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Correlation of strength development of RCA in quaternary blended cementitious system

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Abstract. Recycled concrete aggregate (RCA) obtained from demolished structures can be used for concrete making, and is established as a promising material in the field of construction. In the present study, the effect of RCA on the mechanical properties of different strength concretes admixed with Micro silica, fly ash and nano-silica as a part replacement to cement was considered. The quantity of cement varied from 350-690 kg/m^3 with the additions of Fly ash at 0, 20 and 30%, micro silica at 0, 5, 10 and 15%, and Nano silica at 0, 1, 2, 3 and 4%. The samples were cured for 7, 28, 56 and 90 days and tested for Compressive strength. Split tensile and flexural strength evaluation was carried out on samples which have been cured for 28 days. The workability of fresh concrete was determined. With the help of the tested database, equations for prediction of compressive strength using modified Bolomey's equation were generated. Equations for the flexural strength and split tensile strengths based on compressive strength were developed and compared with equations available in the literature.

Keywords: Bolomey's equation; Construction & Demolition (C&D) waste; fly ash (FA); mechanical properties; Micro silica (SF); Nano silica (NSF)

1. Introduction

Cement is the most widely used construction material. To meet the demand for housing and infrastructure, a considerable amount of cement is produced which in turn affects the environment. Reducing cement consumption and also maintaining sustainable development is the chief concern in the development of the nation. The concrete industry is the largest consumer of natural resources such as sand and gravel. It is a part of the internationally supported strategy to meet sustainable development and environmental goals. Due to this the construction industry has to progressively choose supplementary cementing materials as partial replacements to cement and C&D waste for aggregates, respectively. Fraay *et al*. (1989) stated that the strength of concrete

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mixed with fly ash showed poor performance at a lesser age. Hence, researchers are trying to develop Ternary or Quaternary Blended Concretes by adding a super fine mineral admixture like micro silica, and Nano silica. It has been observed that the properties are found to increase as ageing takes place in case of fly ash whereas the effect of micro silica and Nano silica remain steady.

In the coming years, a large number of structures are to be renovated or demolished, and for this, there is a large-scale requirement of natural aggregate in the construction. To lessen the depletion of natural resources, vast amounts of C&D Wastes are to be utilized for sustainable development. Tam *et al*. (2007) proposed to use recycled concrete aggregate (RCA) in the mix proportioning and given various ways of effective mixing in the concrete. Knaack and Kurama (2013) found that the water absorption and deleterious matter present in the recycled aggregate govern the strength properties of concrete and suggested direct volume replacement is best suited for the RCA concrete mixtures.

The physical properties of the RCA are inferior to the natural aggregates (NA). Padmini *et al*. (2009) stated that the strength of RCA depends on the amount of the adhered mortar attached to the original aggregate and the strength of the parent concrete. In fresh concrete, Yong and Teo (2009) observed that the use of dry RCA reduces its workability due to its more water absorption which can be rectified by using RCA in a saturated condition. Tangchirapat *et al*. (2008) reported the compressive strength of the recycled aggregate concrete decreases up to 6% but, splitting tensile strength of RCA was indifferent to natural aggregates. Etxeberria *et al*. (2007) concluded that there is a decrease in compressive strength due to recycled aggregate. Rao *et al*. (2014) tested the ternary mixture of fly ash and silica fume by partially replacing the cement and reported improved compressive strength while the workability was decreased. Palaskar and Vesmawala (2020) presented the outcomes in terms of mechanical and micro structural characteristics of binary and ternary concrete when exposed to elevated temperature and reported that compressive strength increases up to 400°C; beyond which it decreases and under the SEM it is observed that a sizeable quantity of uneven rose bush like structures. Mazloom *et al*. (2018) have studied the effect of different types of superplasticizers on the compressive strength and flow properties of normal and Self Compacting Concrete utilizing two percentages of silica fume and found poly-carboxylic-ether based SP has showed better workability and strength gain compared to others. Pedro *et al*. (2018) investigated the possibility of producing high-performance concrete (HPC) with both fine and coarse RCA to produce five classes of HPC. Topcu and Sengel (2004) had reported lower workability, strength and higher water absorption when RCA exceeds 30%. Chandra Paul *et al*. (2013) reported that RCA replacement up to 30% of NA had not shown any significant difference in strength and stiffness compared to concrete with natural aggregates, while RCA at 100% replacement had shown reduced strength and stiffness. Durability tests also indicated similar performance, but an increased creep for 30% RCA is significant, which should be also considered in the structural design.

The major problem of RCA, from literature, is strength reduction and high water absorption compared to conventional concrete. All the reported results are with normal grade concrete and mostly with binary blending; limited research was done in the usage of recycled aggregate in high strength concrete with quaternary blending.

1.1 Objectives

It is observed that Bolomey’s equation can be utilized with a little modification for the compressive strength evaluation of recycled aggregate concrete with admixtures. Further, the correlations incorporating flexure and split tensile strength analysis can be done once the concrete strength is predicted. Hence, the study focuses on the influence of the RCA on compressive, flexural, and splitting tensile strength of quaternary blended concrete. The objective of the study is to use modified Bolomey's equation for the prediction of compressive strength, and later the same to be utilized for the determination of other mechanical properties of RCA concrete. The adopted equation formulations are similar to general expressions used but with correction factors for RCA replacement ratio. The proposed expressions have been analyzed with the Pearson correlation coefficient (r). Finally, these equations are compared with those proposed by renowned researchers using the Mean, Std. Dev and CoV.

2. Materials used

2.1 Cement

Ordinary Portland Cement (OPC) 53 grade confirming to Indian standards IS:12269 (2013) was used. The properties of the cementitious materials used for preparing the samples are given in Table 1.

2.2 Recycled coarse aggregate

Concrete material from a demolished structure of 5-10 years old was broken into small pieces with the help of hammers and drilling machine. The foreign matter was sorted out, and later, they were crushed in the lab using a jaw crusher and sieved using 4.75 mm IS sieve to remove the finer particles. The crushed aggregates were washed and dried. The material properties are presented in

Table 1 Physical properties and chemical composition of materials

Properties		Portland cement	Fly ash (FA)*	Micro silica (SF)*	Nano silica (NSF)*
Chemical (%)	CaO	63.4	3.9	0.2	-
	SiO_2	20.1	46.3	95.9	> 99.8*
	Al_2O_3	4.1	28.5	0.3	-
	Fe_2O_3	3.3	18.5	0.3	-
	MgO	3.6	1.8	0.4	-
	Na_2O	0.2	0.2	0.05	-
	K_2O	0.4	0.6	0.6	-
	SO_3	2.1	0.2	0.2	-
	LOI	2.4	2.3	1.5	-
Physical (%)	Average primary particle size	28.2 μm	27.3 μm	150 nm	12 nm
	Specific gravity	3.15	2.5	2.2	2.2

* Information provided by the supplier

Table 2 Summary of physical properties of aoarse Aggregate

Aggregates	Dry rodded density (kg/l)	Water absorption%	Impact strength %	Los Angeles abrasion value %	Aggregate crushing value %	Voids %	Specific gravity	Fineness modulus
NCA	1.47	1.25	31	27	28	42	2.66	6.98
RCA	1.38	2.71	26	31	47	51	2.50	6.925

Table 2. The material was added to concrete in saturated surface dry (SSD) condition due to the higher water absorption. Sieve analysis was carried out as per IS:2386 (1963) for crushed RCA and NA. The particle shape analysis of recycled aggregate is flaky compared to NA.

2.3 Superplasticizer (*SP*)

Superplasticizing admixture is chloride free and based on sulphonated naphthalene polymers which conform to BS 5075, BS: EN 934-2 and with ASTM C494 as Type A and Type F.

Fig. 1 Concrete boulders from a demolished site

Fig. 2 Hammer crushed boulders

Fig. 3 Jaw crushed RCA material for use

Fig. 4 Cube compressive strength test set up

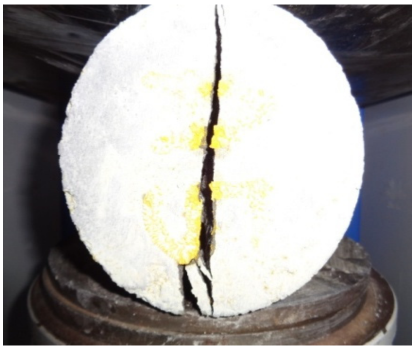

Fig. 5 Split tensile strength test set up

Fig. 6 Flexural strength test set up

2.4 Concrete mixes

The quantity of cement is varied from 350 to 690 kg/m^3, and the water/cement ratio changed from 0.27 to 0.55. The compressive strength is obtained for different ages and constants were obtained. All the mix proportions of concrete are designed by the Design of Experiments method using natural aggregates. The FA, SF and NSF materials were combined with OPC along with four levels of replacement of RCA to make the quaternary blended concrete. The FA, SF and NSF were replaced by direct volume approach while RCA was replaced by a direct weight method. The tests on concrete were conducted as per IS:516 (1959). Figs. 1-3 shows the process involved in making RCA.

3. Tests conducted on hardened concrete

Conventional concrete property vs. recycled concrete property was studied by compression strength test on 150-mm size cubes with curing duration of 7, 28 and 90 days. In one set, nine cubes were cast for each mix. The broken prisms were tested after 56 days under compression as per IS 516 and the obtained results of compressive strength are reduced by 5% as per code. The prisms of size 150 × 150 × 550 mm and cylinder of size 100 × 200mm were cast from the same batches to measure the flexural strength and splitting tensile strength respectively. Figs. 4-6 show the various test set up for various test carried out.

4. Experimental results and discussions

The workability of concrete is found to be decreasing with an increasing percentage of NSF, SF and RCA. This is because the density of NSF and SF is less than cement and RCA density is also less than Normal aggregates.

4.1 Comparisons for compressive strength of conventional concrete with RCA admixed concrete

4.1.1 Effect of RCA on concrete mixtures without any pozzolana

Fig. 7 depicts the compressive strength of concrete with varied cement content at approximately the same amount of water in the mix. It was observed that as the amount of cement is increased, the strengths are in the increasing trend. There is a uniform reduction in the strength when 25% of natural aggregates are replaced by RCA. But for 50% and 100% replacement levels, the strength vs. cement curves flattened as the cement content increased indicating more loss of strength at higher cement content (Fig. 7) which matches with the results of Ahmed (2014). The prediction of compressive strength of concrete can be done using a simplified equation, which depends upon the quantity of cement in one cubic metre volume.

The term 'X' represents total cement content in kg/m^3 and 'Y' indicates 28D cured concrete compressive strength

$$Y = 0.146 * X - 16.202 : R^2 = 94.72\% \quad --- \quad \text{without RCA} \quad (1)$$

$$Y = 0.1506 * X - 20.774 : R^2 = 95.78\% \quad --- \quad \text{with 25\% RCA} \quad (2)$$

$$Y = 0.1287 * X - 14.065 : R^2 = 92.42\% \quad --- \quad \text{with 50\% RCA} \quad (3)$$

$$Y = 0.1252 * X - 16.967 : R^2 = 93.51\% \quad --- \quad \text{with 100\% RCA} \quad (4)$$

4.1.2 Effect of w/c ratio on compressive strength of concrete

Fig. 8 shows the variation of compressive strength of concrete due to RCA and water content. As the water content increases, the strength decreases, which follows Abram's law.

The equations generated for compressive strength vs. w/c ratio are listed below.

$$Y = 16.945 * X^{-1.167} : R^2 = 89\% \quad --- \quad \text{without RCA} \quad (5)$$

$$Y = 15.07 * X^{-1.276} : R^2 = 97\% \quad --- \quad \text{with 25\% RCA} \quad (6)$$

$$Y = 14.755 * X^{-1.229} : R^2 = 98\% \quad --- \quad \text{with 50\% RCA} \quad (7)$$

$$Y = 12.147 * X^{-1.318} : R^2 = 98\% \quad --- \quad \text{with 100\% RCA} \quad (8)$$

where Y = compressive strength after 28D of curing in MPa and X = w/c ratio.

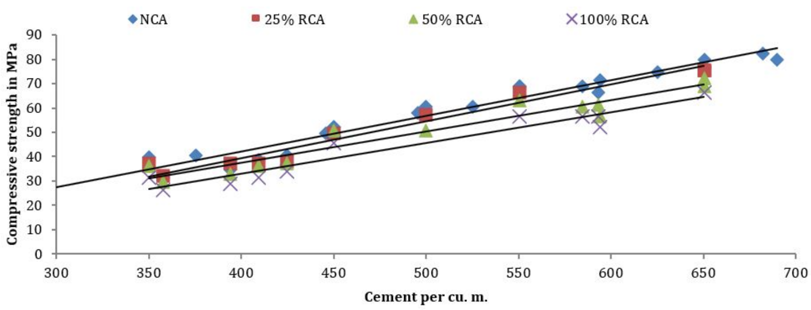

Fig. 7 Effect of cement content on natural and recycled aggregates concrete at 28 days of testing

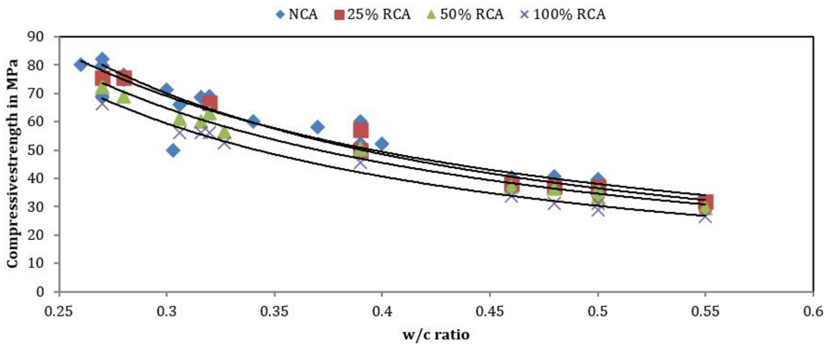

Fig. 8 Effect of water content on natural and recycled aggregates concrete at 28 days of testing

when RCA was replaced by weight to NA, it is observed that around 18% of the strength decreased at 100% replacement level while at 25% replacement had a little or no effect on the strength of concrete. At 50% replacement, the Compressive strength is around 10% less than that of control mix in all cases. It is also possible to improve this condition either by decreasing the w/c ratio or by adding pozzolans. When the replacement of RCA is above 25%, the strength of the mixture decreased in every stage and for the replacement of 50% RCA and at higher w/c, the variation in strength is less. The effect of replacement of RCA on low strength concretes is less compared to the strength of concretes at higher grades when it crosses 60 MPa. This may be due to the presence of mortar cover to RCA.

4.1.3 Effect of binary blending (FA, SF, NSF) of pozzolans on RCA content

Figs. 9, 10 and 11 show the compressive strength of binary blended RCA concrete mixtures with FA, SF and NSF.

4.1.4 Effect of fly ash

Fig. 9 shows the blending of the mixture with fly ash at 20% replacement of cement for all replacement levels of RCA. It is observed that strength is reducing due to the replacement of cement with FA, while replacement of RCA along with FA on strength reduction is marginal even for 50% RCA replacement.

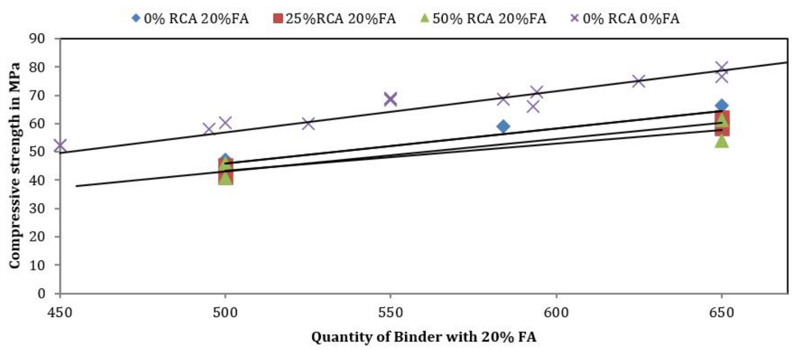

Fig. 9 Effect of fly ash on RCA content

$$Y = 0.1221 * X - 14.356 \quad \text{with} \quad R^2 = 88.81\% \quad --- \quad \text{without RCA} \qquad (9)$$

$$Y = 0.114 * X - 13.781 \quad \text{with} \quad R^2 = 94.25\% \quad --- \quad \text{with 25\% RCA} \qquad (10)$$

$$Y = 0.0958 * X - 4.5857 \quad \text{with} \quad R^2 = 83.93\% \quad --- \quad \text{with 50\% RCA} \qquad (11)$$

Where Y = compressive strength of 20% fly ash concrete after 28D of curing in MPa and X = total quantity of binder in kg/m^3.

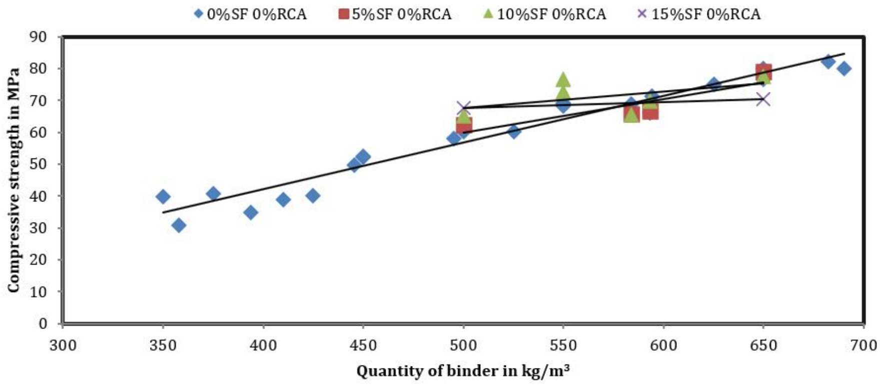

Fig. 10 Effect of Micro silica on cube compressive strength without RCA

Table 3 Effect of micro silica on RCA concrete with various binder quantities

Cement	SF	RCA	No of days cured concrete Compressive strength			
			7	28	56	90
500	5%	25%	35.33	51.77	57.65	62.90
650	5%	25%	47.07	74.16	77.69	88.20
593	5%	50%	*	60.21	*	*
500	5%	50%	34.35	51.73	54.04	59.23
650	5%	50%	52.35	70.67	73.00	83.85
593	5%	100%	*	59.28	*	*
500	10%	25%	36.82	55.41	56.75	64.11
650	10%	25%	46.22	69.95	76.77	82.80
593	10%	50%	*	59.29	*	*
500	10%	50%	34.11	52.38	53.34	60.13
650	10%	50%	43.54	67.08	72.14	80.70
593	10%	100%	*	53.33	*	*
500	15%	25%	33.35	54.34	56.01	62.41
650	15%	25%	46.62	65.98	75.83	80.20
500	15%	50%	35.22	50.02	53.62	58.20
650	15%	50%	43.42	64.35	71.26	80.20

* Not cast/tested

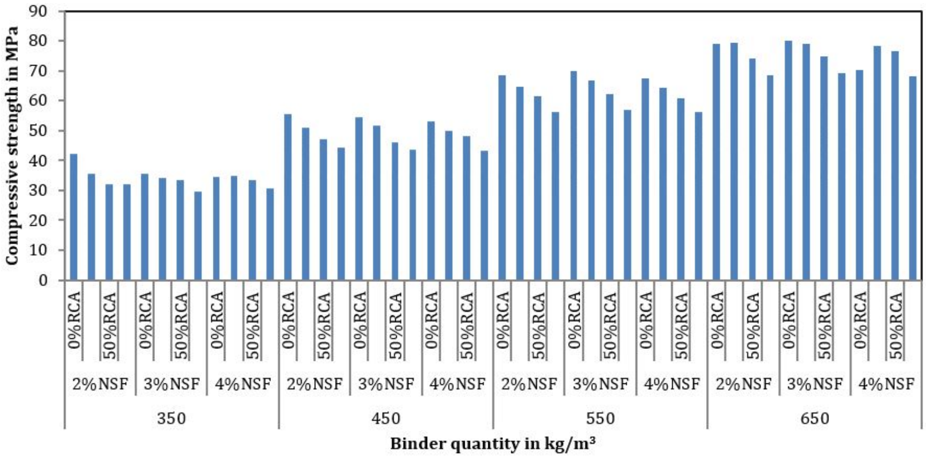

Fig. 11 Effect of Nano silica blending on RCA concrete cube strength

4.1.5 Effect of micro silica

Fig. 10 and Table 3 show the blending of cement with micro silica up to 15%. The important observation is that when cement is replaced with micro silica, the strength is on an increasing mode. However, when replacement is done along with RCA, the strength of 100% RCA concrete is not improving.

4.1.6 Effect of nano-silica

Fig. 11 shows the variation of the compressive strength of RCA concrete with NSF. The compressive strengths of all mixes improved due to the addition of NSF at all levels of addition. The addition had a positive impact on the strength improvement of RCA concrete also. The enhancement in strength is around 5 to 10% for RCA concrete. As the quantity of NSF present in the mixture is less and replacement is also not significant at higher ages, NSF has to be blended with SF and FA for economical purposes and for the improvement in properties at earlier ages.

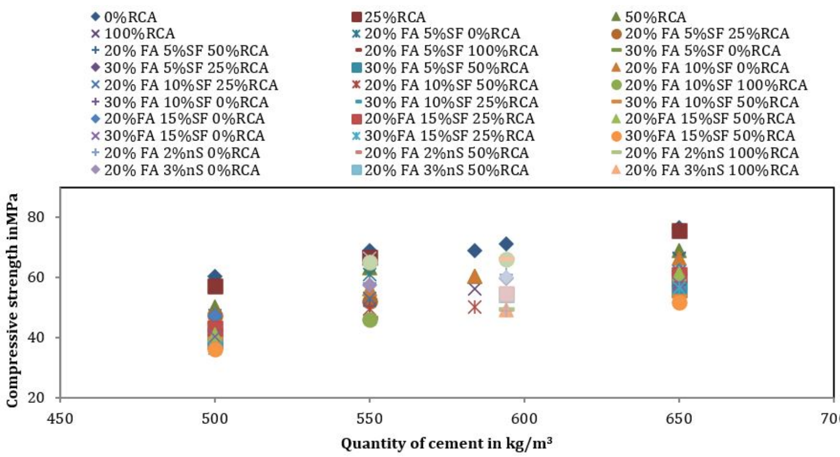

Fig. 12 Effect of the ternary blending of Pozzolans on RCA content

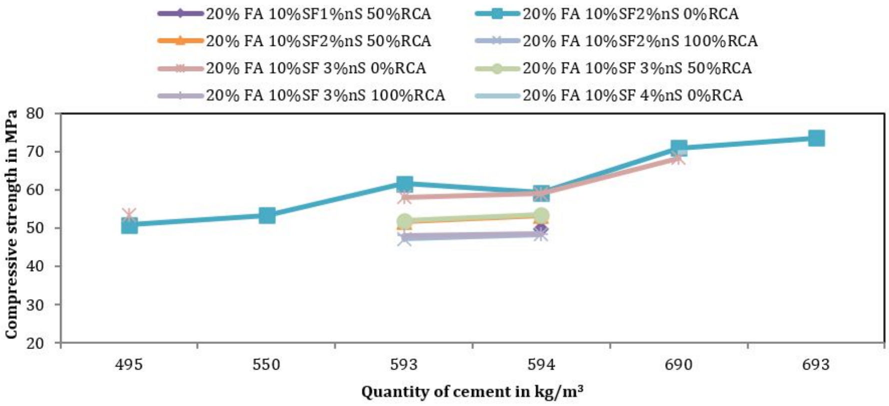

Fig. 13 Effect of the quaternary blending of FA, SF and NSF on RCA concrete

4.1.7 The ternary blending of pozzolans

In the triple blending of concrete, mixtures were prepared with a combination of FA+SF, FA+NSF and SF+NSF along with the four replacement levels of RCA. Fig. 12 shows the variation of strength due to the change in binder content at 28 days of testing. The blending of the pozzolans is improving the strengths than the control concrete with RCA. However, it is less than that of the control mix without admixtures. This is due to the replacement of cement by blended pozzolans as this had reduced the total cement quantity in a mix in the range of 22 to 35%.

4.1.8 The quaternary blending of pozzolans

Fig. 13 shows the quaternary blending of concrete mixtures (both NA and RCA) prepared with a combination of FA, SF, and NSF. The presence of pozzolana in 100% of Recycled aggregate (RA) concrete had given higher strength than pure RA concrete indicating that pozzolans contribute to higher strength even in Recycled aggregate concrete. It is clear from Fig. 13 the presence of pozzolans in 100% concrete contributes to increase in strength; compared to RA concrete without pozzolans and the increase is about 9% percentage. However, this strength is less than that of concrete without any pozzolana and RCA.

5. Compressive strength prediction by Bolomey's equation

The model for prediction of compressive strength is started with Bolomey's equation on plain concrete and then arriving at generalized equations using pozzolanic reactions. When the cement was replaced with pozzolans, their effect was analyzed by suitably modifying the quantities in cement by using efficiency factors of the pozzolans. When the NA was replaced with RCA, their effect was also analyzed by suitably modifying the percentage amounts of RCA in concrete. The basic equation is presented, and other equations are developed using a similar approach.

$$\text{Compressive strength in Mpa} = \mathrm{A} \times \left[\frac{\text{cement}}{\text{water}} - 0.5\right] \tag{12}$$

The above equation was modified with efficiency factors of Pozzolans and using a reduction factor for RCA at a different replacement with natural aggregates. The test results of RCA were

Table 4 Constants for the quaternary blending of concrete

Constants		No of days cured			
		7	28	56	90
Constant	A	16.540	25.457	26.86	29.416
RCA	RR	0.928	0.824	0.79	0.8094
NSF	K1	2.240	1.328	1.31	*
SF	K2	0.622	0.748	0.73	0.675
FA	K3	0.327	0.340	0.64	0.607

Table 5 Constants for the binary blending of concrete

Binary blending with FA					
Constants		No of days cured			
		7	28	56	90
Constant	A	16.49	25.30	27.08	29.48
FA	K3	0.39	0.35	0.64	0.61
RCA	RR	0.94	0.83	0.76	0.77
Binary blending with SF					
Constant	A	16.55	25.46	27.17	29.32
SF	K2	0.41	0.75	0.68	0.65
RCA	RR	0.93	0.75	0.68	0.65
Binary blending with NSF					
Constant	A	16.64	25.37	27.04	*
NSF	K1	2.06	1.23	1.54	*
RCA	RR	0.93	0.83	0.78	*

validated with Ozbakkaloglu *et al*. (2017) with a mean of 0.93.

$$CS\ in\ MPa = A \times \left[\frac{cement + k_1 \times NSF + k_2 \times SF + k_3 \times FA}{water + 0.6 \times SP} - 0.5\right] \times (RR)^{\%RCA} \tag{13}$$

where A = multiplying constant, RR = reduction factor for RCA, K1, K2, K3 = efficiency factors for Nano Silica, Micro Silica and Fly ash respectively were shown in Table 4.

5.1 Effect of RCA on binary blended concrete

Table 5 shows the presence of FA and SF has improved the strength of concrete with age up to 56 days, while the efficiency factors of NSF is maximum at 7 days indicating atypical behaviour for NSF. The introduction of RCA as partial replacement of NA has caused a reduction in strength for RCA quantities more than 25% for all the combinations of mixes tried and for all curing periods. However, there is not much change in RA concrete when RCA is less than 25% for all the combinations of pozzolans in concrete mixtures.

Table 6 Constants for the ternary blending of concrete

Constants		No of days cured			
		7	28	56	90
Ternary blending with SF+FA					
Constant	A	16.517	25.49	26.16	29.42
SF	K2	0.611	0.73	0.73	0.677
FA	K3	0.333	0.33	0.64	0.61
RCA	RR	0.931	0.82	0.79	0.81
Binary blending with SF					
Constant	A	16.494	25.347	26.99	*
NSF	K1	1.81	1.278	1.31	*
FA	K3	0.36	0.355	0.64	*
RCA	RR	0.94	0.83	0.79	*
Binary blending with NSF					
Constant	A	16.506	25.46	26.86	*
NSF	K1	3.211	1.21	1.31	*
SF	K2	0.468	0.73	0.73	*
RCA	RR	0.926	0.82	0.79	*

5.2 Effect of RCA on ternary blended concrete

Table 6 refers to the ternary blending of concrete in which the combinations of FA+SF, FA+NSF and SF+NSF were considered along with RCA at different ages of testing in compression. It was observed that the replacement of NA with RCA at 7 days of curing is not much significant as the strength is low. However, at higher ages, the strength reduction is between 8 to 18% depending on the combination of pozzolans. This indicates that there is a strength improvement due to the presence of pozzolans in the concrete with NA and RCA at 28 days age and beyond. On the contrary, the strength gain is maximum for concrete with NSF at the age of 7 days, and later its effect is reducing. Therefore, the combinations are effective in improving the strength of concrete.

5.3 Effect of RCA on quaternary blended concrete

Table 4 and Fig. 13 refer to the impact of the combination of three pozzolans on RCA concrete. The pozzolanic constant for NSF is decreasing while the constants of FA and SF are improving with age after prolonged curing period. As a large quantity of NSF cannot be used due to workability and cost, a small replacement is enough for improving the strength of normal concrete. Therefore, the blending is effective in improving the efficiencies of all pozzolans and also showing an improvement in RCA concrete. This finally shows a reduction in strength up to 31% as against 34% for 100% RCA concrete. The quantity of cement replaced is 32%, apart from the reduction in loss of strength and also saving the cement.

6. Flexural and split tensile strength

While generating the equations for Flexural and Split Tensile Strength, general expressions that were used popularly were considered. Later modification factors were added. After formulating the equations, the results were checked with the well-known equations for above statistical values.

6.1 Prediction of flexural strength using the compressive strength of cubes

$$\textbf{flexural strength in MPa} = \mathbf{a} \times \sqrt{\mathbf{f_{cu}}} \times \mathbf{RR}^{\%\mathbf{RCA}} \tag{14}$$

Where f_c = cube compressive strength, a = multiplying constant = 0.74 and RR = 1.03 = RCA replacement. The equation was derived based on 102 samples of flexure beams, and marginal improvement in the flexural strength due to the presence of RCA is observed. The comparison of the observed values with renowned researchers was shown in Table 7.

6.2 Prediction of Split tensile strength using the compressive strength of cubes

$$\textbf{Split tensile strength in MPa} = \mathbf{a} \times \mathbf{f_{cu}^{b}} \times \mathbf{RR}^{\%\mathbf{RCA}} \tag{15}$$

where f_{cu} = cube compressive strength, a = multiplying constant = 0.354, b = 0.612 and RR = 0.91 = RCA replacement factor. The equation is based on 200 samples of 100 mm diameter × 200 mm long cylinders. Many authors presented the prediction model for split tensile strength in the form of exponential law for concrete cured under normal conditions. In this model, the ratio of split tensile strength to compressive strength is decreasing with an increase in the compressive strength beyond 80 MPa. This is in line with the findings of Arıoglu *et al*. (2006). The equations of split tensile strength were compared with the well-recognized works in the field of RCA and presented in Table 8.

Generally, the aggregate type, shape and strength is not a factor in normal grade concrete, but in case of high strength concrete and RCA mixtures, any changes in the properties of the coarse

Table 7 Comparison of flexural strength values with renowned authors work

S. No.	Authors	Flexural strength equations	Mean	Std Dev	CoV
1	IS:456 (2000)	$0.7\sqrt{f_{ck}}$	1.24	0.15	12%
2	Xiao *et al*. (2006)	$0.75\sqrt{f_{cu}}$	1.08	0.14	13%
3	Ozbakkaloglu *et al*. (2017)	$f_r = \frac{3.49 - 0.55RCA\%}{\left({w_{eff}}/{b}\right)^{0.5}}$	1.11	0.20	18%
4	Gholampour *et al*. (2017)	$f_r = 0.022 \times (1.2 - 0.002RCA\%) \times \left(2.3 - 0.3\frac{w_{eff}}{c}\right)^{6.9}$	1.06	0.18	17%
6	Carrasquilio *et al*. (1981)	$0.94\sqrt{f_c'}$	0.86	0.11	13%
7	Present study	$0.72\sqrt{f_{cu}} \times (1.04)^{\%RCA}$	1.00	0.11	11%

Table 8 Comparison of Split Tensile Strength values with renowned authors work

S. No.	Authors	Split tensile strength equations	Limitations Plain/ FRC/RCA	Mean	Std Dev	CoV
1	IS:5816 (1970)	$0.45\sqrt{f_{ck}}$	Plain	1.38	0.17	12%
2	Xiao *et al.* (2006)	$0.24[f_{cu}]^{0.65}$	RCA	1.30	0.16	12%
3	ACI:318 (2011)	$0.49\sqrt{f_{cu}}$	RCA and plain after modifying with cube strength	1.17	0.16	13%
4	Behnood *et al.* (2015)	$0.219 f_c{}^{0.75}$	Without fibre (Non-linear analysis)	0.96	0.11	12%
5	Behnood *et al.* (2015)	$0.423 \times f_c{}^{0.554} \times (age)^{0.026}$	f_c greater than 22.33 Without fibre (tree analysis)	1.00	0.13	13%
6	Rashid *et al.* (2002)	$0.47 f_c{}^{0.56}$	Plain HSC	0.96	0.12	13%
7	Ozbakkaloglu *et al.* (2017)	$f_{st} = \frac{2.52 - 0.32RCA\%}{\left(^{w_{eff}}/_{b}\right)^{0.5}}$	Only agg no fibre	1.03	0.18	17%
8	Carrasquilio *et al.* (1981)	$Splitting\ strength\ (MPa) = 0.54\sqrt{fc'}$		1.06	0.14	13%
9	Present study	$f_{st} = 0.354(f_{cu})^{0.612}(0.91)^{\%\mathrm{RCA}}$	f_{cu} = cube compressive strength of the concrete	1.00	0.04	4%

aggregate would influence the tensile-compressive strength relationship of the material. A marginal increase in split tensile and flexural strength respectively is observed for RCA admixture concrete which may be due to the surface texture of the particles, and this improvement in the strength has to be compared with the similar mixture of concrete, but not with the NA concrete since the interfacial transition zone (ITZ) characteristics had a greater impact on the strength of concrete at higher grades.

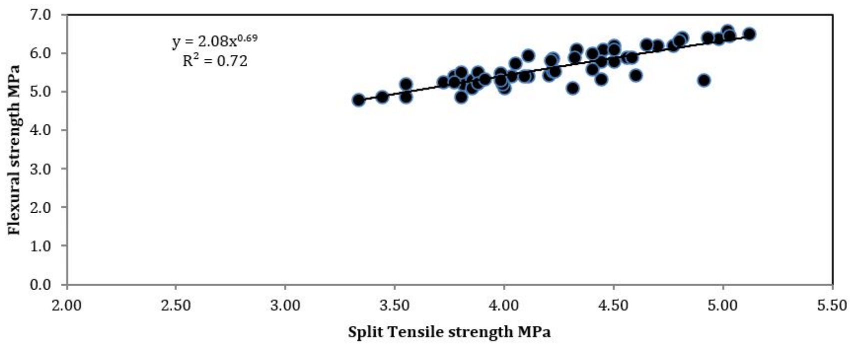

Fig. 14 Relation between flexural strength and split tensile strength at 28 days of curing

6.3 The relation between split tensile strength and flexural strength

The testing of cylinders is simple, and there was a saving of material. The observed values of flexural and split tensile strengths were shown in Fig. 14. Based on the test results, the proposed relation is shown below whose R2 at 71%.

$$\mathbf{flexural\ strength} = \mathbf{2.08} \times (\mathbf{split\ tenile\ strength})^{\mathbf{0.69}} \quad (16)$$

7. Final equations proposed

Compressive strength of concrete in MPa

$$CS\ in\ MPa = A \times \left[\frac{cement + k_1 \times NSF + k_2 \times SF + k_3 \times FA}{water + 0.6 \times SP} - 0.5\right] \times (\mathrm{RR})^{\%RCA} \quad (17)$$

for the values of the constants, refer to Tables 4 to 6.

$$\mathbf{Flexural\ strength\ in\ MPa} = \mathbf{a} \times \sqrt{\mathbf{f_{cu}}} \times \mathbf{RR}^{\mathbf{\%RCA}} \quad (18)$$

where f_c = cube compressive strength, a= multiplying constant = 0.74 and RR = 1.03 = RCA replacement factor.

$$\mathbf{Split\ tensile\ strength\ in\ MPa} = \mathbf{a} \times \mathbf{f_{cu}}^{\mathbf{b}} \times \mathrm{RR}^{\mathbf{\%RCA}} \quad (19)$$

where a = multiplying constant = 0.354, b = 0.612 and RR = 0.98 = RCA replacement factor. The equation is based on 200 samples of 100 mm diameter × 200 mm long cylinders.

8. Conclusions

Based on experimental results, the following conclusions are drawn.

- Reduction in strength was observed with curing time of 7, 28 and 56 days of all mixes with 25% RCA, 50% RCA and 100% RCA.
- There is a reduction in strength when fly ash replacement increased from 0 to 20% and 30%. However, the reduction in 56 days strength is considerably less compared to decrease in 28 days strength. A similar trend was observed for Micro silica when the quantity was more than 10%.
- The presence of Nano silica enhanced the concrete compressive strength in the initial ages.
- The presence of FA in SF and NSF mixtures is useful for strength gain and workability, while SF and NSF mixtures have a problem of workability in ternary mixtures.
- An equation is proposed for the prediction of compressive strength of quaternary blended recycled aggregate concrete based on the fractions of pozzolanic materials.
- Strength prediction equations for flexural and split tensile strengths in terms of compressive strength were proposed for quaternary blended recycled aggregate concrete.

- The presence of RCA in concrete shows a positive effect on flexural and split tensile strengths.

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Conflict of interest

There is no conflict of interest for the authors.

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