aggregate can contain various contaminants such as chlorides, sulphates, carbonates, organic matter etc depending on the source of parent concrete. Despite all the inferior qualities, many researchers have shown that it can be a reliable alternative of natural coarse aggregate (NCA) in concrete (M C Rao et al 2010; Nassar and Soroushian 2012; Parekh and Modhera 2011). Although the potential for the use of coarse RCA has now been widely acknowledged and promoted, however lack of widespread reliable data on RCA characteristics and its influence on concrete performance can restrict its use to full potential. For durable and effective utilization of RCA in concrete, a wide range of test data on concrete made with various materials and combinations, and different replacement levels of RCA are needed.

Self compacting concrete (SCC) is considered as one of the most revolutionary development in high performance concrete in the recent decades. SCC is known for its exceptional performance and uniformity, which outperform the qualities of conventional concrete. It was developed by Okamura and associates (1989) in Japan and considered as a highly workable concrete that can flow through densely reinforced and complex structural elements and adequately fill all voids without segregation, excessive bleeding and the need for vibration or other mechanical consolidation (Ozawa et al 1989; Khatib 2008; Khayat 1999). The deformability, filling capacity, and stability of SCC were studied using field-oriented tests. The reported study was undertaken to examine the suitability of coarse RCA for use in self compacting concrete. The use of RCA in SCC is a relatively new research area on which a very limited scientific research has been carried out (Grdic et al 2010; Kou and Poon 2009; Guneyisi et al 2014). The results of this study will contribute significantly to the existing literature in addition to building standards and codes on the use of RCA in structural concrete in India. Furthermore, it will also help to develop confidence in the use of recycled materials by stakeholders, especially future users of RCA concrete in the world.

II. Materials

In this study the materials used were ordinary Portland cement (OPC), Microsilica, natural fine aggregate, natural coarse aggregate, coarse recycled concrete aggregate and superplasticizer. An ordinary Portland cement of Grade 53 and specific gravity 3.18 conforming to IS12269:1987 was used in all compositions. The microsilica which was used as a powder material in SCC was obtained from Elkem India. The typical chemical composition and some physical properties of cement and microsilica are tabulated in table1. The natural river sand was utilised as fine aggregate and crushed basalt from local quarry was used as coarse aggregate conforming to IS383:1970. The recycled aggregate used in the investigation was obtained from the cubes tested in concrete technology laboratory. The strength of parent concrete from which the recycled aggregate was obtained ranged between 20 - 30 MPa. The physical properties of fine and coarse aggregates are given in table 2. The superplasticizer used was a polycarboxylic-ether polymer based admixture, commercially branded as Auramix 400 obtained from Fosroc chemicals.

Table 1. Chemical composition of cement and silica fume

	SiO_2	Al_2O_3	Fe_2O_3	CaO	LOI
Cement	20.9	4.7	3.4	65.4	0.9
Microsilica	91.03	0.39	2.11	1.5	4.05

Table 2. Physical properties of aggregates

Characteristics	Natural Coarse Aggregate	Recycled Coarse Aggregate	Fine Aggregate
Specific Gravity	2.65	2.19	2.60
Bulk Density, kg/m^3	1614	1356	1690
Water Absorption, %	1.31	5.64	0.84
Fineness Modulus	7.2	6.96	2.36
Impact Value, %	9.88	17.36	--

III. Mix Composition

For the purpose of the experiment two series of self compacting concrete mixtures were produced in the laboratory using pan mixer. In each series natural coarse aggregates were substituted by coarse recycled concrete aggregates in the ratio of 0%, 20 %, 40%, 60%, 80% and 100% by volume. The preliminary mix design was carried out using Nan-Su method for target strength of 30 MPa and 40 MPa. After the initial mix design, the trial mixes were prepared and tested for the fresh properties of SCC as per guidelines (EFNARC 2002). The design mixes which failed to satisfy the requirements of fresh properties of SCC; were revised by fine tuning the mix proportions till all the requirements were met. The final mix compositions adopted are presented in table 3. The quantity of ingredients required for making 1 m^3 of concrete were kept constant in each series, with the exception of small variations in the quantity of superplasticiser for the purpose of achieving equal consistency in all the mixes. To counteract the effect of higher water absorption of recycled aggregate, all the aggregates were immersed in water for 24 hours and surface dried before use.

Table 3. Details of mixes for $1m^3$ concrete

Mix Type	Cement, Kg	Coarse Aggregate, Kg		Fine Aggregate, Kg	Silica Fume, Kg	Water Kg	Dose of SP, Kg
		Normal	Recycled				
X0	348	804	0	970	115	185	4.6
X20	348	644	133	970	115	185	4.6
X40	348	483	266	970	115	185	4.6
X60	348	322	399	970	115	185	4.6
X80	348	161	532	970	115	185	5.5
X100	348	0	666	970	115	185	5.5
Y0	380	805	0	990	135	191	6.2
Y20	380	644	133	990	135	191	6.2
Y40	380	483	266	990	135	191	6.2
Y60	380	322	399	990	135	191	6.2
Y80	380	161	532	990	135	191	6.9
Y100	380	0	666	990	135	191	6.9

IV. Test Methods And Procedures

4.1 Fresh state properties

For a concrete to be characterised as self compacting it should possess the following key abilities in its fresh state i.e. flowability, passing ability, viscocity and segergation resistance, these abilities of SCC were tested by various methods as specified by EFNARC. In this experiment slump flow test was used to check flowing ability, T_{500} slump flow and V Funnel test were used for determining the viscocity. The passing ability of concrete mixes was checked by performing L-box test with 3 rebars and segregation resistance was observed by means of sieve stability test. Table 4 gives the recommended values of fresh state properties of SCC by EFNARC for structural purpose for different tests.

Table 4. Typical ranges of values for different tests for SCC

Method	Unit	Typical range of values	
		Minimum	Maximum
Slump Flow	mm	650	800
T_{500} slump flow	Sec	2	5
V-Funnel	Sec	6	12
L-box	(h2/h1)	0.8	1.0
Sieve Segregation	%	0	15

4.2 Hardened state properties

4.2.1 Strength properties

The hardened SCC mixes were tested for compressive, flexural and splitting tensile strengths. The compressive strength test was performed using compression testing machine of 3000 kN capacity at the age of 3, 7, 28 and 90 days as per IS516-1959. The cube specimens of 100 x 100 x 100 mm size were adopted for the test. The flexural and tensile strength were measured at 28 days according to IS516:1959 and IS5816:1999 respectively. The details of size, number of specimens and test methods are presented in table 5.

Table 5. Details of strength test program

Property	Age at test, days	Number of specimens	Size of specimen in mm	Test Method specified by
Compressive strength	3, 7, 28, 90	144	100 x 100 x 100	IS 516-1959
Split Tension Test	28	36	300 diameter &150 Height	IS 5816-1999
Flexure test	28	36	100 x 100 x 500	IS 516-1959

4.2.2 Permeability Properties

The permeability is the root cause for lack of durability. The permeability of concrete is defined as the ease with which it allows the fluids to pass through it. The permeability properties of SCC mixes were analysed by means of two tests, water absorption by immersion, and absorption by capillary action (sorptivity).

4.2.2.1 Water absorption test

Water absorption test was carried out on 100 mm cube specimens at the age of 28 days as per ASTM C642. After 28 days of curing the specimens were taken out and allowed to dry. The drying was carried out in a hot air oven at a temperature of 105ºC. The drying process was continued, until the difference in mass between two successive measurements agreed closely. The dried specimens were cooled at room temperature and then immersed in water. The specimens were taken out at regular interval of time, surface dried using a cloth and weighed. This process was continued till the weights became constant. The water absorption is then calculated as below.

$$\text{Percentage Water Absorption} = (W_s - W_d) \times 100 / W_d$$

Where, W_s – Weight of specimen at fully saturated condition.
W_d – Weight of oven dried specimen.

4.2.2.2 Sorptivity test

Sorptivity is a measure of the capillary force exerted by the pore structure causing fluids to be drawn into the body of the material. It is calculated as the rate of capillary rise in a concrete specimen placed in 2 to 5 mm deep water. For one-dimensional flow, the relation between absorption and sorptivity is given by, $i = St^{0.5}$ where, i is the cumulative water absorption per unit area of inflow surface, *S* is the sorptivity and *t* is the elapsed time. The test was conducted in the laboratory on 100 mm cubic specimens preconditioned by drying in an oven at 105^{o}C to the constant mass. After cooling, the sides of the concrete samples were sealed and the initial weight was taken. The samples were then kept in a tray with 2 to 5 mm depth immersed in water. At selected intervals of 30 minutes; the samples were removed and were weighed after blotting off excess water. The gain in mass per unit area versus the square root of time was plotted. The slope of the best fitting line was reported as the sorptivity.

4.3 Ultrasonic pulse velocity (UPV)

The cube specimens of size 100 x 100 x 100 mm were used for the UPV test. The average values were taken from three cubes obtained from each mixture using the Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT). The test was done in accordance with IS 13311:1992 in direct transmission state. All of the specimens were tested at the saturated conditions, at the age of 28 days and 90 days.

V. Results And Discussion

5.1 Fresh State Properties

The results of fresh state properties of all SCC mixes are presented in table 6. All the series X mixes exhibited good horizontal slump spread except mix X100. The mix X100 shown a slump flow of 620 mm which is just short of acceptable range and satisfied SF1 flow class as per EFNARC 2005. All the other mixes in this series have shown slump flow between 670-765 mm satisfying SF2 and SF3 flow class which is suitable for all general structural applications. In Y series mixes, mix Y20 and Y60 satisfied SF1 slump flow class which is appropriate for thin and slightly reinforced concrete structures, whereas all other mixes exhibited slump flow appropriate for SF2 flow class. The T_{500} slump flow is the time for which concrete reaches the diameter of 500 mm and it is measured during execution of slump flow test. The mixes of both the series recorded the T_{500} time in between 2.08 – 3.41 seconds which belongs to VS2 viscocity class. The V funnel times for all the mixes was well within accpetable range of 6-12 seconds and satisfied VF1 viscocity class which is an indication of good filling ability even with congested reinforcement. The L-box ratio for all mixes were as per the acceptance criteria of 0.8 to 1 and satisfied PA2 class which is applicable for all civil engineering structures. All the mixes showed horizontal slump flow without any bleeding at the periphery which indicates good deformability and segregation resistance which was also revealed by segregation resistance test as all the mixes showed segregation resistance within the limit of 15%.

Table 6. Results of fresh state properties of SCC

Mix Type	Slump Flow, mm	T_{500} Slump Flow, sec	V Funnel, Sec	L - Box	Segregation Resistance %
X0	670	2.57	6.51	0.92	9.53
X20	740	2.08	6.07	0.98	8.45
X40	720	2.38	6.19	0.93	8.92
X60	765	2.15	6.62	0.95	8.51
X80	700	2.81	7.13	0.97	10.2
X100	620	3.15	7.86	0.90	11.8
Y0	680	2.87	6.32	0.90	10.15
Y20	645	3.45	7.08	0.85	11.20
Y40	670	3.08	6.71	0.92	9.88
Y60	640	3.41	7.41	0.87	11.65
Y80	720	2.51	5.16	0.95	10.04
Y100	650	3.1	6.71	0.90	12.35

5.2 Strength Investigations

5.2.1 Compressive stength

The results of the compressive strength of the concrete for both series at the age of 3, 7, 28 and 90 days are shown in Table 7. Each presented value is the average of three measurements. It can be seen that at all the test age as the replacement of natural coarse aggregate by coarse recycled concrete aggregate increased, the compressive strength of the concrete decreased. This variation was found similar to the results reported by other researchers (Shi-cong Kou et al 2011; R Somna et al 2012; P. Saravanakumar and G. Dhinakaran 2013). This was due to the adhered cement mortar to the recycled aggregate which had higher porosity and was weaker than the natural aggregate. In series X mixes the reduction in 28 days compressive strength with each replacement level is 3.75%, 5.80%, 12.16%, 14.63% and 15.94% respectively. Whereas in series Y mixes the reduction in 28 days compressive strength is observed to be 5.05%, 7.06%, 9.25%, 9.63% and 10.06% respectively. This indicates that as the strength of the concrete increases the microstructure of the concrete with recycled aggregate gets improved. This was in agreement with the conclusion drawn by Tabsh and Abdelfatah (2009), that the percentage loss in compressive or tensile strength due to the use of recycled aggregate is more significant in a weak concrete than in stronger one. The figure 1 and 2 also revealed that, up to 7 days the rate of gain of strength is almost same in both series of mixes and at later age the difference in strength is more. This is due to the fact that the adhered mortar in recycled aggregate is either partially hydrated or fully hydrated which therefore acting as a seeding for gain of early strength.

Table 7. Results of strength investigations

Mix Type	Compressive Strength, N/mm^2				Tensile Strength, N/mm^2	Flexural Strength, N/mm^2
	3 days	7 days	28 days	90 days	28 days	28 days
X0	15.50	27.16	38.07	46.77	4.94	7.61
X20	15.28	26.78	36.64	44.27	4.49	7.34
X40	15.15	26.95	35.86	41.97	4.21	6.82
X60	15.25	26.20	33.44	39.05	3.73	6.34
X80	14.90	25.83	32.50	37.82	3.26	5.75
X100	15.00	25.50	32.00	36.67	3.12	5.14
Y0	25.72	35.87	46.69	54.60	5.97	9.28
Y20	25.40	33.66	44.33	51.92	5.8	8.82
Y40	25.15	34.66	43.39	50.55	5.48	8.35
Y60	23.78	30.67	42.37	48.88	5.16	7.78
Y80	23.17	30.83	42.19	47.80	4.95	7.56
Y100	20.17	28.67	41.99	47.63	4.86	7.32

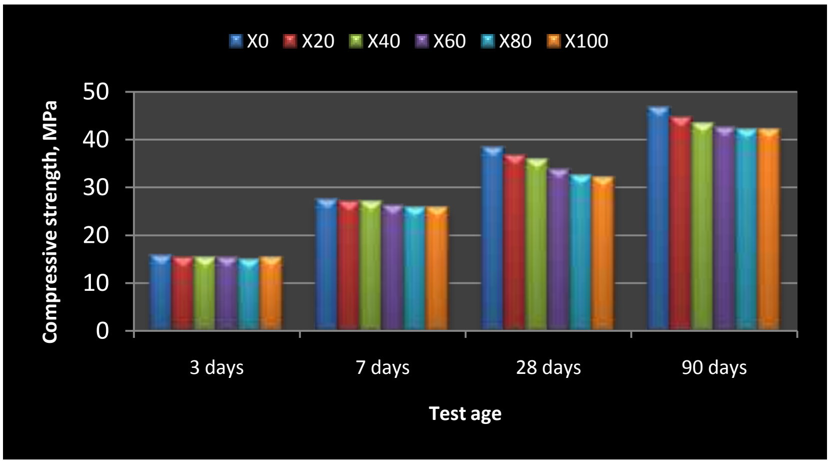

Figure 1. Age of test Vs Compressive strength (X series)

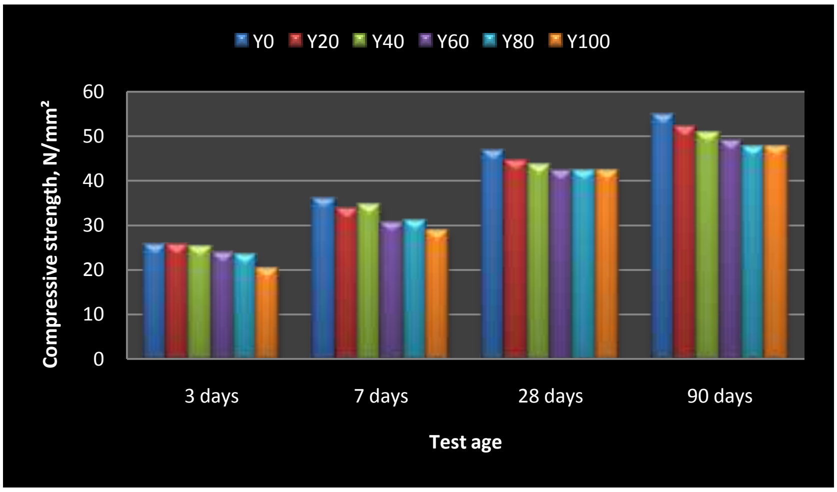

Figure 2. Age of test Vs Compressive strength (Y series)

5.2.2 Split tensile strength

The splitting tensile strength of the concrete mixes cured in water at the age up to 28 days is shown in figure 3. The results showed that the variation in splitting tensile strength with recycled aggregate content was similar to that observed for compressive strength. The splitting tensile strength decreased with increase in recycled aggregate. At 28 days, the reduction in splitting tensile strength of the series X mixes with increasing RCA content was recorded as 9.1%, 14.8%, 24.5%, 34.0% and 36.8% respectively. Whereas in series Y mixes the reduction in splitting tensile strength was 2.8%, 8.2%, 13.5%, 17.1% and 18.6% respectively with increasing RCA. This can be attributed to improvement in transition zone of recycled aggregate with increasing compressive strength. Visual examination of crushed test specimens was carried out to assess the failure mode of recycled concrete specimens. The failure pattern showed that aggregate splitting was evident in most RCA mixes. Figure 4 indicates the correlation between the 28 days compressive strength and a split tensile strength for both series of mixes. The correlation holds good for both series of mixes however series X mixes shown better correlation between the two strengths.

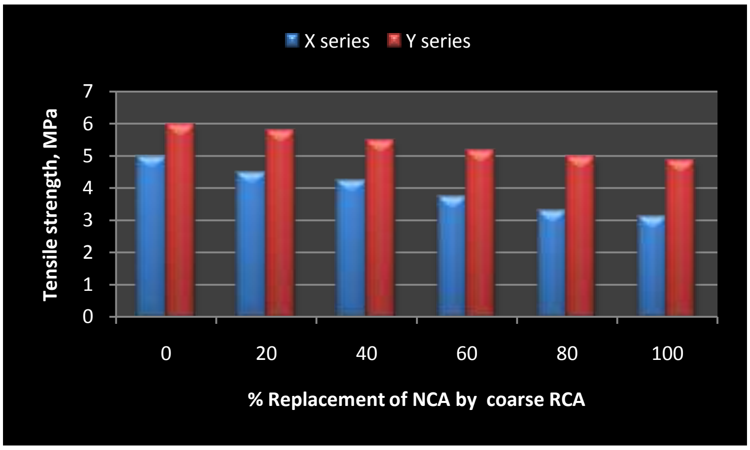

Figure 3. Results of Tensile strength

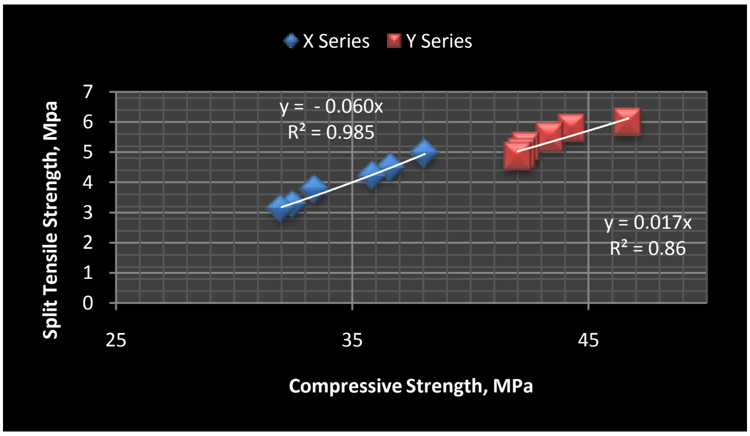

Figure 4 Compressive Strength Vs tensile strength

5.2.3 Flexural strength

The results of flexural strength are tabulated in table7 . The influence of RCA was clearly seen in the flexural strength results. The results followed the same trend as that of the compressive and split tensile strength. As the replacement of coarse recycled concrete aggregate increased the flexural strength decreased. Figure 5 shows the corelation between compressive strength and flexural strength for both the series of mixes. From the figure, it is evident that the correlation holds good for both the series of mixes with R^2 value above 0.90. The corelation between flexural and split tensile strength shown in figure 6 also indicated good relationship for both series of mixes. However the R^2 value for Y series mixes was better than that of X series mixes.

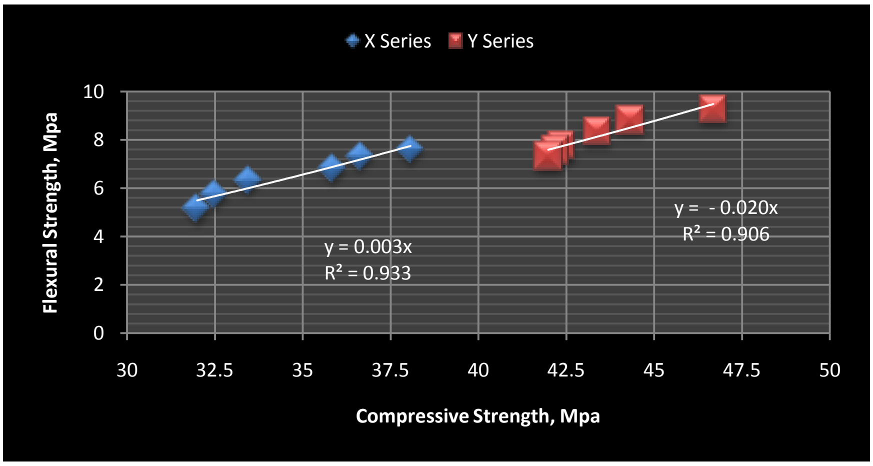

Figure 5. Compressive Strength Vs Flexural strength

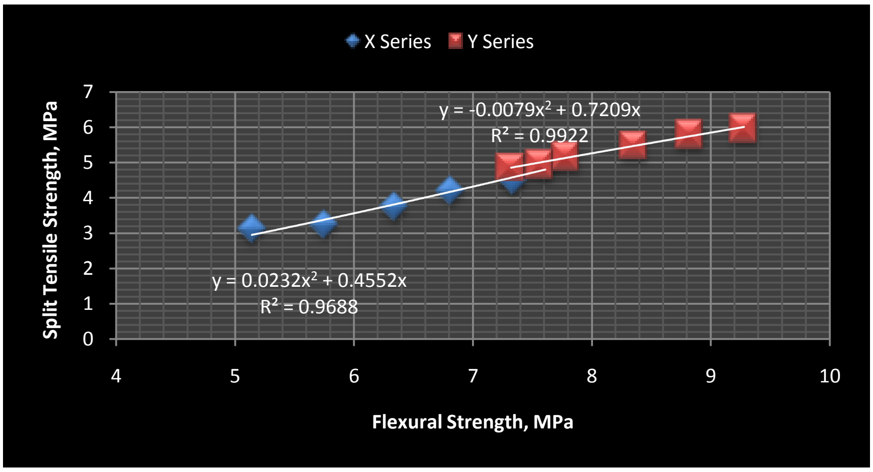

Figure 6. Flexural strength Vs tensile strength

5.3 Results of Permeability test

5.3.1 Water Absorption test

Water absorption and sorptivity are the indicators of permeability of concrete. The results of water absorption test are shown in table 8. From the results it is clear that the water absorption is directly proportional to percentage of recycled aggregate. As the recycled aggregate increased the water absorption also increased, which was the result of higher initial water absorption of recycled concrete aggregate. The percent increase in water absorption with increasing RCA was recorded as 21.29%, 27.51%, 30.86%, 35.64% and 40.90% respectively for series X mixes, whereas for Y series mixes the change was 12.08%, 14.65%, 22.87%, 26.99% and 32.39% respectively compared to mix containing no recycled aggregate. However the initial water absorption of coarse recycled concrete aggregate was 330% higher than that of natural coarse aggregate. The relative water absorption between the two series of mixes shown in figure 7, indicates that for higher strength concrete mixes the water absorption was on lower side. This was the result of more binder content used in these mixes which improved the micro structure of concrete along with contributing to strength.

Table 8 Results of Water absorption and sorptivity test

% replacement of NCA by RCA	% Water absorption		Sorptivity coefficients in cm/s$^{1/2}$	
	X series	Y series	X series	Y series
0	4.18	3.89	0.00109	0.00096
20	5.07	4.36	0.00120	0.00112
40	5.33	4.46	0.00153	0.00129
60	5.47	4.78	0.00190	0.00165
80	5.67	4.94	0.00216	0.00193
100	5.89	5.15	0.00262	0.00207

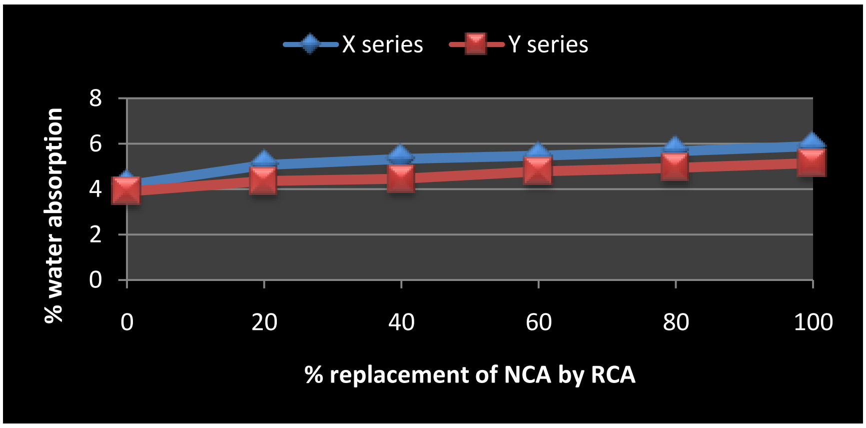

Figure 7 RCA content Vs Water absorption

5.3.2 Sorptivity test

Table 8 and figure 8 illustrates the result of sorptivity coefficents of Series X and Y respectively with . The maximum sorptivity coefficient was reported by mixes containing 100% recycled coarse aggregate. The result showed that the amount of sorptivity increased with replacement of NCA by RCA, which is attributed to the presence of more and longer capillaries in RCA as a consequence of its own porosity. This has been reported also by other researchers (Kou and Poon 2012; Salomon and Helene 2004). It was also observed that the maximum percentage increase in sorptivity for series X mix is 2.4 times, whereas it was 2.1 times in Y series mix compared with mix containing no RCA. This was an indication of improvement in pore structure of the concrete mixes with increase in strength. The correlation between water absorption and sorptivity coefficients is as shown in figure 9. The correlation showed good relationship for both series of mixes with R^2 value above 0.80. However the R^2 value of series Y mixes is above 0.95 which further justifies improvement in pore structure of the concretes.

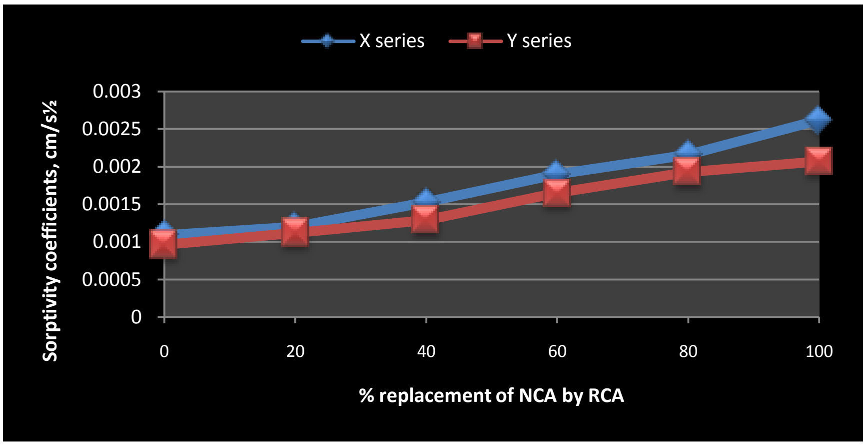

Figure 8. Recycled aggregate content Vs sorptivity coefficients

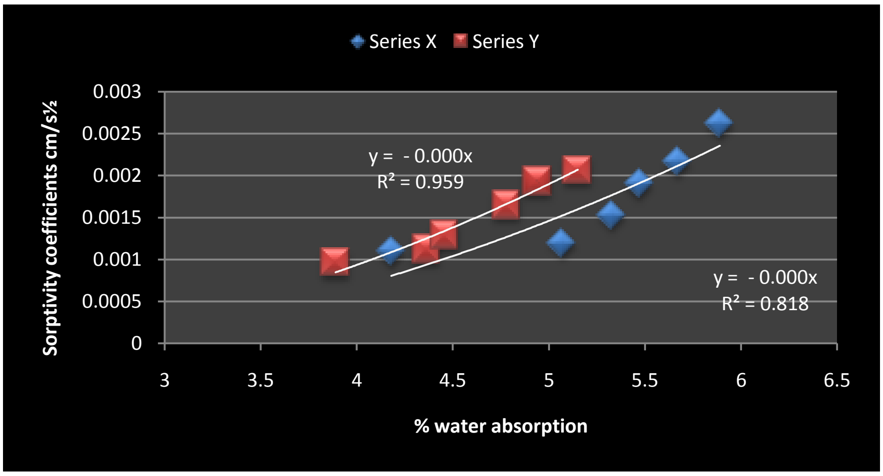

Figure 9. water absorption Vs sorptivity coefficients

5.4 UPV test results

Table 9 UPV values of concrete mixes

% replacement of NCA by RCA	28 days		90 days	
	X series	Y series	X series	Y series
0	3.508	4.484	4.192	5.319
20	3.436	4.374	4.048	5.208
40	3.344	4.149	3.906	5.208
60	3.267	4.016	3.891	4.651
80	3.174	3.831	3.636	4.347
100	3.086	3.610	3.516	4.273

The UPV test was used to predict the characteristic of the internal particles of concrete and the quality of the concrete. The UPV values of both series of specimens were in the range of 3.086 km/s to 4.484 km/s at 28 days and 3.436 km/s to 5.319 km/s at 90 days duration. The values tend to increase with the age. However, the values decreased as the replacement level of the recycled aggregate increased. As per IS 13311(Part1) the concrete is classified as in good condition, if its UPV value falls in the range of 3.5 km/s – 4.5 km/s. At 28 days, all specimens in Y series were evidently characterized as in good condition. However in X series only one mix (X0) satisfied this condition. At 90 days all the mixes of both series clearly satisfied criteria of good condition. The pore structure in the concrete might have impact on the UPV values. Even though the adhered mortar is porous and it would reduce the UPV as proven in the experiment, as long as the UPV values lie within the good category, the particular concrete does not contain any large voids or cracks which would affect the structural integrity. Therefore, the RCA is still considered suitable to replace natural coarse aggregate in large portions as long as it achieves the target strength. Figs. 10 and 11 show correlation between UPV and compressive strength at 28 and 90 days respectively. The Y series mixes showed improvement in R^2 value with increasing age compared to X series mixes.

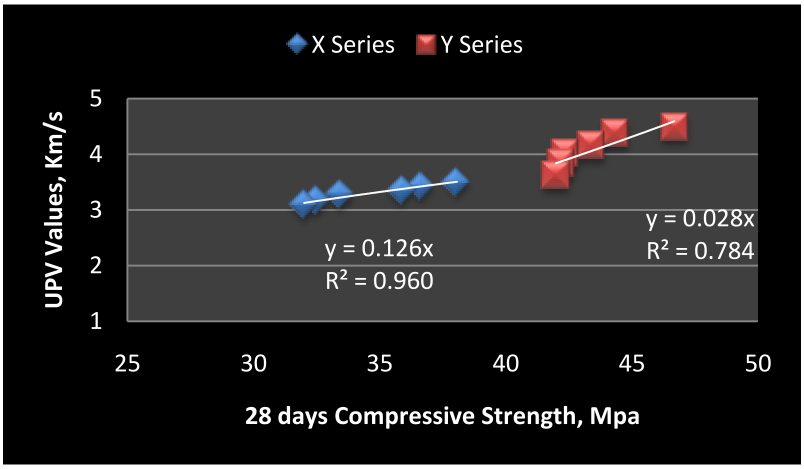

Figure 10 Comp. strength Vs UPV Values (28 days)

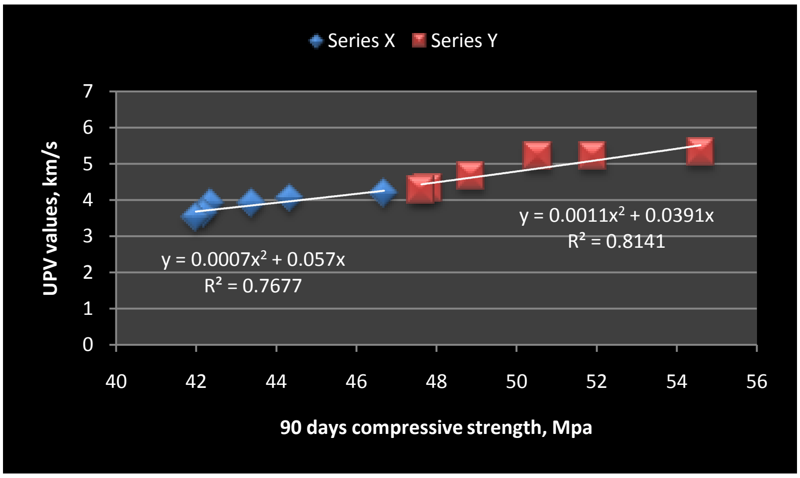

Figure11. Comp. strength Vs UPV (90 days)

VI. Conclusions

- The effect of RCA on fresh properties of SCC is negligible, since all the mixes in both series have shown good fresh state abilities.
- The increase in RCA content reduces the compressive strength but the obtained strength for each replacement level was above the targeted strength for both series. The split tensile strength and flexure strength also shown same trend as that of compressive strength.
- In higher strength SCC, the rate of reduction of strengths was less which is an indication of improved microstructure of concrete.
- The sorptivity and water absorption increased with the increase in recycled aggregate content.
- All the mixes exhibited good UPV values at 90 days indicating improvement in microstructure of RCA concrete at later age.
- From the above conclusions, it is clear that RCA can be a potential ingredient for producing self compacting concrete considering the economy and sustainability in concrete production.

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