Performance assessment of nano-Silica incorporated recycled aggregate concrete

Bibhuti Bhusan Mukharjee*1 and Sudhirkumar V Barai^{2a}

¹Department of Civil Engineering, Biju Patnaik University of Technology, Odisha, India ²Department of Civil Engineering, Indian Institute of Technology Kharagpur, Kharagpur, India

(Received December 27, 2018, Revised October 2, 2019, Accepted October 15, 2019)

Abstract. The present study targets to access the consequence of utilization of coarse aggregates retrieved from waste concrete as a substitution of coarse fraction of natural aggregates and silica nano-particles as partial substitution of cement using principles of factorial design. Furthermore, procedures of design of experiments are employed to examine the effect of use of recycled aggregates and nano-silica. In this investigation, compressive strength found after at 7, 28, 90 and 365 days, split and flexural tensile strength, ultrasonic pulse velocity and rebound number and are chosen as responses, whereas the percentages of recycled coarse aggregates (RCA%) and nano-silica (NS(%)) are selected as factors. Analysis of Variance has been conducted on the experimental results for the selected responses with consideration the both factors, which indicates that RCA (%) and NS (%) have substantial impact on the various responses. However, the present analysis depicts that interaction between factors has considerable effect on the chosen parameters of concrete. Furthermore, validation experiments are carried to validate these models for compressive and tensile strength for 100% RCA and 1% NS. The results of comparative study indicates that that the error of the estimation determined using the relevant models are found to be small (\pm 5%) in comparison with the analogous experimental results, which authenticates the calculated models.

Keywords: ANOVA; colloidal nano-silica; recycled aggregate concrete; design of experiments

1. Introduction

The demolition of old concrete infrastructures is causing significant material flows of concrete debris that creates several environmental problems. The non-availability of sufficient space for dumping of these materials, pollution and high cost of waste treatment are such problems faced by many countries (Trankler et al. 1996). Simultaneously, lack of natural recourses to mitigate the growing demands of quantity of natural aggregates for concrete industry is another problem faced by human civilization. Moreover, cost of natural aggregates are increased many folds by transporting these from lager distances to construction site. In other words, lack of natural resources for production of aggregates, growing requirements for raw materials and environmental issues associated with waste generated during construction and demolition activity, and shortage of dumping sites encourages researchers for searching an innovative application of these materials.

Therefore, researchers and engineers are trying for effective utilization of recycled waste concrete by generating aggregates for production concrete as it produces enormous environmental benefits, for instance; decrease of

*Corresponding author, Associate Professor E-mail: capgs.bbmukharjee@bput.ac.in,

bibhuti.2222@gmail.com

^aProfessor

E-mail: skbarai@civil.iitkgp.ernet.in

Copyright © 2019 Techno-Press, Ltd. http://www.techno-press.org/?journal=acc&subpage=7 emission of CO_2 to air of other pollutants and preservation of natural sources (Taha *et al.* 2014). Aggregates retrieved from waste concrete pieces may be divided into coarse and fine fractions according to their grading. However, previous studies demonstrated that characteristics of these aggregates were poorer to that of natural aggregates because of the existence of old porous attached mortar in it (Rao *et al.* 2011, Mukharjee and Barai 2015b). The effects of using recycled aggregates as a fractional or entire substitution of natural aggregates in making concrete mixes are well explained and extensively documented in literature.

The first collective information about usage of aggregates produced from waste concrete pieces for the generating new concrete was available in the review work by Nixon (1978). De Oliveira and Vazquez (1996) studied experimentally the impact of adsorbed moisture of recycled aggregates on the compressive strength (CS) of newly fabricated RAC. In this study, the influences of varying moisture conditions (dry, saturated and semi-saturated) of recycled aggregates on the CS of RAC were compared. Minor reduction in CS was detected for concrete made from dry and fully saturated Recycled Coarse Aggregates (RCA) as compared to that semi saturated RCA. Batayneh et al. (2007) produced RCA by recycling the specimens of previous laboratory investigations and utilized those aggregates as substitution of natural aggregates for fabrication of new concrete. The outcome of this study was that the decrease in CS of concrete made with the 20% substitution of natural aggregates of by recycled crushed concrete was around 13%. Reduction of mechanical properties of concrete with the replacement of Natural

Coarse Aggregates (NCA) was reported in other studies (Ajdukiewicz and Kliszczewicz 2000, Rakshvir M. and Barai 2006, Shah et al. 2013, Prusty et al. 2015, He et al. 2015, Mukharjee and Barai 2014c, Liang et al. 2017). The durability of concrete was also substantially by the incorporation of recycled aggregates in concrete (Levy and Helene 2004, Saravanakumar and Dhinakaran 2013). Several approaches such as modification in mixing approach, various treatments for improving the behavior of RCA and addition of pozzolanic materials have been proposed in literature for enhancement of behavior of concrete. Polymer based treatment methods were quite efficient in modifying the properties of RCA and properties similar to NCA could be achieved (Spaeth and Tegguer 2013). Tam and Tam (2008) developed two mixing techniques known as Two-Stage Mixing Approach (silica fume) (TSMAs) and Two-Stage Mixing Approach (silica fume and cement) (TSMAsc), which were modification of Two-Stage Mixing Approach (TSMA). The behavior of RAC produced with aforementioned methods enhanced as silica fume fills the space inside RCA and porosity of old attached mortar was significantly reduced. Li et al. (2009) utilized coating technique using Fly ash, Silica fume, and blast furnace slag for production of improvement of RAC and concluded that combined effect of cement and these products was significant in enhancing improving CS of RAC because of increased packing density.

Research and innovations in the concrete technology with the application of Nano-technology has led to produce new nano-sized materials to be applied in cement and concrete. The use nano-materials could improve the characteristics cement paste and mortar as these particles bring modification in nano-scale effectively by reducing pores of C-H-S, augmenting the rate of hydration and decreasing crystal size of Ca(OH)₂ (Pacheco-Torgal et al. 2013). Increase in CS and reduction of water absorption of cement mortar due to the addition of Nano-Silica (NS) was reported (Mukharjee and Barai 2014a). The enhancement in compressive and tensile strength in addition to reduction in void present could be achieved with the utilization of NS (Said et al. 2012, Mukharjee and Barai 2014d). The CS of 100% RAC was improved with the addition of small percentages of colloidal NS along with the reduction of water absorbing characteristics (Hosseini et al. 2011, Mukharjee and Barai 2015b).

Calculation of optimum quantity of materials for mix designing of concrete containing many constituents and performance constraints are complicated and time consuming, which can be simpler with the implementation of methods of statistical methods. Furthermore, analysis of variance (ANOVA) was proven as effective method that can analyze the influence of various effects of selected factors (Montgomery 2013). The influence of NS(%) and W/C ratio on the strength and water absorption of mortar was investigated using factorial design (Mukharjee and Barai 2014b). The main effects and interaction effects of various factors were studied and models were developed. Validation of experiments was conducted for verification of predicted results by developed model. Moura et al. (2007) adopted the Two-way ANOVA for assessment of the impact of copper slag, the w/c ratio and the interaction of these factors on strength of concrete. The ANOVA test showed that both factors had a considerably impact strength of concrete mixes. Correia *et al.* (2009) used 3² factorial design to model fresh concrete consistency, 7, and 28 Days CS with water cement ratio and fresh concrete waste content as factors. The ANOVA of fresh and hardened concrete test results revealed that the selected factors were significantly affecting the properties of RAC. López-Gayarre *et al.* (2009) also used factorial methods for determining the influence of recycled materials on various properties of concrete. Moreover, different types of soft computing methods were adopted for predicting various properties of concrete (Park *et al.* 2013, Duan and Poon 2014, Abdollahzadeh *et al.* 2016).

From extensive review of accessible literatures, it can be observed that several studies have been conducted for examining behavior of concrete containing RAC. Moreover, several techniques are proposed for improvement of characteristics of RAC. After the development nanomaterials, a number of research works have been conducted to examine their impact of NS on cement based materials. Review of previous works also indicates about the application of DOE for determining the effects of various factors on different parameters of concrete. However, statistical investigations associated with utilization of NS and RAC are hardly found in existing studies. Under the above background, the scopes of the present work are presented as follows:

• Preparation of concrete according to the factorial combinations of factorial design plan with consideration of various levels of NS(%) and RCA(%).

• Determination of compressive and tensile strength, rebound number, ultrasonic pulse velocity of desired mixes.

• Analysis of the test results using Two-way ANOVA and illustration of results using contour, main effect and interaction plots.

2. Experimental program

Experiments were conducted in laboratory by introducing RCA produced from waste concrete pieces in place of natural aggregates. Furthermore, varying amount of nano-silica was incorporated in both NAC and RAC to access the impact of these materials.

2.1 Materials

Ordinary Portland Cement (OPC) of 43 grade procured from local market confirming to IS 8112, (1959) was utilized for making trial mixes as per factorial combinations. Standard laboratory experiments were performed to access the different characteristics of cement. The cement was having specific gravity 3.12, consistency 32%, fineness 306 m²/kg and initial setting time and final setting time 135 min and 295 min respectively. The CS of cement was found to be 37.96 MPa, 44.2 MPa and 48.02 after 3, 7, 28 days of curing respectively. Colloidal form of NS, which was available in liquid form and made of fine amorphous, non-porous and spherical particles, was

Table 1 Characteristic of various types aggregates used in designing concrete mixes

Aggregate Type	Bulk density (kg/m ³)		Specific Gravity	Specific	Impact Value	Los Angeles	Crushing Value
	Loose	Compact	(Apparent)	Ulavity	(%)	value (%)	(%)
NFA	1525	1698	2.66	2.62	-	-	-
NCA	1504	1654	2.81	2.72	15.35	19.72	15.11
RCA	1321	1418	2.67	2.46	34.85	36.56	31.52

incorporated mix as substitution of cement. Various experimental tests were conducted laboratory for characterization of NS. The colour of NS used was white and specific gravity and solid content were 1.12 and 39% respectively. Similarly, pH value, SiO2 content and particle size of NS were 10.11, 99.1% and 8-20 nm respectively.

For measuring particle size and visual inspection of particles of NS were performed using Transmission Electron Microscope (TEM), owing to the lack of direct measurement of nao-particle. The images of NS acquired in bright field by TEM are illustrated in Fig. 1, which indicates about the spherical shape and non-agglomerated form of NS. The investigation conducted on images stated about the variation of particles of colloidal NS between 8 and 20 nm. The sand obtained from nearby river bed which confirmed zone II specification of Indian standard (IS 383, 1970) was employed as fine fraction of aggregates for making concrete. The pieces of concrete were collected from the demolition site of a 30 year old building. These concrete pieces were crushed in laboratory and RCA were produces after performing screening and sieving of theses crushed materials. Crushed dolerite having nominal size of 20 mm was employed as coarse fraction of natural aggregates for designing mixes. Different laboratory tests have been conducted over various types of aggregates and outcome of these tests Tabulated in Table 1.

2.2 Factorial design of experiments

In this study, the percentage of recycled coarse aggregates and NS incorporated were taken as factors for design of experiment, which were designated as RCA(%) and NS(%) respectively. The RCA(%) was chosen as 0 and 100%, whereas the NS(%) were fixed at 0, 0.75%, 1.5% and 3%. Each combination of factors had three replications. MINITAB 16 (a statistical software) was employed for randomization of various combinations. The responses for this analysis were CS (7, 28, 90 and 365 days), tensile strength (spilt and flexural) and non-destructive test (Rebound Number and Ultrasonic Pulse Velocity). Furthermore, the significance level for rejection of null hypothesis in hypothesis testing was kept at 5%.

2.3 Mixing, fabricating and testing of specimens

In the designing concrete mixes for various combinations of factors after randomization, the guidelines of IS 10262 (2009) were followed. Eight numbers of different mixes with three numbers of replications were fabricated considering the selected factors and their levels.

Fig. 1 Transmission Electron Microscope (TEM) of Nano-Silica

Table 4 shows the detail estimates of amount of materials in concrete mixes. Water of the concrete laboratory fulfilling the criteria for normal human consumption was employed for preparing trial mixes. Trial slump tests were conducted for RAC mixes for determination of additional quantity of water to mitigate high water absorption of RCA. The results of those tests indicated that additional 10% water together



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Mix	RCA	NS	Cement	NCA	RCA	NFA	NS	Water
No	(%)	(%)	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)
1	0	0.00	450.000	1180	-	640	-	180
2	0	0.75	446.625	1180	-	640	3.375	180
3	0	1.50	443.250	1180	-	640	6.750	180
4	0	3.00	436.500	1180	-	640	13.500	180
5	100	0.00	450.000	-	1067	640	-	180
6	100	0.75	446.625	-	1067	640	3.375	180
7	100	1.50	443.250	-	1067	640	6.750	180
8	100	3.00	436.500	-	1067	640	13.500	180

Table 2 Composition of concrete mixes (1 m³)

with required quantity of water was required to achieve workability similar to NAC. Therefore, 10% of calculated water was added the stipulated water as additional quantity for RAC mixes during production of RAC.

Initially, in the mixing process of materials in designing concrete specimens, water and colloidal NS were stirred properly to avoid agglomeration of particles. Then, aggregates and cement were mixed for two minutes with low speed for dry mixing of materials. After dry mixing of materials, mixture of water and NS were poured into mixer slowly and mixing operation was continued for further two minutes. The materials were kept out of mixer and placed into designated moulds and kept for 24 h under controlled environment after completion of mixing operation. The specimens were kept out of moulds after 24 h and under water curing process is employed to prevent loss of water from specimens. The cubical specimens of size 150 mm were used for determination of CS after 7, 28, 90 and 365 days of curing. The CS was determined using 3000 kN compressive testing machine in the line with Indian standard specifications (IS 516, 1959). split tensile strength (STS) test was performed on cylindrical specimen of 150 mm $\Phi \times 300$ mm height in accordance to Indian standards (IS 5816, 1999). Furthermore, 28 days flexural tensile Strength (FTS) were determined by utilising the prisms of size 100 mm×100 mm×500 mm in accordance with IS 516 (1959) employing 100 kN universal testing machine. Ultrasonic Pulse Velocity (UPV) test was conducted on 150 mm cubes following the procedures of BIS code (IS 1331: part 1 1992). Other non-destructive test Rebound Number (RN) was carried out by employing Schmit Hammer and following the guidelines of BIS code (IS 1331: part 2 1992). At least twenty numbers of measurements were considered for RN test.

3. Results and discussion

To analyze the impact of NS(%) and RCA(%) on behavior of concrete mixes, factorial design with two factors have been adopted according to procedures given by Montgomery (2010). In this analysis, the levels of RCA(%) are 0 and 100% and the levels of NS(%) are 0, 0.75%, 1.5% and 3%). Each combination is replicated thrice to access the variation. Following section represents detailed analysis of outcome of this study.



Fig. 2 Individual value plots of (a) 7 Days CS (b) 28 Days CS (c) 90 Days CS (d) 365 Days CS



Fig. 3 Contour plots of (a) 7 Days CS (b) 28 Days CS (c) 90 Days CS (d) 365 Days CS

3.1 Compressive strength

The individual tests results of the 7, 28, 90, and 365 days CS are furnished in Fig. 1 (a)-(d), which indicates about CS enhances with rising NS (%) and declines with the introduction of RCA. Moreover, the values of three replicates for each test are close to each other and standard deviation lies within acceptable limits. Fig. 3(a) shows the contour lines of 7 days CS of concrete made with varying RCA(%) and NS(%). Values of Contour lines of declines with rise in RCA(%), which indicates that 7 days CS decreases with rise in percentages of replacement of NCA. The decrease of CS is attributed to the substandard properties of RCA. However, contour values rise with the augmentation in NS(%), which confirms about the strengthening of RAC with the incorporation of NS particles. The contour lines of 28 days CS of concrete containing RCA and NS is illustrated in Fig. 3(b). Contour lines of 28 days CS shows a declining trend with the rise quantity of recycled aggregates, which is due to the to the poor bonding between the RCA and mortar matrix.

The contour plot also shows that the 28 days CS of NAC with 3% NS is highest and lowest RAC without NS lowest. The major basis of lowering of CS of RAC is because of the residual adhered mortar that prevents formation of improper bond between the two phases. However, the introduction of NS fills the voids of old mortar and substantial enhancement in ITZ acting as a pozzolanic material. Fig. 3(c) and (d) represent the contour lines of 90 and 365 days CS of concrete with varying RCA(%) and NS(%).Lower contour lines are obtained with the increase in RCA(%) and higher values are achieved with increasing NS(%), this sort of nature of lines are similar to 7 and 28 days CS.

The data generated by performing CS test after various curing time have been analyzed by ANOVA and the results are illustrated in Table 3. The main effects of NS(%) and RCA(%) have substantial effect on CS after various curing days as the p-values are less than 0.05. Poor properties of RCA and beneficial effects of NS are primarily attributed to this type of findings. However, the outcomes of ANOVA analysis of CS indicate interaction between NS(%) and RCA(%) have no substantial impact on CS of concrete. The equations developed are

7 days CS=34.90-0.0425×RCA(%)+1.35×NS(%)
$$R^{2}=0.91$$
 (1)

28 days CS=41.9-0.0687×RCA(%)+2.47×NS(%)
$$R^{2}=0.94$$
 (2)

0 days CS=46.2-0.0596×RCA(%)+2.14×NS (%)
$$R^{2}=0.87$$
 (3)

9

365 days CS=47.6-0.0495×RCA(%)+2.00 NS×(%)
$$R^2=0.84$$
 (4)

The main effects plots of 7 days CS with varying RCA(%) and NS(%) shows that the 7 days CS changes from 36.67 MPa to 32.41 MPa because of the rise in RCA(%) from 0 to 100%, which could be because of alternation in properties of aggregates used in concrete (Fig. 4a). Moreover, this reduction CS of concrete is because of

Properties	Source	Sum of Squares	Degree of freedom	Mean Square	F-value	<i>p</i> -value	Remarks
7 days CS	RCA (%)	108.50	1	108.50	153.01	0.000	significant
	NS (%)	55.17	3	18.39	25.93	0.000	significant
	Interaction	3.21	3	1.07	1.51	0.2503	Not significant
	Error	11.35	16	0.71			
	Total	178.23	23				
	RCA (%)	283.18	1	283.18	261.26	0.000	significant
	NS (%)	185.13	3	61.71	56.93	0.000	significant
28 days CS	Interaction	6.87	3	2.29	2.11	0.1387	Notsignificant
	Error	17.34	16	1.08			
	Total	492.52	23				
	RCA (%)	213.25	1	213.25	109.23	0.000	significant
	NS (%)	135.60	3	45.20	23.15	0.000	significant
90days CS	Interaction	18.38	3	6.13	3.14	0.055	Not significant
	Error	31.24	16	1.95			
	Total	398.47	23				
365 days CS	RCA (%)	146.72	1	146.72	74.60	0.000	significant
	NS (%)	121.12	3	40.40	20.54	0.000	significant
	Interaction	14.85	3	4.95	2.52	0.055	Notsignificant
	Error	31.47	16	1.97			
	Total	314.23	23				
	RCA (%)	0.611	1	0.611	66.68	< 0.0001	significant
Split Topsilo	NS (%)	0.569	3	0.189	20.73	< 0.0001	significant
Strength	Interaction	0.051	3	0.017	1.88	0.174	Not significant
Strength	Error	0.146	16	0.009			
	Total	1.379	23				
	RCA (%)	1.054	1	1.054	52.75	< 0.0001	significant
Flexural	NS (%)	1.278	3	0.426	21.32	< 0.0001	significant
Tensile Strength	Interaction	0.008	3	0.002	0.14	0.933	Not significant
	Error	0.319	16	0.019			
	Total	2.660	23				
Rebound Number	RCA (%)	37.50	1	37.50	87.29	< 0.0001	Significant
	NS (%)	35.29	3	11.76	27.38	< 0.0001	Significant
	Interaction	0.42	3	0.14	0.32	0.8085	Not significant
	Error	6.87	16	0.43			
	Total	80.08	23				
Ultra sonic velocity	RCA (%)	0.67	1	0.670	59.68	< 0.0001	Significant
	NS (%)	0.71	3	0.240	21.11	< 0.0001	Significant
	Interaction	0.02	3	0.005	0.50	0.6859	Not significant
	Error	0.18	16	0.011			
	Total	1.57	23				

Table 5 ANOVA Table for various selected responses

the development of poor ITZ when RCA content increases. However, analysis of main effect plot for the factor the NS(%) indicates that the 7 days CS increased from 32.55 MPa to 36.62 MPa with rise in NS(%) zero to 3%.

This enhancement in CS with the use of NS could be because of reduction in the amount of voids of RCA and mortar matrix with pozzolanic products; henceforth, improving bond existing between various phases. The main effect plots 28 days CS with different NS(%) and RCA(%) is indicates that 28 days CS declines from 45.15 MPa to 38.27 MPa as RCA(%)rises from zero to 100%, which proves that substantial degradation of 28 days CS occurs, when the replacements of normal aggregates are carried.

The aforementioned degradation in CS is due to the poor quality of recycled aggregates to virgin aggregates. However, considerable improvement in 28 days CS with the rise in NS(%) is detected as the value CS changes from 37.88 MPa to 45.56 MPa with enhancement of the level NS(%) from zero to three. This rise in CS with the introduction of NS in concrete could be because of the formation of stronger ITZ by filling of voids within it in addition to the improvement in the binding capacity of aggregates. Fig. 4(c) indicates that 90 days CS declines from 48.96 MPa 43.00 MPa, when the RCA(%) changes from zero to 100. However, the 90 days CS rises from 43.15 MPa to 49.59 MPa as NS(%)rises from zero to 3%. Fig. 4(d) shows 365 days CS declines from 50.19 MPa 45.24 MPa, when RCA(%) rises from zero to 100%, and increases from 45.15 MPa to 50.93 MPa as NS (%)increases from zero to 3 %. The analysis of main effects plots for CS after various curing days concludes about the presence of considerable influence of main effects of RCA(%) and





Fig. 4 Plots for main effects of CS after (a) 7 Days (b) 28 Days (c) 90 Days (c) 365 Days

Fig. 5 Interaction plots for CS after (a) 7 Days (b) 28 Days (c) 90 Days (d) 365 Days

NS(%) on strength parameters. Interaction plots generated during analysis of data of CS after various curing time indicate interaction effects of RCA(%) and NS(%) on strength of are not so significant as interaction lines are neither close to each other or nor intersecting between them (Fig. 5). Interactions of effects are known to be significant



Fig. 6 (a) Individual value plots of STS. (b) Individual plots of FTS. (c) Contour plot of STS. (d) Contour plot of STS

the effect of one factor on the response is different with the alternation of level of other factor. However, the effects of NS(%) in both types of concrete mixes are similar irrespective of the type of aggregate used.

3.2 Tensile strength

The individual results of STS and STS tests which indicate about decrease in tensile strength with the introduction of RCA as a substitute of NCA (Fig. 6(a) and (b)).

However, enhancement in tensile strength is detected with introduction NS in concrete. The contour plot developed from the analysis of tensile strength results for varying RCA(%) and NS(%) are illustrated in Fig. 6c and d. The plots indicate the declining values of contour lines with rise in amount of RCA(%)and contour values are started increasing with the rise in NS(%), which could be owing to the fact that use RCA as a substitute of NCA have considerable impact on tensile strength of mix, as the bond between RCA and mortar is weaker that NCA and mortar. This could be due to the fact that old mortar of RCA is porous in nature and incapable of forming required bond with mortar phase. Therefore, more number of void spaces is created in concrete and the ITZ of RAC becomes inferior to NAC. However, the introduction of NS produces strong mix by absorbing Ca(OH)₂ crystal and denser by filling the void spaces by silica particles. Therefore, the both STS and FTS of concrete are enhanced with the use of NS and making a significant enhancement in tensile strength characteristics. The ANOVA analysis results of tensile strength parameters of concrete with varying NS(%) and RCA(%) shows that p-values for main effects of RCA(%) and NS(%) are less than 0.05 (Table 2). This indicates about substantial impact of main of effects RCA(%) and NS(%) on tensile parameters of concrete. However, absence of substantial impact of interaction of RCA(%) and NS(%) on STS and FTS is detected from the analysis. The relationship between the response and factors are given in the following equations:

STS=2.17-0.00319×RCA(%)+0.137×NS(%)
$$R^{2}$$
=0.84 (5)

FTS=4.32-0.00419×RCA(%)+0.206×NS(%) $R^{2}=0.87$ (6)

The main effect plots for STS and FTS of mixes with varying NS(%) and RCA (%) is shown in Fig. 7(a) and (b). It can be noticed from the plot that STS reduces from 2.35 MPa to 2.02 MPa when RCA(%)rises from zero to 100% i.e., the STS decreases considerably with the full substitution of aggregates. Conversely, STS of concrete changes from 1.99 MPa to 2.4 MPa as NS(%)rises from zero to three, which concludes that rise NS(%) brings substantial upgrading in STS of concrete. Addition of NS fills voids of concrete (NAC and RAC) without NS. Similarly, FTS values reduces from 4.59 MPa to 4.18 MPa when the RCA(%) changes zero to 100%. However, FTS increases from 4.15 MPa to 4.75 MPa as NS(%) rises from zero to 3%. The explanations of this type behavior of FTS



Fig. 7 (a) Main effect plots for STS. (b) Main effect plots for FTS. (c) Interaction plots for STS. (d) Interaction plots for FTS

of concrete are similar to the explanations given for STS of concrete. The above analysis concludes that the main effects of RCA(%) and NS(%)have considerable impact on the tensile strength characteristics of concrete. Fig. 7(c) and (d) represent the interaction plots of the responses STS and FTS with varying RCA(%) and NS(%). These plots demonstrates about the lack of significant interaction of RCA(%) and NS(%) as the interaction lines are neither close nor crossing each other, which means the effect of alternation of NS(%) in both NAC and RAC has similar effect on tensile strength parameters of concrete for both levels of RCA(%) and reduces with the alternation in RCA(%) from 0 to 100% for every level of NS(%).

3.3 Non-destuctive test results

As Non-Destuctive Test (NDT) are mainly carried out to know behavior of concrete with out breaking the specimnes and these are primaily suface meusrements, they are influencely by the presence of voids in concrete. Fig. 8a-d illustrate the individual results and conour plots of the RN and UPV tests conducted on concrete specimens.

UPV=4.47-0.00349×R+0.142×NS(%)
$$R^{2}$$
=0.85 (8)

It can be seen that contour plots for these parameters of concrete shows a decreasing trend with increasing percentages of RCA. This reduction of NDT parameters with increasing RCA content could be attributed to the enhancement of voids in concrete mixes. However, the contour values increases with increase in NS(%). Primarily, NDT values enhance with reduction of voids in concrete, thus, incorporation of NS increases these values as NS addition reduces the quantity of voids present in concrete. Tables 11 and 12 demonstatres the results of ANOVA for test results of RN and UPV of concrete mixes with the chosen factors for the study are RCA(%) and NS(%). The ANOVA results of RN test provides a conclusion that NS(%) and RCA(%) have significant effect on respnses as higher F-value and lower p-value could be seen from the Table 11. However, the intreaction of the factors NS(%) and RCA(%) is not so significatnt as p-value is more than 0.05. Form the Table 12, it can be seen that the *F*-value is 59.68 and *p*-value less than 0.001 for the factor RCA (%), which confirms that RCA(%) have sigificant influence on RN of concrete. This type of behaviour of concrete is primarily attibuted to fact that voids of concrete enhances with incrportaion of RCA. However, there is a reduction quantity of voids with the addition of NS, which is main reason for p-value close to zero for NS(%). However, the intreaction of the NS(%) and RCA(%) have no significatnt effcet on the RN of concrete. The relationship between the Nondestructive parameters and factors are given in the following equations

RN=26.3-0.0250×RCA(%)+1.08×NS(%)
$$R^{2}=0.90$$
 (7)

Fig. 9(a) and (b) show the main effects plots for the for RN and UPV of concrete with varying RCA(%) and NS(%). The mean RN values decreases from 27.71 to 25.21



Fig. 8 (a) Individual plots of RN. (b) Individual plots of UPV. (c) Contour plot of RN. (d) Contour plot of UPV



Fig. 9 (a) Main effect plots for RN. (b) Main effect plots for UPV. (c) Interaction plots for RN. (d) Interaction plots for UPV



Fig. 10 Comparisons between predicted and experimental results of (a) CS (b) TS

with change of RCA(%) from zero to 100%, which is due to augmentation in amount of voids with the introduction of 100% RCA. However, RN values rises from 24.9 to 28.28 when the percentage of NS increases from zero to three, which is primarily because of lessening of amount of void spaces. Similarly, UPV values decreases 4.65 to 4.32 km/s from with the change of RCA(%) from 0 to 100 and increases from 4.27 to 4.72 km/s when NS(%) level changed from 0 to 3. The explanations for this type of response are similar to that of RN. The plots showing interaction of the factors for the responses UPV and RN are shown in Fig. 9(c) and (d) respectively.

The study concludes that interaction of RCA(%) and NS(%) are not considerably affecting the RN and UPV values of concrete as interaction plots for different levels of factors are parallel to each other.

3.4 Validation experiments

In the previous section statistical models are developed. Here, validation experiments are carried to validate these models for compressive strength (CS) and tensile strength (TS) for 100% RCA and 1% NS. The samples were prepared as per the methods described earlier. The results of the confirmation experiment and predicted values by empirical model are presented in Fig. 10.

The error was calculated between the experimental observations and predicted results using various empirical models. The results of comparative study indicates that that the error associated with predicated values using the related models are low (\pm 5%) when compared to corresponding laboratory results, which authenticates the calculated models. In the current study, general factorial design is employed to model the various parameters of concrete and the outcome of study has been satisfactory.

4. Conclusions

The collective impact of utilization recycled aggregates and colloidal Nano-Silica has been in current research work. A full factorial design with RCA(%) and NS(%) as factors and CS (found after 7, 28, 90 and 365 days), split and flexural strength, and rebound number and ultrasonic pulse velocity as responses has been considered. Two-way ANOVA has been utilized for analyzing of laboratory test data to access the impact of designated factors. Furthermore, validation experiments have been conducted for concrete mixes containing 1% NS. The conclusions obtained from the use of the factorial design in studying the nano-silica incorporated recycled concrete behavior has been illustrated below:

• The individual value and contour plots for CS demonstrates that strength enhances with augmentation of NS content in concrete and declines with substitution of natural aggregates. The significant impact of RCA(%) and NS(%) could be detected from main effect plots and ANOVA table which could be attributed to the inferior characteristics of RCA and beneficial effects of NS in concrete. However, no substantial impact of interaction of RCA(%) and NS(%) and NS(%) has been observed, which could be inferred from ANOVA table and interaction plots.

• Improvement in tensile behavior of concrete with the utilization of NS and declination of tensile strength with 100% RCA has been detected from individual and contour plots. Furthermore, main effects of RCA(%) and NS(%) has substantial influence on tensile strength of concrete as p-value close to zero has been seen from ANOVA Table. However, interaction plot and ANOVA study concludes no substantial impact of interaction of RCA(%) and NS(%) on tensile strength.

• The ANOVA test results and plots for Non-Destructive test results indicate that RCA(%) and NS(%) have major impact on these parameters. However, interactions of RCA(%) and NS(%) have no considerable impact on Non-destructive characteristics of concrete.

• The experimental results of CS and TS of concrete mixes containing 1% NS was compared with predicted results of the model. The error calculated between the experimental observations and the predicted values of concrete was in the satisfactory limits.

References

Abdollahzadeh, G., Jahani, E. and Kashir, Z. (2016), "Predicting of compressive strength of recycled aggregate concrete by genetic programming", *Comput. Concrete*, **18**(2), 155-163. http://dx.doi.org/10.12989/cac.2016.18.2.155.

- Ajdukiewicz, A. and Kliszczewicz, A. (2002), "Influence of recycled aggregates on mechanical properties of HS/HPC", *Cement Concrete Compos.*, 24(2), 269-279. https://doi.org/10.1016/S0958-9465(01)00012-9.
- Batayneh, M., Marie, I. and Asi, I. (2007), "Use of selected waste materials in concrete mixes", *Waste Manage.*, 27(12), 1870-1876. https://doi.org/10.1016/j.wasman.2006.07.026.
- Correia, S.L., Souza, F.L., Dienstmann, G. and Segadães, A.M. (2009), "Assessment of the recycling potential of fresh concrete waste using a factorial design of experiments", *Waste Manage.*, 29(11), 2886-2891. https://doi.org/10.1016/j.wasman.2009.06.014.
- De Oliveira, M.B. and Vazquez, E. (1996), "The influence of retained moisture in aggregates from recycling on the properties of new hardened concrete", *Waste Manage.*, **16**(1), 113-117. https://doi.org/10.1016/S0956-053X(96)00033-5.
- Duan, Z.H. and Poon, C.S. (2014), "Factors affecting the properties of recycled concrete by using neural networks", *Comput. Concrete*, 14(5), 547-561. http://dx.doi.org/10.12989/cac.2014.14.5.547.
- He, Z.J., Liu, G.W., Cao, W.L., Zhou, C.Y. and Jia-Xing, Z. (2015), "Strength criterion of plain recycled aggregate concrete under biaxial compression", *Comput. Concrete*, 16(2), 209-222. https://doi.org/10.12989/cac.2015.16.2.209.
- Hosseini, P., Booshehrian, A. and Madari, A. (2011), "Developing concrete recycling strategies by utilization of nano-SiO₂ particles", *Waste Biomass Valoriz.*, 2(3), 347-355. http://dx.doi.org/10.1007/s12649-011-9071-9.
- IS: 10262 (2009), Indian Standard Concrete Mix Proportioning-Guidelines, Bureau of Indian Standards, New Delhi.
- IS: 1331 (1992), Indian Standard Non-destructive Testing of Concrete-Method of Test: Part 2 Rebound Hammer, Bureau of Indian Standards, New Delhi.
- IS: 1331 (1992), Indian Standard Non-destructive Testing of Concrete-Method of Test: Part 1 Ultrasonic Pulse Velocity, Bureau of Indian Standards, New Delhi.
- IS: 383 (1970), Indian Standard Specification for Coarse and Fine Aggregate from Natural Sources, Bureau of Indian Standards, New Delhi.
- IS: 516 (1959), Indian Standard Methods of Tests for Strength Concrete, Bureau of Indian Standards, New Delhi. (Reaffirmed in 1999)
- IS: 5816 (1999), Indian Standard Splitting Tensile Strength of Concrete-method of Test, Bureau of Indian Standards, New Delhi.
- IS: 8112 (1989), Indian Standard Specification 43 Grade Ordinary Portland Cement Specification, Bureau of Indian Standards, New Delhi.
- Levy, S.M. and Helene, P. (2004), "Durability of recycled aggregates concrete: a safe way to sustainable development", *Cement Concrete Res.*, **34**(11), 1975-1980. https://doi.org/10.1016/j.cemconres.2004.02.009.
- Li, J., Xiao, H. and Zhou, Y. (2009), "Influence of coating recycled aggregate surface with pozzolanic powder on properties of recycled aggregate concrete", *Constr. Build. Mater.*, **23**(3), 1287-1291. https://doi.org/10.1016/j.conbuildmat.2008.07.019.
- Liang, J.F., Yang, Z.P., Yi, P.H. and Wang, J.B. (2017), "Stressstrain relationship for recycled aggregate concrete after exposure to elevated temperatures", *Comput. Concrete*, **19**(6), 609-615. https://doi.org/10.12989/cac.2017.19.6.609.
- López-Gayarre, F., Serna, P., Domingo-Cabo, A., Serrano-López, M.A. and López-Colina, C. (2009), "Influence of recycled aggregate quality and proportioning criteria on recycled concrete properties", *Waste Manage.*, **29**(12), 3022-3028. https://doi.org/10.1016/j.wasman.2009.07.010.
- Montgomery D.C. (2013), *Design and Analysis of Experiments*, Wiley India Pvt. Ltd., New Delhi, India.

- Moura, W.A., Gonçalves, J.P. and Lima, M.B.L. (2007), "Copper slag waste as a supplementary cementing material to concrete", *J. Mater. Sci.*, **42**(7), 2226-2230. https://doi.org/10.1007/s10853-006-0997-4.
- Mukharjee, B.B. and Barai S.V. (2014a), "Characteristics of Mortars containing colloidal Nano-silica", *Int. J. Appl. Eng. Res.*, 9(1), 17-22.
- Mukharjee, B.B. and Barai, S.V. (2014b), "Assessment of the influence of nano-silica on behavior of mortar using factorial design of experiments", *Constr. Build. Mater.*, 68, 29-37. https://doi.org/10.1016/j.conbuildmat.2014.06.074.
- Mukharjee, B.B. and Barai, S.V. (2014c), "Influence of incorporation of nano-silica and recycled aggregates on compressive strength and microstructure of concrete", *Constr. Build. Mater.*, **71**, 570-578. https://doi.org/10.1016/j.conbuildmat.2014.08.040.
- Mukharjee, B.B. and Barai, S.V. (2014d), "Influence of nano-silica on the properties of recycled aggregate concrete", *Constr. Build. Mater.*, 55, 29-37. https://doi.org/10.1016/j.conbuildmat.2014.01.003.
- Mukharjee, B.B. and Barai, S.V. (2015a), "Characteristics of sustainable concrete incorporating recycled coarse aggregates and colloidal nano-silica", *Adv. Conc. Constr.*, 3(3), 187-202. http://dx.doi.org/10.12989/acc.2015.3.3.187.
- Mukharjee, B.B. and Barai, S.V. (2015b), "Development of construction materials using nano-silica and aggregates recycled from construction and demolition waste", *Waste Manage. Res.*, 33(6), 515-523. https://doi.org/10.1177/0734242X15584840.
- Nixon, P.J. (1978), "Recycled concrete as an aggregate for concrete-a review", *Mater. Struct.*, **11**(65), 371-378. http://dx.doi.org/10.1007/BF02473878.
- Pacheco-Torgal, F., Miraldo, S., Din, Y. and Labrincha, J.A. (2013), "Targeting HPC with the help of nanoparticles: An overview", *Constr. Build. Mater.*, **38**, 365-370. https://doi.org/10.1016/j.conbuildmat.2012.08.013.
- Park, W.J., Noguchi, T. and Lee, H.S. (2013), "Genetic algorithm in mix proportion design of recycled aggregate concrete", *Comput. Concrete*, **11**(3), 183-199. https://doi.org/10.12989/cac.2013.11.3.183.
- Prusty, R., Mukharjee, B.B. and Barai, S.V. (2015), "Nanoengineered concrete using recycled aggregates and nano-silica: Taguchi approach", *Adv. Conc. Constr.*, 3(4), 253-268. http://dx.doi.org/10.12989/acc.2015.3.4.253.
- Rakshvir, M. and Barai, S.V. (2006), "Studies on recycled aggregates-based concrete", *Waste Manage. Res.*, 24(3), 225-233. https://doi.org/10.1177/0734242X06064820.
- Rao, M.C., Bhattacharyya, S.K. and Barai, S.V. (2011), "Influence of field recycled coarse aggregate on properties of concrete", *Mater. Struct.*, 44(1), 205-220. https://doi.org/10.1617/s11527-010-9620-x.
- Said, A.M., Zeidan, M.S., Bassuoni, M.T. and Tian, Y. (2012), "Properties of concrete incorporating nano-silica", *Constr. Build. Mater.*, **36**, 838-844. https://doi.org/10.1016/j.conbuildmat.2012.06.044.
- Saravanakumar, P. and Dhinakaran, G. (2013), "Durability characteristics of recycled aggregate concrete", *Struct. Eng. Mech.*, **47**(5), 701-711. https://doi.org/10.12989/sem.2013.47.5.701.
- Shah, A., Jan, I.U., Khan, R.U. and Qazi, E.U. (2013), "Experimental investigation on the use of recycled aggregates in producing concrete", *Struct. Eng. Mech.*, 47(4), 545-557. https://doi.org/10.12989/sem.2013.47.4.545.
- Spaeth, V. and Tegguer, A.D. (2013), "Improvement of recycled concrete aggregate properties by polymer treatments", *Int. J. Sust. Built Environ.*, 2(2), 143-152. https://doi.org/10.1016/j.ijsbe.2014.03.003.
- Taha, R., Al-Nuaimi, N., Kilayli, A. and Salem, A.B. (2014), "Use

of local discarded materials in concrete", *Int. J. Sust. Built. Environ.*, 3(1), 35-46.

https://doi.org/10.1016/j.ijsbe.2014.04.005.

- Tam, V.W.Y. and Tam, C.M. (2008), "Diversifying two-stage mixing approach (TSMA) for recycled aggregate concrete: TSMAs and TSMAsc", *Constr. Build. Mater.*, 22(10), 2068-2077. https://doi.org/10.1016/j.conbuildmat.2007.07.024.
- Trankler, J., Walker, I. and Dohman, M. (1996), "Environmental impact of demolition waste-an overview on 10 years of research and experience", *Waste Manage.*, **16**(1-3), 21-26. https://doi.org/10.1016/S0956-053X(96)00061-X.

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