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Experimental Studies on Utilization of Recycled Concrete Aggregates in various moisture conditions and Recycled Fine Aggregates in Normal Grade Concrete Mixes

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Abstract: **The first part of the study deals with testing of Recycled Aggregate Concrete (RAC) mixes with Recycled Coarse Aggregate (RCA) in Air Dry (AD), Saturated Surface Dry (SSD), Saturated Surface Wet (SSW) and Surface Wet (SW) conditions and at different levels of replacement for Natural Coarse Aggregate (NCA), so as to assess their influence, on fresh and hardened properties of RAC. The second part, deals with testing of concrete mixes with Recycled Fine Aggregate (RFA) at different replacement levels for Natural Fine Aggregate (NFA). Two fractions of coarse aggregates are used in the mix design viz., 60% (< 20 mm and > 10mm) and the remaining 40 % (< 10 mm and > 4.75mm). At any replacement level of RCA, slump is found to be lowest in AD condition and highest in SSW. The slump is found to reduce with increase in RCA content. At all RCA replacement levels, the AD condition, yields maximum compressive strength, followed by SSD (-11%), SW (-25%) and SSW (-30%). The test results with respect to compressive strength at 7 and 28 days, density and split tensile strength are statistically analysed, to determine their correlation as well as the ratio between them. An empirical equation is proposed to compute the normalized value taking into account the prime variants of the study. It is also observed that, slump value decreases as the percentage replacement of RFA increases and reaches zero for 100% replacement. At all levels of RFA replacement, concrete mixes possess, higher 28 days strength, than the mix with NFA. A linear equation is proposed to compute the normalized 28 days strength for different RFA replacement levels. It is concluded that, since quantum of concrete waste generation is obviously much less than concrete requirement in construction sector, the possible replacement levels may be fixed as 20% RCA and RFA. Test results for such replacement levels indicate, that RAC possesses very similar properties of Natural Aggregate Concrete (NAC), except for workability requirements, which can be circumvented with the use of 0.8% superplasticizer (SP).**

Keywords: **Concrete waste, Recycled Coarse Aggregate (RCA), Recycled Fine Aggregate (RFA), Recycled Aggregate Concrete (RAC), Air Dry (AD), Saturated Surface Dry (SSD), Saturated Surface Wet (SSW), Surface Wet (SW), Natural Fine Aggregate (NFA), Natural Coarse aggregate (NCA), Natural Aggregate Concrete(NAC).**

I. INTRODUCTION

The utilization of Concrete waste sourced from construction and demolition waste, to produce RAC mixes, instead of disposing them off to landfill purposes, is considered as an important engineering based strategy, oriented towards sustainable construction, as, it can minimize the ill effects of indiscriminate landfills, as well as, serve the cause of resource conservation. Concrete waste can be processed to recover RCA and RFA. Numerous experimental studies are conducted by researchers around the world; to assess the potential of RCA, to produce RAC mixes, so as to, possess similar properties of NAC, in both fresh and hardened state.

Concrete mix design is generally based on two moisture conditions: AD and SSD. These moisture conditions are achievable in laboratory conditions, whereas, aggregates in stockpiles, ready mix plants, and in concrete mixes will not be at these moisture conditions. In actual field conditions, such as on-site mixing or even in ready mix plants, the assumed SSD condition of the aggregate cannot be ensured. In such cases, the amount of water must be adjusted, so as to include the moisture conditions of the aggregate , or ,estimate the possible change in fresh and hardened properties of concrete mixes so that, appropriate field corrections can be introduced.

A. Note on Moisture Conditions

AD: The surface of the aggregate is dry and the internal pores may be partially filled with water. This condition may occur during summer season. The aggregates absorb water from the mix resulting in reduction of free water content.

SSD: This is achieved under laboratory conditions, when all the pores are completely filled with water but no free water remains on the surface of the aggregate. Aggregates in this condition will not contribute to free water content nor absorb water from the mix.

SW: The surface of the aggregate is wet and the internal pores may not be filled with water. This condition may occur, if aggregates are exposed to brief period of rain. The aggregates contribute water to the mix, resulting in increase of free water content.

SSW: All the pores are completely filled with water and the surface of the aggregate contains free water. Aggregates in a stockpile, during rainy seasons, will typically be in this condition and will contribute to large increase in free water content.

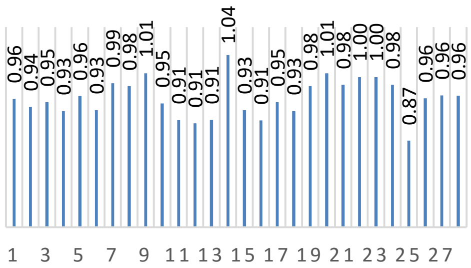
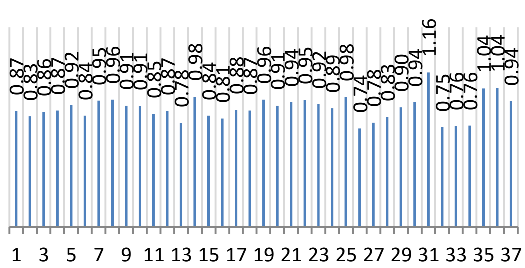
Measuring or at best estimating and compensating for moisture in the aggregates is desirable in the preparation of concrete mixes. Based on this premise, the first part of the experimental study deals with testing of RAC mixes with RCA in different moisture conditions and at different levels of replacement for NCA, so as to assess their influence, on fresh and hardened properties of RAC. The second part of the experimental work, deals with testing of concrete mixes with RFA at different replacement levels for NFA.

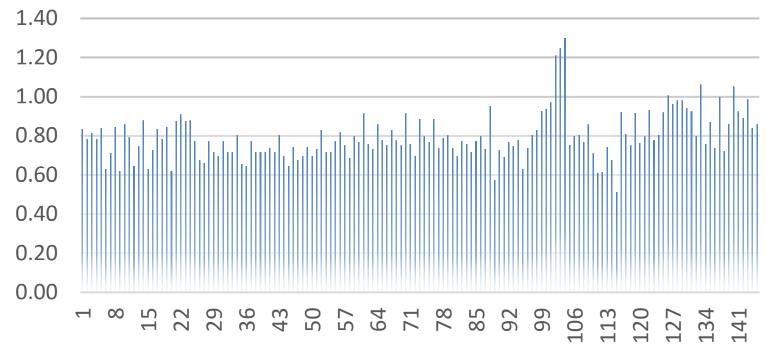
II. LITERATURE REVIEW

Review of Literature on RCA and RAC

Review articles related to the use of RCA in RAC mixes are published in the literature [1] to [7]. Several experimental studies are pursued to gain a better insight about the physical, chemical, strength and durability aspects of RCA as well as RAC [8] to [37]. The studies are also oriented towards mitigating some of the deficient aspects, so as to make, RCA as a valuable resource in concrete production. The 28 days compressive strength test results reported in literature [8] to [37], are normalized with respect to the corresponding control mix. The normalized values are shown in Table I, in the form of bar charts.

TABLE I: NORMALIZED VALUES OF 28 DAYS COMPRESSIVE STRENGTH OF RAC MIXES

1 *RCA Replacement Level – 20%*	**2** *RCA Replacement Level – 50%*
	
Number of Test Results = 28; Mean Value (μ) = 0.96; Standard deviation(σ) = 0.04, Minimum Value = 0.87, Maximum value = 1.04	Number of Test Results = 37; μ = 0.89; σ = 0.09, Minimum Value = 0.74, Maximum value = 1.16
3 *RCA Replacement Level – 100%*	



Number of Test Results = 145; μ = 0.79; σ = 0.12, Minimum Value = 0.51, Maximum value = 1.3

Summary of Statistical Analysis

The summary of statistical analysis of normalized values of test results, available in the literature [8] to [37], pertaining to compressive strength, tensile strength and modulus of elasticity are listed in Table II.

TABLE II: SUMMARY OF STATISTICAL ANALYSIS

Normalized Properties of RAC	Statistics	RCA Replacement Levels		
		20%	50%	100%
28 day's Compressive strength	μ	0.96	0.89	0.79
	σ	0.04	0.09	0.12
28 day's Split Tensile strength	μ	0.97	0.89	0.86
	σ	0.05	0.13	0.11
Modulus of Elasticity	μ	0.90	0.74	0.71
	σ	0.08	0.23	0.09

i. The average normalized values of compressive and tensile strength and modulus of elasticity of RAC mixes indicate that, the RAC made with 20% to 30% of RCA is very similar to NAC [8],[10],[21].

ii. As the replacement level increases, compressive, tensile strength and modulus of elasticity of RAC mix decreases. The maximum reduction of 21% in compressive strength is indicated at 100% RCA replacement level. The statistical results show a 15% lower elastic modulus with 30% RCA, which is in line with the observation reported in an experimental study [21].

iii. The literature review indicates that, most of the studies are performed in SSD condition of the aggregates.

Water Absorption Characteristics of RCA

The reports available in the literature [8], indicate that RCA has the following distinctive characteristics than NCA, due to the presence of adhered mortar.

i. Water absorption is three to six times higher than that of NCA.

ii. The porosity of the recycled aggregates ranges from 3.2% to 12% for the coarse and the fine fractions, respectively, whereas the porosity of the NCA is relatively low (0.5–1.5%).

iii. The absorption capacities of RCA and NCA are about 4.44 and 0.80% respectively.

The absorption characteristics and surface moisture conditions of aggregates are important properties, which can affect the design of RAC mixes with RCA.

Review of Literature on RFA

The utilization of RFA has not been the subject of thorough studies, since it is believed that, their greater water absorption can jeopardize the final results. However replacement of RFA up to 30% is feasible, as the RAC properties are found to be quite similar to NAC, [38]. In another study [20], RAC mixes are prepared by replacing the natural aggregates with 100% recycled counter parts along with mineral additions and reduced water cement ratio. The compressive strength is found to be 30 MPa for reference concrete and 25 MPa for RAC with 100% replacement of both fine and coarse aggregates. The mineral additions also helped the strength and durability properties.

III. OBJECTIVES AND APPROACH

The main objectives of the study are:

1) To assess the variation of fresh and hardened properties of concrete mixes, with respect to moisture absorption characteristics of RCA, in AD, SSD, SW, SSW condition and at different replacement levels.

2) To study the influence of RFA with different replacement levels for NFA on the fresh and hardened properties of concrete.

RAC mixes are produced with 20, 40, 60 and 100% RCA as replacements for NCA. In all the mixes, RCA is used in all the four moisture conditions. The RAC mixes are produced by replacing NFA with RFA at 20, 40, 60 and 100% replacement level. Slump and compaction factor tests are conducted to assess the fresh properties of concrete mix. Compression tests are performed on 150 mm cubes to determine the 7 days and 28 days compressive strength along with split tensile test on cylinder specimens.

A. Materials

43 grade Ordinary Portland cement (OPC) is used throughout the experimental studies. The concrete waste is collected from the dump yard located at city outskirts and is processed to recover RCA and RFA. The Characteristics of the materials used in the experimental study are given in Table III.

B. Mix Design

The Control Mix (CM) with NCA and NFA is designed as per IS 12062:2009 for target strength of 20 MPa. The mix proportion corresponds 1:1.96:3.26 (Cement: Fine Aggregate: Coarse Aggregate) with water-cement ratio as 0.55. Two fractions of coarse aggregates are used in the mix design viz., 60% is passing 20 mm and retained on 10mm sieve and the remaining 40 % is passing 10 mm and retained on 4.75mm IS sieve.

TABLE III: PHYSICAL CHARACTERISTICS OF MATERIALS

Cement			43 grade	
1	Specific Gravity		3.04	
2	Fineness (%)		6.43	
3	Standard Consistency (%)		31	
4	Initial Setting Time (min)		60	
5	Final Setting Time (min)		210	
6	28 Day Compressive Strength(MPa)		46.33	
Fine Aggregate			**NFA**	**RFA**
1	Specific Gravity		2.61	2.31
2	Fineness Modulus		2.705	2.597
3	Compacted Bulk Density (kg/m^3)		1601.08	1584.4
4	Bulking (%)		37.5	56.92
Coarse Aggregate			**NCA**	**RCA**
1	Specific Gravity (< 20mm >10mm)		2.66	2.46
2	Water Absorption (%) (< 20mm >10mm)		0.7	2.89
3	Crushing Value (%) (< 12.5mm >10mm)		25	31
4	Impact Value (%) (< 12.5mm >10mm)		22	31.37
5	Fineness Modulus		6.625	6.59
6	Compacted Bulk Density (kg/m^3)	<20mm, >10mm	1551	1432
		<10mm, > 4.75mm	1524	1193
7	Elongation Index (%) (20mm, >16mm; 10mm,> 6.3		17.27	12.23
8	Flakiness Index (%) (20mm, >16mm; 10mm, > 6.3)		14.27	11.2
9	Angularity Number	20mm, > 16mm	10.42	7.8
		10mm, > 6.3	12.62	11.21

IV. INFLUENCE OF MOISTURE CONDITIONS AND REPLACEMENT LEVELS OF RCA ON FRESH AND HARDENED PROPERTIES OF RAC

A. Mix Constituents

In all the mixes, cement, NFA and water content are maintained at the same level. Based on RCA replacement levels, NCA and RCA contents, are varied as per their specific gravities, so as to have the same yield as that of the control mix. The Mix constituents, for different RCA replacement levels are given in Table IV.

TABLE IV: MIX CONSTITUENTS (kg / m^3)

Contents in kgs	RCA Replacement levels				
	0%	20%	40%	60%	100%
Cement	350	350	350	350	350
NFA (Sand)	686	686	686	686	686
NCA (< 20, > 10)	685.8	548.64	411.48	274.32	0.0
NCA (< 10, > 4.75)	457.2	365.76	274.32	182.88	0.0
RCA (< 20, > 10)	0.0	126.18	252.37	353.72	630.93
RCA (< 10, > 4.75)	0.0	84.12	168.24	252.37	420.62
Water	192	192	192	192	192

B. Fresh Properties of Concrete Mix

The test results of twenty mix compositions with five different levels of RCA replacement (0, 20, 40, 60,100%) and with four different moisture conditions are listed in Table V. The influence of RCA replacement levels and moisture conditions of aggregates on the fresh properties of RAC mixes in terms of slump values is shown in Fig. 1. At any replacement level of RCA, slump is found to be lowest in RAC mix with coarse aggregates in AD condition and highest value in SSW condition. The slump is found to reduce with increase in RCA replacement levels. These observations with respect to slump are very well complimented by compaction factor test results.

TABLE V: SLUMP AND CF VALUE OF THE CONCRETE MIX

Mix Composition	AD		SSD		SW		SSW	
	Slump (mm)	CF	Slump (mm)	CF	Slump (mm)	CF	Slump (mm)	CF
Control Mix (0% RCA)	40	0.9	78	0.93	83	0.95	110	0.97
RAC with 20% RCA	20	0.87	45	0.92	78	0.94	97	0.96
RAC with 40% RCA	20	0.85	38	0.91	70	0.94	89	0.95
RAC with 60%RCA	0	0.81	24	0.89	64	0.93	78	0.94
RAC with 100%RCA	0	0.77	0	0.85	35	0.91	67	0.92

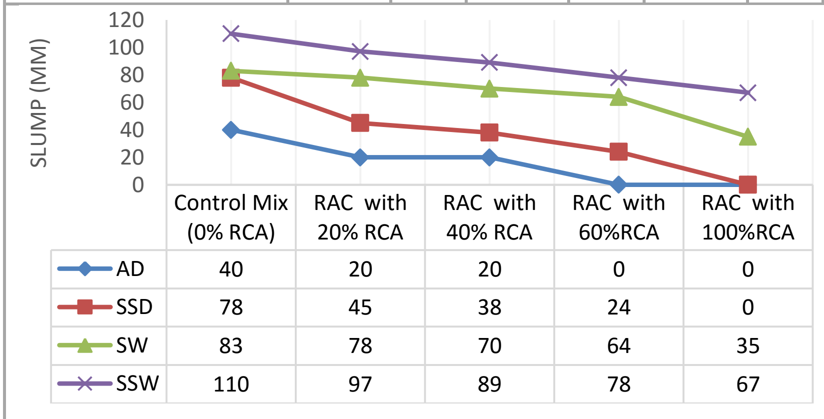


Fig.1: Slump Characteristics of RAC mixes

C. Strength Properties

Compressive Strength

For each mix composition, eight cube specimens are prepared, for each of the four types of moisture conditions of the aggregate. Four cubes are tested at the end of seven days and the other four at the end of 28 days. Test results for 7 and 28 days compressive strength of one hundred sixty cube specimens, with different mix compositions, are listed in Table VI.

TABLE VI: 7 AND 28 DAYS COMPRESSIVE STRENGTH RESULTS (MPa)

Mix Composition	AD		SSD		SW		SSW	
	7 days	*28 days*	*7 days*	*28 days*	*7 days*	*28 days*	*7 days*	*28 days*
Control Mix (0% RCA)	21	38	21	36	16	29	13	29
	21	38	20	40	17	26	13	22
	21	34	20	36	16	23	13	21
	21	34	22	35	13	25	14	24
RAC with 20% RCA	20	31	17	33	16	25	13	21
	21	32	18	24	15	26	13	27
	19	34	17	28	15	27	15	23
	19	36	17	30	14	26	14	28
RAC with 40% RCA	21	29	16	27	16	27	15	24
	20	26	16	27	16	27	13	23
	21	33	17	27	17	27	12	24
	16	25	16	21	16	21	14	20
RAC with 60% RCA	19	38	18	19	13	29	13	25
	20	38	17	26	17	21	14	23
	19	37	18	31	15	23	13	16
	20	33	17	29	13	25	13	25
RAC with 100% RCA	18	34	18	35	16	26	15	24
	20	35	19	33	16	26	15	25
	16	31	19	31	15	26	16	25
	18	33	19	31	15	24	15	25

Correlation between 7 and 28 days strength

Fig. 2 illustrates the scatter diagram between 7 and 28 days Compressive Strength. A high positive correlation is observed between them in all the mixes considered in this study. This indicates that, increase in 7 days strength of concrete mixes, also results, in a corresponding increase in the 28 days strength.

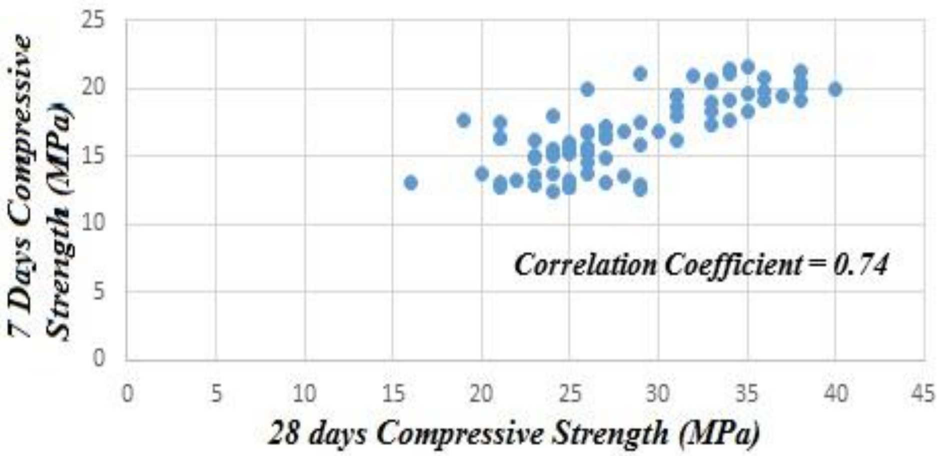


Fig.2: Correlation between 7 and 28 days Compressive Strength

Ratio of 7 days and 28 days strength

This aspect with respect to RAC mixes with different RCA contents is examined and results are tabulated in Table VII. The tabulated values are based on the average values of strengths listed in Table VI

TABLE VII: RATIO OF 28 DAYS TO 7 DAYS STRENGTH

Mix Composition	AD			SSD			SW			SSW		
	$\square_{7}$	$\square_{28}$	$\frac{\mu_{28}}{\mu_7}$	$\square_{7}$	$\square_{28}$	$\frac{\mu_{28}}{\mu_7}$	$\square_{7}$	$\square_{28}$	$\frac{\mu_{28}}{\mu_7}$	$\square_{7}$	$\square_{28}$	$\frac{\mu_{28}}{\mu_7}$
Control Mix (0% RCA)	21.0	36.0	1.7	20.8	36.8	1.8	15.5	25.8	1.7	13.3	24.0	1.8
RAC with 20% RCA	19.8	33.3	1.7	17.3	28.8	1.7	15.0	26.0	1.7	13.8	24.8	1.8
RAC with 40% RCA	19.5	28.3	1.5	16.3	25.5	1.6	16.3	25.5	1.6	13.5	22.8	1.7
RAC with 60% RCA	19.5	36.5	1.9	17.5	26.3	1.5	14.5	24.5	1.7	13.3	22.3	1.7
RAC with 100% RCA	18.0	33.3	1.9	18.8	32.5	1.7	15.5	25.5	1.6	15.3	24.8	1.6
Descriptive Statistics of $\frac{\mu_{28}}{\mu_7}$			μ = 1.68				σ = 0.11					

i. It is observed that $\frac{\mu_{28}}{\mu_7}$,is found to be in the range of 1.5 to 1.9 and in most of the cases as 1.7. The descriptive statistics indicates a mean value of 1.68 with a very small standard deviation = 0.11. Hence, the ratio of, 7 days and 28 days strength of RAC mixes with different RCA content and with different surface conditions can be treated as a deterministic quantity, being approximately equal to 0.6.

ii. This observation is in compliance with the general observation pertaining to strength of conventional concrete mixes that," *the ratio of 28-day to seven-day strength usually lies between 1.3 and 1.7 and generally is less than 1.5*". In other words the seven-day strength is normally in the range of "60% to 75% of the 28-day strength and is found usually to be above 65%".

Correlation between density and 28 days compressive strength

The scatter diagram of experimental results of eighty cube specimens for density and 28 days compressive strength is shown in Fig.3. The correlation coefficient = 0.15, indicates a very small positive correlation between density and 28 days compressive strength of concrete mixes. Hence, it is concluded that, density alone, cannot be considered as the single most important factor, to estimate the strength aspect of RAC mixes.

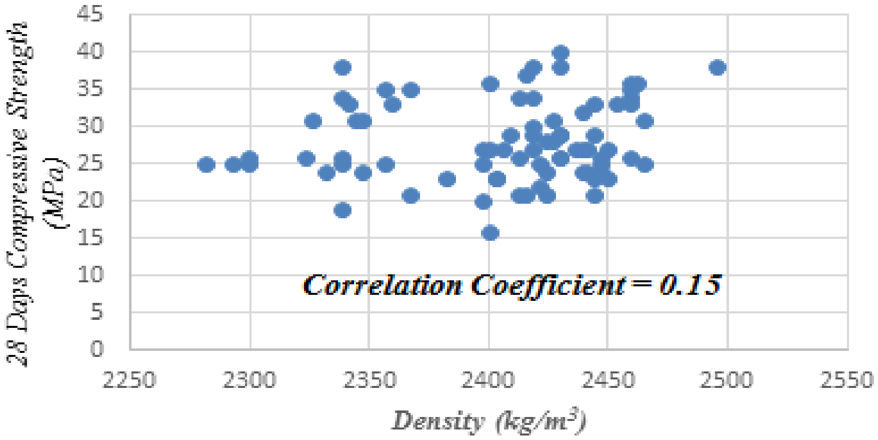


Fig.3: Correlation between Density and Compressive Strength

Normalized values of 28 days Compressive Strength

The individual test results of all the five mix compositions and four different moisture conditions are normalized, with respect to the mean value of test results for control mix with moisture condition of aggregates as AD. These are listed in Table VIII and Fig.4 represents bar charts and trend lines. It is observed that, for any given moisture condition of the aggregate, the compressive strength decreases as the level of RCA replacement increases, and more so in SSD condition.

TABLE VIII: NORMALIZED VALUES OF 28 DAYS COMPRESSIVE STRENGTH

Mix Composition	μ_{DRY}	*Normalized values = Test Results / $\mu_{DRY\ 0\%RCA}$*			
		AD	**SSD**	**SW**	**SSW**
Control Mix(0% RCA)	36.0	1.06	1.01	0.82	0.79
		1.05	1.10	0.73	0.61
		0.94	1.01	0.63	0.58
		0.95	0.97	0.69	0.68
RAC with 20% RCA	33.3	0.87	0.90	0.69	0.57
		0.88	0.66	0.72	0.75
		0.95	0.78	0.76	0.64
		1.00	0.83	0.71	0.77
RAC with 40% RCA	28.3	0.82	0.76	0.76	0.66
		0.73	0.74	0.74	0.62
		0.90	0.74	0.74	0.65
		0.69	0.57	0.57	0.55
RAC with 60% RCA	36.5	1.05	0.54	0.80	0.69
		1.04	0.72	0.58	0.64
		1.03	0.85	0.63	0.45
		0.91	0.82	0.69	0.70
RAC with 100% RCA	33.3	0.94	0.96	0.71	0.67
		0.96	0.92	0.73	0.69
		0.85	0.87	0.72	0.69
		0.91	0.86	0.65	0.69

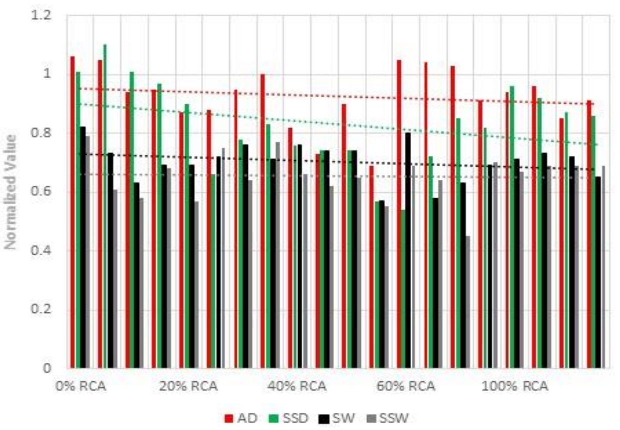


Fig.4: Graph between Normalized value Vs Percentage replacement of RCA

Descriptive Statistics

The descriptive statistical parameters of normalized values of 28 days compressive strength as listed in Table VIII, are reported in Table IX. At all replacement levels, the AD condition, yields maximum compressive strength, followed by SSD (-11%), SW (-25%) and SSW (-30%) conditions. This is possible, as in AD condition, moisture in aggregates, is partly below their absorption value, causing reduction of free water content

TABLE IX: DESCRIPTIVE STATISTICS

Statistical Parameters	Surface Condition of Aggregates			
	AD	**SSD**	**SW**	**SSW**
Mean	0.93	0.83	0.70	0.65
Standard Deviation	0.10	***0.15***	0.07	0.08

Empirical equation for Normalized value

The mean of normalized values listed in Table VIII are listed in Table X, along with the mean values obtained from descriptive statistical analysis which are normalized with respect to AD condition.

TABLE X: NORMALIZED MEAN VALUES

Mix Composition	AD		SSD		SW		SSW	
	μ test results	μ_{stats}	μ test results	μ_{stats}	μ test results	μ_{stats}	μ test results	μ_{stats}
0 % RCA	1.00	1.00	1.02	0.90	0.72	0.8	0.67	0.7
20% RCA	0.93		0.79		0.72		0.68	

40% RCA	0.79		0.70		0.70		0.62	
60% RCA	1.01		0.73		0.68		0.62	
100% RCA	0.92		0.90		0.70		0.69	

The standard deviation σ is selected as 0.15, since, this corresponds to the highest value in Table IX. With these statistical values, the following empirical equation is proposed, to compute the strength of concrete mixes, made with different levels of RCA replacement and with different moisture conditions.

$$f_N = k - \frac{0.15\ x\ RCA(\%)}{100} \quad \text{.....................} \ (1)$$

k = reduction factor plotted along Y- axis, for different surface conditions of coarse aggregates along X axis, as shown in the Fig.5, RCA (%) – Replacement level, f_N = Normalized value with respect to AD condition.

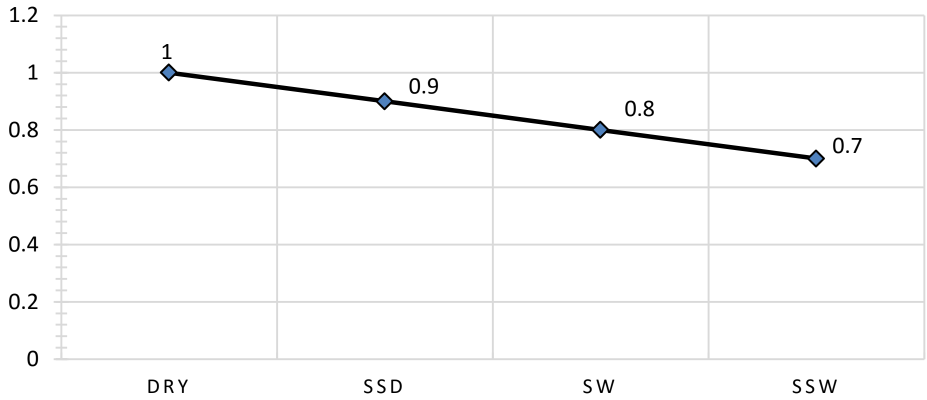


Fig.5: *k* values for different surface conditions of coarse aggregates

The mean of normalized values listed in Table X, along with the trend line based on linear hypothesis and the computed values as per the empirical equation are shown in the Fig.6. The equation (1) is found to capture the quintessential influence of prime variants, such as, RCA replacement levels and moisture conditions of aggregates on compressive strength of RAC mixes.

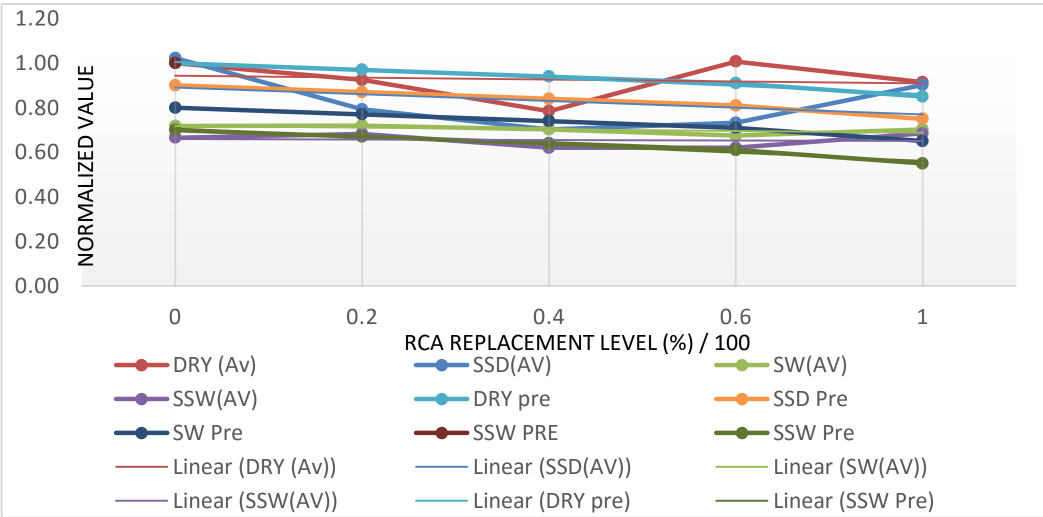


Fig.6: Comparison of Experimental Trend Lines with Computed values

Split Tensile Strength

Test results, of sixty cylinder specimens, with different mix compositions and surface conditions of aggregates are listed in Table XI. Experimental results indicate that the split tensile strength is relatively insensitive to RCA content in RAC mixes. Fig.7 represents the graph between normalized tensile strength and moisture condition of aggregate. The dry surface condition yields the highest value and shows a linear decreasing trend towards the lowest value for SSW condition. The high value of R^2, as a statistical measure, indicates the closeness of the data fitted to linear trend.

TABLE XI: 28 DAYS SPLIT TENSILE STRENGTH (MPA)

Mix Composition	AD		SSD		SW		SSW	
	Test Results	μ	*Test Results*	μ	*Test Results*	μ	*Test Results*	μ
Control Mix (0% RCA)	2.36	2.30	2.21	2.27	1.61	1.86	1.28	1.45
	2.24		2.35		2.09		1.43	
	2.32		2.26		1.88		1.64	
RAC with 20% RCA	2.35	2.30	2.12	2.20	1.77	1.80	1.43	1.43
	2.29		2.22		1.84		1.53	
	2.26		2.26		1.8		1.32	
RAC with 40% RCA	2.18	2.30	2.32	2.22	1.8	1.75	1.44	1.46
	2.42		2.34		1.84		1.59	
	2.29		2		1.6		1.36	
RAC with 60% RCA	2.69	2.58	2.26	2.29	1.7	1.78	1.7	1.54
	2.45		2.29		1.78		1.49	
	2.61		2.32		1.87		1.42	
RAC with 100% RCA	2.36	2.36	2.26	2.35	1.92	1.89	1.7	1.65
	2.34		2.41		1.91		1.64	
	2.37		2.38		1.84		1.61	
μ_{grand}		2.37		2.27		1.82		1.51
Normalized with respect to dry condition		1.00		0.96		0.77		0.64

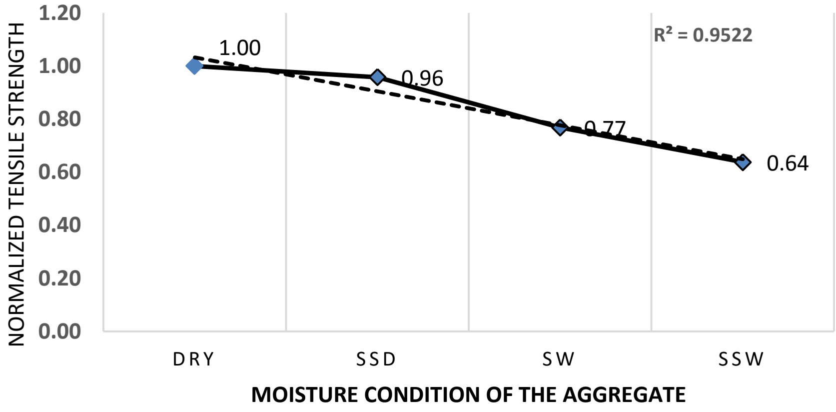


Fig.7: Graph between normalized tensile strength and moisture condition of the aggregate

Ratio of Split tensile to Compressive Strength

The ratio between, mean values of split tensile strength and compressive strength for different mix compositions with different surface conditions of coarse aggregates are shown in Table XII

TABLE XII: RATIO OF SPLIT TENSILE TO COMPRESSIVE STRENGTH

Mix Composition	μ_{DRY}			μ_{SSD}			μ_{SW}			μ_{SSW}		
	σc	σt	σt / σc	σc	σt	σt / σc	σc	σt	σt / σc	σc	σt	σt / σc
Control Mix (0% RCA)	36.0	2.3	0.06	36.8	2.2	0.06	25.9	1.86	0.07	23.9	1.45	0.06
RAC with 20% RCA	33.4	2.3	0.07	28.6	2.2	0.08	26.0	1.8	0.07	24.6	1.43	0.06
RAC with 40% RCA	28.3	2.3	0.08	25.3	2.2	0.09	25.3	1.75	0.07	22.4	1.46	0.07
RAC with 60% RCA	36.3	2.5	0.07	26.3	2.2	0.09	24.3	1.78	0.07	22.4	1.54	0.07
RAC with 100% RCA	33.0	2.3	0.07	32.5	2.3	0.07	25.4	1.89	0.07	24.7	1.65	0.07

The mean value of the ratio of tensile to compressive strength is found to be in the range of 0.07 with a very small standard deviation = 0.01. In customary words, this can be stated as; *the split tensile strength is approximately equal to (1/14) th of compressive strength*.

V. TEST RESULTS OF CONCRETE MIXES WITH RFA

Mix Constituents

The concrete mixes are produced with 20, 40, 60 and 100% RFA, as replacements for NFA. The weight of individual constituents of mixes is indicated in Table XIII.

TABLE XIII: MIX CONSTITUENTS WITH REPLACEMENT OF RFA

Contents in kgs	RFA Replacement levels				
	0%	20%	40%	60%	100%
Cement	350	350	350	350	350
Sand (NFA)	686	550.4	411.6	274.4	0
RFA	0	119.32	241.47	362.20	603.68
NCA (< 20, > 10)	685.8	685.8	685.8	685.8	685.8
NCA (< 10, > 4.75)	457.2	457.2	457.2	457.2	457.2
Water	192	192	192	192	192

Fresh Properties

Slump and Compaction factors are determined for all the five mix variants with different levels of RFA replacement for NFA. These are listed in Table XIV. Fig.8 represents the reduction of slump with % increase in RFA content.

TABLE XIV: WORKABILITY MEASURES OF CONCRETE MIX

Mix Composition	**Slump (mm)**	**CF**
Control Mix (0% RFA)	78	0.934
Mix with 20% RFA	35	0.898
Mix with 40% RFA	18	0.856
Mix with 60%RFA	5	0.804
Mix with 100%RFA	0	0.733

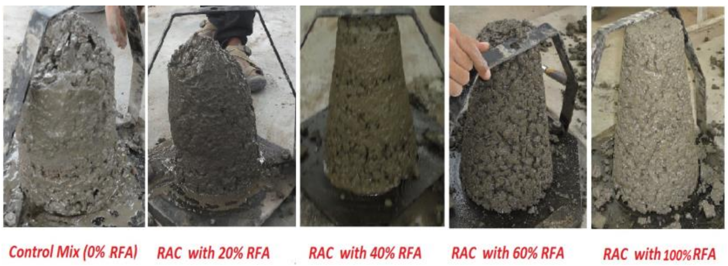


Fig.8: Reduction of slump with % increase in RFA content.

It is observed that, slump value decreases as the percentage replacement of RFA increases and reaches zero for 100% replacement. This may be attributed to porous nature and greater moisture absorption property of RFA, due to the presence of a thin layer of cement paste on the surface and the possibility of similar size particles with cement paste only. This can result in reduced water content so as to impair the mobility of the mix.

Strength Properties

Compressive and split tensile Strength

Test results pertaining to forty cube specimens and fifteen cylinder specimens with different mix compositions are listed in Table XV.

Correlation between 7 and 28 days compressive strength

The scatter diagram of experimental results for 7 and 28 days compressive strength is shown in Fig.9. The correlation coefficient ≈ 0.9, indicates that they have nearly a perfect positive correlation. The value of R^2 = 0.78, indicates that the linear regression line, is a fairly accurate representation of correlation between them.

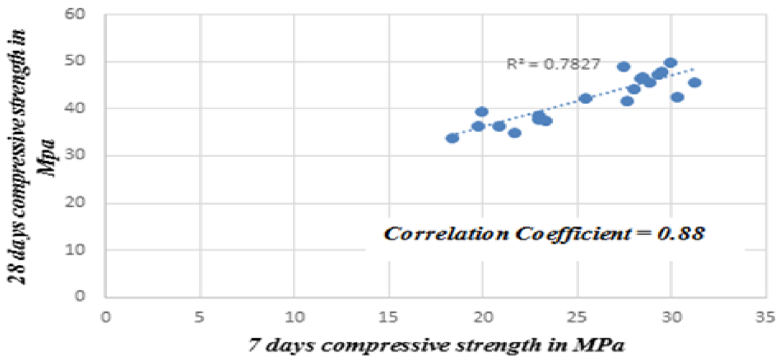


Fig. 9 Scatter Diagram

TABLE XV: STRENGTH PROPERTIES OF CONCRETE MIXES WITH RFA

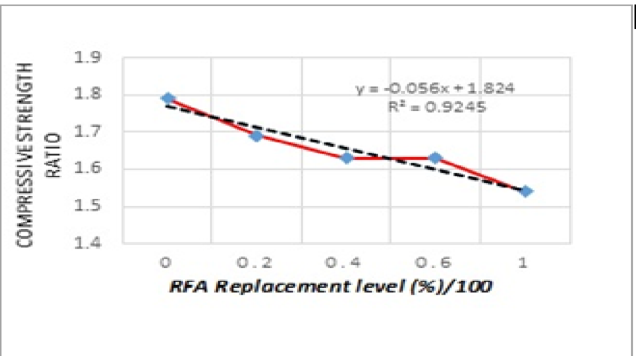
Mix Composition	Density kg/m^3	7days Compressive Strength (MPa)	28 days Compressive Strength (MPa)	Split Tensile Strength (MPa)
Control Mix (0% RCA)	2459	20.81	36.38	2.21
	2420	19.93	39.59	2.35
	2400	19.74	36.48	2.26
	2459	21.61	35.11	-
RAC with 20% RFA	2382	18.32	34.03	2.02
	2412	23.25	37.44	2.46
	2453	22.88	37.85	1.96
	2486	22.92	38.60	-
RAC with 40% RFA	2400	29.41	48.08	2.38
	2474	28.34	46.63	2.26
	2462	31.14	45.75	2.50
	2441	27.37	48.95	-
RAC with 60% RFA	2412	28.39	46.91	2.38
	2382	29.91	49.91	2.83
	2397	28.79	45.60	2.58
	2415	29.24	47.45	-
RAC with 100% RFA	2382	25.37	42.28	2.40
	2353	27.56	41.82	2.49
	2388	30.26	42.60	2.31
	2356	27.98	44.32	-

3) Empirical equation for the ratio of strengths at 7 and 28 days for different RFA replacement levels

This is obtained based on the average values of 7 and 28 days compressive strength of different RAC mixes listed in Table XV. The average values of the ratio, f28 / f7, for different RFA replacement levels along with linear regression plot are indicated in Table XVI. The very high value of R2, indicates that, the linear regression equation, is a fairly accurate representation of the ratio of the variation of strengths at 7 and 28 days, for different RFA replacement levels

TABLE XVI: (f28 / f7) FOR RFA REPLACEMENT LEVELS

RFA Replacement Levels (%) /100	f_{28} / f_7
0	1.79
0.2	1.69
0.4	1.63
0.6	1.63
1	1.54
Descriptive Statistics	
Mean	1.656
Standard Deviation	0.06861



Using the mean and standard deviation as listed in Table XVI, following equation is proposed to yield a conservative estimate of the ratio between 28 and 7 days strength for different RFA replacement levels.

$$\frac{f_{28}}{f_7} = 1.65 - 0.07\,\frac{RFA(\%)}{100} \text{ .... (2)}$$

The performance of the equation (2), in terms of its estimate, vis-à-vis, the experimental and the trend line is shown in Fig.10 (Series 1: Experimental Values, Series 2: Predicted from equation (2).

Fig.10: (f28 / f7) Estimate

4) Normalized relationship between 28 days compressive strength and % replacement level of RFA.

The average values of test results in Table XV, for each of the mix variants are normalized with respect to the average value for the control mix with 0% RFA. It is interesting to observe that, at all levels of RFA replacement, concrete mixes possess higher 28 days strength fN 28 than the control mix. The trend in variation is described through linear regression as well as through a second order polynomial as shown in Fig.11.

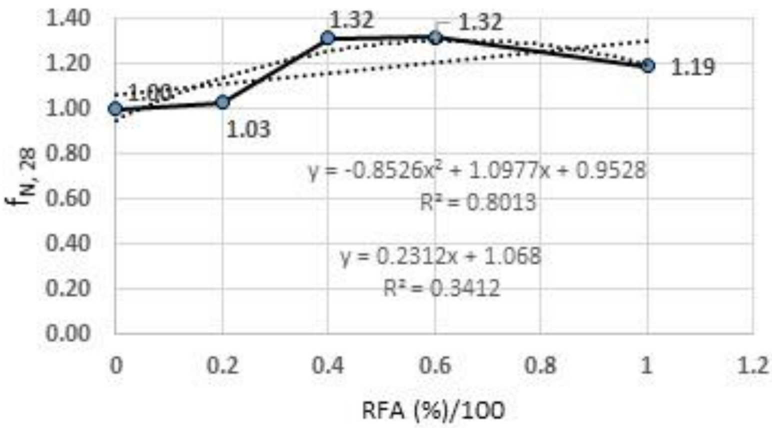


Fig.11: Trend Lines

The high value for R^2, suggests that the variation is best described through a second order polynomial as

$$f_{N\,28} = 0.95 + 1.1\,\frac{RFA(\%)}{100} - 0.85\left(\frac{RFA(\%)}{100}\right)^2$$

The linear regression equation can be formulated as: $f_{N\,28} = 1.07 + 0.23\,\frac{RFA(\%)}{100}$ **.......................(3)**

The Comparison of f_N 28 values, computed from both linear and second order polynomial regression equations are summarized in the Table XVII. Since the % difference is very minimal, it is concluded that the linear equation is quite adequate to compute f_N 28 for different RFA replacement levels for a material like concrete.

TABLE XVII: % DIFFERENCE IN THE COMPUTED VALUES OF 28 DAYS COMPRESSIVE STRENGTH

RFA Replacement Level (%)	Second Order Polynomial	Linear	% Difference
0	0.95	1.07	12.63
20	1.14	1.12	-1.76
40	1.25	1.16	-7.34
60	1.30	1.21	-7.36
100	1.20	1.30	8.33

VI. INFERENCES

i. The test results with respect to strength of RAC mixes in the aforementioned experimental works, indicate that, both RCA and RFA can be used even up to 100% as replacement for natural materials.

ii. The slump characteristics of RAC mixes with RCA is shown in Fig.1, from which it is observed, that under SSD condition, the target slump of 75 mm is not attained in all RAC mixes. Similarly, Slump and CF values for all the mix variants with different levels of RFA are listed in Table XIV. It is observed that the target slump of 75 mm is not attained in all mixes with RFA content.

iii. Since quantum of concrete waste generation is obviously much less than concrete requirement in construction sector, the possible replacement levels are fixed as 20% RCA and RFA. Test results for such replacement levels, indicate that, RAC possesses very similar properties of NAC, except for workability requirements. This is addressed in the following part of the experimental work.

VII. ENHANCEMENT OF WORKABILITY OF RAC USING SUPERPLASTICIZER

This part of the experimental study deals with the utilization of RCA and RFA at 20% replacement levels along with superplasticizers (SP), so as to improve the fresh properties of RAC mixes. Both NCA and RCA are used in SSD condition. Fresh properties are assessed on concrete mixes with 0.4%, 0.6% and 0.8% dosage of SP. It is observed that, in mixes with 20% recycled content, either as RCA or RFA or both, the target slump value is achieved with 0.8% SP content. These are listed in Table XVIII. The improvement of workability with addition of SP is shown in Fig.12.

TABLE XVIII: SLUMP AND CF VALUES OF RAC MIXES WITH SP

Mix Designation	Workability	
	Slump (mm)	Compaction Factor
CM with 0%SP	80	0.923
20 RCA with 0.8%SP	100	0.902
20 RFA with 0.8%SP	115	0.933
20(RCA+RFA) with 0.8%SP	108	0.926

Fig.12: Enhancement of Workability with SP

VIII. CONCLUSIONS

i. At any replacement level of RCA, Slump is found to be lowest in RAC mix with coarse aggregates in AD condition and highest value in SSW condition. The slump is found to reduce with increase in RCA replacement levels.

ii. At all RCA replacement levels, the AD condition, yields maximum compressive strength, followed by SSD (-11%), SW (-25%) and SSW (-30%) conditions. This is possible, as in AD condition, moisture in aggregates, is partly below their absorption value, causing reduction of free water content.

iii. The ratio of 7 days and 28 days strength of RAC mixes, with different RCA content and with different surface conditions, can be treated as a deterministic quantity, being approximately equal to 0.6.

iv. The empirical equation (1) proposed, to compute the strength of RAC mixes, made with different levels of RCA replacement and with different moisture conditions can yield acceptable result.

v. Slump value decreases as the percentage replacement of RFA increases and reaches zero for 100% replacement.

vi. At all levels of RFA replacement, concrete mixes, possess, higher 28 days strength, than the mix with NFA. The normalized value with respect to control mix with 0% RFA, can be computed from the proposed equation (3).

vii. RAC mixes with 20% RCA or RFA with 0.8% SP can meet the requirements of properties of normal grade concrete, both in fresh and hardened state. Considering the quantum of concrete waste expected to be available for recycling, it seems viable, to limit usage of RCA and RFA to the extent of 20% in RAC mixes, even though higher replacement levels are possible.

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