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Nano-engineered concrete using recycled aggregates and nano-silica: Taguchi approach

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Abstract. This paper investigates the influence of various mix design parameters on the characteristics of concrete containing recycled coarse aggregates and Nano-Silica using Taguchi method. The present study adopts Water-cement ratio, Recycled Coarse Aggregate (%), Maximum cement content and Nano-Silica (%) as factors with each one having three different levels. Using the above mentioned control parameters with levels an Orthogonal Array (OA) matrix experiments of L9 (34) has selected and nine number of concrete mixes has been prepared. Compressive Strength, Split Tensile Strength, Flexural Tensile Strength, Modulus of Elasticity and Non-Destructive parameters are selected as responses. Experimental results are analyzed and the optimum level for each response is predicted. Analysis of 28 days CS depicts that NS (%) is the most significant factor among all factors. Analysis of the tensile strength results indicates that the effect of control factor W/C ratio is ranked one and then NS (%) is ranked two which suggests that W/C ratio and NS (%) have more influence as compared to other two factors. However, the factor that affects the modulus of elasticity most is found to be RCA (%).Finally, validation experiments have been carried out with the optimal mixture of concrete with Nano-Silica for the desired engineering properties of recycled aggregate concrete. Moreover, the comparative study of the predicted and experimental results concludes that errors between both experimental and predicted values are within the permissible limits. This present study highlights the application of Taguchi method as an efficient tool in determining the effects of constituent materials in mix proportioning of concrete.

Keywords: recycled aggregate concrete; nano-silica; design of experiments; Taguchi method

1. Introduction

Currently, with the developments in concrete technology and flexibility in designing, concrete has proven to be the leading construction material. Therefore, huge quantities of natural aggregates are consumed with the enormous increase in the consumption of concrete. Furthermore, the lack of availability of dumping sites for the disposal of waste concrete is creating major problem as it increases transport and disposal cost for dumping of waste products (Tam *et al*. 2009, Coelho and

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de Brito 2011). In addition to the environmental benefits such as reducing the demand on lands for waste disposal, the recycling of construction and demolition (C&D) wastes helps in preserving natural resources and minimization of the cost of waste treatment (Hao *et al*. 2009, Lin *et al*. 2010). Waste concrete pieces collected from C&D waste are undergone series of operation such as screening, crushing and sieving for preparation of recycled aggregates. These aggregates could be used as substation of natural aggregates for fabrication of new concrete, which are termed as Recycled Aggregates (RA). Recycled Coarse Aggregates (RCA) were having lesser strength, more porous and higher water absorption capacity as comparison to the Natural Coarse Aggregates (NCA) (de Juan and Gutiérrez 2009, Tam and Tam 2009). The aforementioned characteristics of RCA lead to lack of strong bonding between cement paste and RCA in concrete made as compared to NCA. Furthermore, it was found that maximum reduction of compressive strength (CS) of concrete mixes made with 50% RCA was about 15% and this value was around 40% for 100% Recycled Aggregate Concrete (RAC). Therefore, these aggregates had significant influence on the properties of concrete (Rakshvir and Barai 2006, Rao *et al*. 2009). Previous research works revealed that improvement in properties of RAC could be achieved by adding pozzolanic materials during fabrication of RAC mixes. Elhakam et al. (2012) concluded that the addition of 10% silica fume to RAC mixes enhanced the mechanical behavior of RAC. Moreover, incorporation fly ash in RAC mixes enhanced the long-term resistance to carbonation, chloride ingress and sulfate erosion (Limbachiya *et al*. 2012). Berndt (2009) recommended that RAC mixes made with 50% blast furnace slag as partial replacement of cement produced the superior mechanical and durability properties.

The rapid advancements in nanotechnology have given way to a new line of research in field of concrete technology. The main advances have been in the Nano-science of cementations material is analyzing the basic phenomena of cement hydration at Nano-scale level. Previous studies illustatred that improvements in Interfacial Transition Zone (ITZ) could be achieved with the addition of nano-materials, especially Nano-Silica (NS) due to the increase in rate formation of Calcium-Silicate-Hydrate (C-S-H) (Pacheco-Torgal *et al*. 2010). Moreover, addition of NS contributed to the efficient particle packing in concrete due to filling of the micro and Nano-pore and leading to enhanced mechanical and durability properties. The CS and bond strength of paste containing NS were found to be higher than that made with silica fume especially at early ages (Qing *et al.* 2007). Moreover, the study revealed that NS consumed the calcium hydroxide (CH) crystals, reduced the orientation of CH crystal, and lessened the crystal size of CH gathered at the interface. It was stated that silica nano-particles were more efficient in enhancing strength than SF and concluded that NS behaved not only as filler to improve the mortar cement microstructure but also as a promoter of pozzolonic reaction. Berra *et al*. (2012) revealed that addition of NS to cementious mixes reduced the workability owing to immediate reaction between the NS and cementitious material with production of a gel having high water retention capacities. Several studies illustrated that incorporation of NS in concrete was quite useful in producing significant modification in its behavior. Said *et al*. (2012) found that the improvements in compressive and split tensile strength of concrete along with reduction of porosity with the addition of NS. Hosseini et al. (2011) stated that fully RAC mixes with 3% of NS as replacement of cement produced CS more that of NAC. Moreover, the incorporation of NS made the microstructure dense, uniform and free from voids. However, higher dosage of the NS influenced workability of RAC owing to several problems for example dispersion problems and conglomeration of NS particles. Improvement in tensile strength and non-destructive parameters of concrete in addition to CS was reported (Mukharjee and Barai 2014).

In industry, Design of Experiments (DOE) are used to systematic investigation of the process or product variables, which influences the quality of final product after selecting the conditions of process and components of the product. It is very essential to get the most of the information from each experiment with the limited resources. Additionally, well-planned experiments ensure about the assessment of the significance of important factors (Montgomery 2012). Taguchi Design, based on the DOE approach, is a robust parameter design methodology of product or process design dealing with the minimization of variation. Taguchi design uses an Orthogonal Array system, which facilitates analyzing many factors with few numbers of runs. Several studies comprising of application of Taguchi approach in field of cement and concrete are available in literature. Turkmen *et al*. (2008) used Taguchi method for determination of quantity of materials required to achieve optimum physical properties such as porosity, capillarity, water absorption, unit-weight, and Ultrasonic Pulse Velocity (UPV). The variables selected for the experimental investigation were mineral admixture, Water to binder ratio (W/B), curing regime and curing time. Among aforementioned parameters, curing regime is most affecting parameter, which affected capillarity coefficient, capillary porosity, UPV, and porosity. However, the study demonstrated that (W/B) was the most influential factor on the water absorption and dry-unit weight of concrete mixes. Ozbay *et al*. (2009) adopted water-cementitious material ratio, water content, fine aggregate to total aggregate percent, fly ash content, air entraining agent content, and super plasticizer content as factors and concrete mixtures were designed in a L18 orthogonal array. Compressive and splitting tensile strength, air content, water permeability, UPV, and water absorption were the chosen as responses, which were analyzed and for individual response optimum mix proportion was determined. Olivia and Nikraz (2012) applied Taguchi method for optimization of concrete mixtures made with fly ash geo-polymer with consideration of the effects of factors such as aggregate content, alkaline solution to fly ash ratio, sodium silicate to sodium hydroxide ratio, and curing method. The set of materials chosen in this study after conducting analysis had optimum Mechanical properties and durability characteristics. Lin *et al*. (2004) adopted Taguchi Approach to select the optimal mixture proportioning of RAC based on requirement of slump and CS. The analysis depicted that both slump and CS of concrete indicated that the optimal properties could be achieved with water-cement ratio (W/C) of 0.5, 42.0% coarse aggregate, 100% natural river sand, crushed brick of 0%, and as-is recycled coarse aggregates.

From broad literature survey, it is observed that investigations in the area of application of NS in RAC are rarely available in literature. Moreover, considering variable engineering and mechanical properties of RAC along with NS, a large number of experiments are necessary for deciding suitable mixture for obtaining the optimum properties. Therefore, Taguchi method is adopted in this study for reduction of number of experiments and selection of a mix proportions of concrete to achieve optimum response. Under the aforementioned background, this present study aims to achieve the following objectives:

- Determination of properties of RCA collected from field source
- Selection of factors and their levels
- Selection of the Orthogonal Array matrix Experiment
- Preparation and testing of concrete specimens
- Analysis of the experimental results and Prediction the Optimum Levels
- Conduction of verification experiment and compare with Taguchi predicted results

2. Materials and methods

2.1 Materials

In this study, the Portland Slag Cement of 43 Grade was used for the production of concrete mixes. Standard tests have been performed and results of those tests are illustrated in Table 1. The cement used for this experimental work was supplied by Ultratech Cement Co., India. The results of 7 and 28 days CS of the cement were found to be 33.87 MPa and 48.3 MPa respectively.

Table 1 Physical properties of Portland slag cement

Specification		Portland Slag Cement: Requirement of IS 455 (1989)	Test Results
Fineness		225 m2 kg-1	235 m2 kg-1
Setting Time(min)	Initial	30	90
	Final	600	300
Consistency		-	34%
Specific Gravity		3.15	3.02

The RCA used in this experimental work were retrieved from waste concrete collected from the site of a demolished building in Jhargram (a city of Eastern India). The large pieces of waste concrete, which were free from impurities, brought to the laboratory and broken in to small pieces. The pieces greater than 20 mm were crushed by jaw crusher and were sieved through the required sieves in order to make it 20 mm well graded nominal size aggregates. The percentage of aggregates required to pass in particular sieve size were segregated as per BIS standard (IS 383 1970). Natural Coarse Aggregates (NCA) of 20 mm well-graded nominal size were used for production of concrete mixes. The river sand confirming to Zone II (IS 383 1970) was used as Natural Fine Aggregates. The standards tests for determination of physical and mechanical properties of the aggregates have been conducted and results of those tests are tabulated in Table 2.

Table 2 Physical and mechanical properties of aggregates

Property of aggregate		NCA	RCA	Difference between NCA and RCA (%)	NFA
Specific Gravity		2.9	2.36	19	2.66
Water Absorption (%)		0.5	4.6	800	0.2
Bulk Density (kg m-3)	Compacted	1870	1570	16	1560
	Loose	1810	1160	36	-
Flakiness Index (%)		23	12.04	47	-
Elongation Index (%)		34	35.18	3	-
Crushing Value (%)		24.67	34.5	39	-
Impact Value (%)		26.53	36.57	38	-

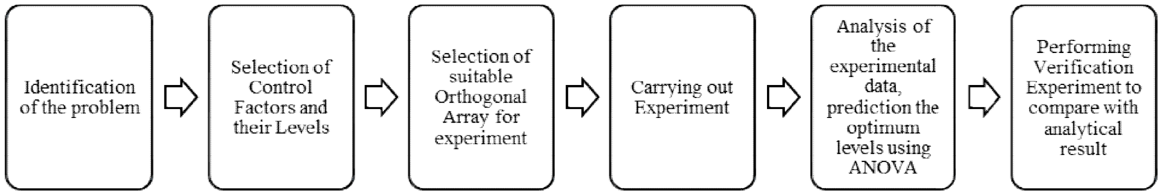


Fig. 1 Schematic diagram showing the procedures of Taguchi Approach

Colloidal NS having particles size 9-20 nm was used for the experimental work. NS particles were consisting of an amorphous SiO2 core with a hydroxylated surface, which were insoluble in water. The pozzolanic reactivity of NS was high due to high surface area and possession of unsaturated bonds. The used NS is having solid content 40% and density 1.2 gm cc-1.

2.2 Taguchi method and research model

Taguchi proposed a method for optimizing quality of process or product known as the Taguchi Method or Taguchi Approach. This method provides a sustainable approach to industrial experimentation. Taguchi Approach offers a generalized definition for quality of performance regarding performance as the major component of product or process quality. The goal of this method is to determine the combination of control factor, which generate satisfactory responses considering variability in process. This method consists of an orthogonal array (OA) experiment (well defined minimum no. of experiment), which produces much reduced variance of experiments with best level of control factors and also improves the efficiency and effectiveness of DOE. The standard procedures of Taguchi Approach are as shown Fig. 1.

Based on the process or product, the number of factors and their levels, there may be many possible ways in which an experiment can be laid out. A standard OA table has been developed to facilitate experimental design. Taguchi's orthogonal arrays are fractional orthogonal designs. These designs can be used to estimate main effects using only a few experimental runs. Proper OA can be selected knowledge of the number of factors and their levels. Taguchi's signal-to-noise ratios (SN) are functions of the observed responses over an outer array. Dividing system variables based upon their SN is most important in this method. SN ratio of factors is system control inputs. Noise factors are those variables, which are usually uncontrollable. Depending upon the objective of the robust parameter design experiment, Taguchi proposed three numbers of statistics of SN ratio. These formulations are dependent upon the experimental goal whether to maximize, minimize or equalize to the target value.

- Smaller the Better (For making the system response as small as possible) Choose when the goal is to minimize the response.

$$SN_S = -10 \log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

- Nominal the Best (For reducing variability around a target) choose when the goal is to target the response and it is required to base the S/N ratio on standard deviation only.

$$SN_T = 10 \log\left(\frac{y^2}{S^2}\right) \tag{2}$$

• Larger the Better (For making the system response as large as possible) choose when the goal is to maximize the response.

$$SN_L = -10\ \log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{3}$$

The results of Taguchi analysis are expressed in the form of main effect plots for SN ratio, which illustrates the effect of selected factors on responses. Based on previous studies the factors levels of these mix parameters are chosen, which are as stated follows

- Water-Cement Ratio or W/C ratio
- Maximum Cement Content (kg m^{-3})
- RCA (%)
- Nano-Silica (%)

Based on recommendation of previous researchers the levels of each control factors have been fixed and shown in Table 3.

Orthogonal array is normally decided based upon the factors and their variation levels. In this present investigation, L9 orthogonal array (OA) has been selected and the mix proportions for one cubic meter of concrete are presented in Table 4.

Table 3 Control parameters and levels

	Control Parameters	Level 1	Level 2	Level 3
A	Water Cement Ratio (W/C)	0.39	0.42	0.45
B	RCA (%)	0	50	100
C	Maximum Cement Content (Kg/m3)	350	400	450
D	Nano-Silica (%)	0	1.5	3

Table 4 Details of mix concrete proportions according Orthogonal Array (L9).

Trial Mix	W/C ratio	Recycled Coarse Aggregate (%)	Maximum Cement Content(kg m^{-3})	Nano-Silica (%)
1	0.39	0	350	0.0
2	0.39	50	400	1.5
3	0.39	100	450	3.0
4	0.42	0	400	3.0
5	0.42	50	450	0.0
6	0.42	100	350	1.5
7	0.45	0	450	1.5
8	0.45	50	350	3.0
9	0.45	100	400	0.0

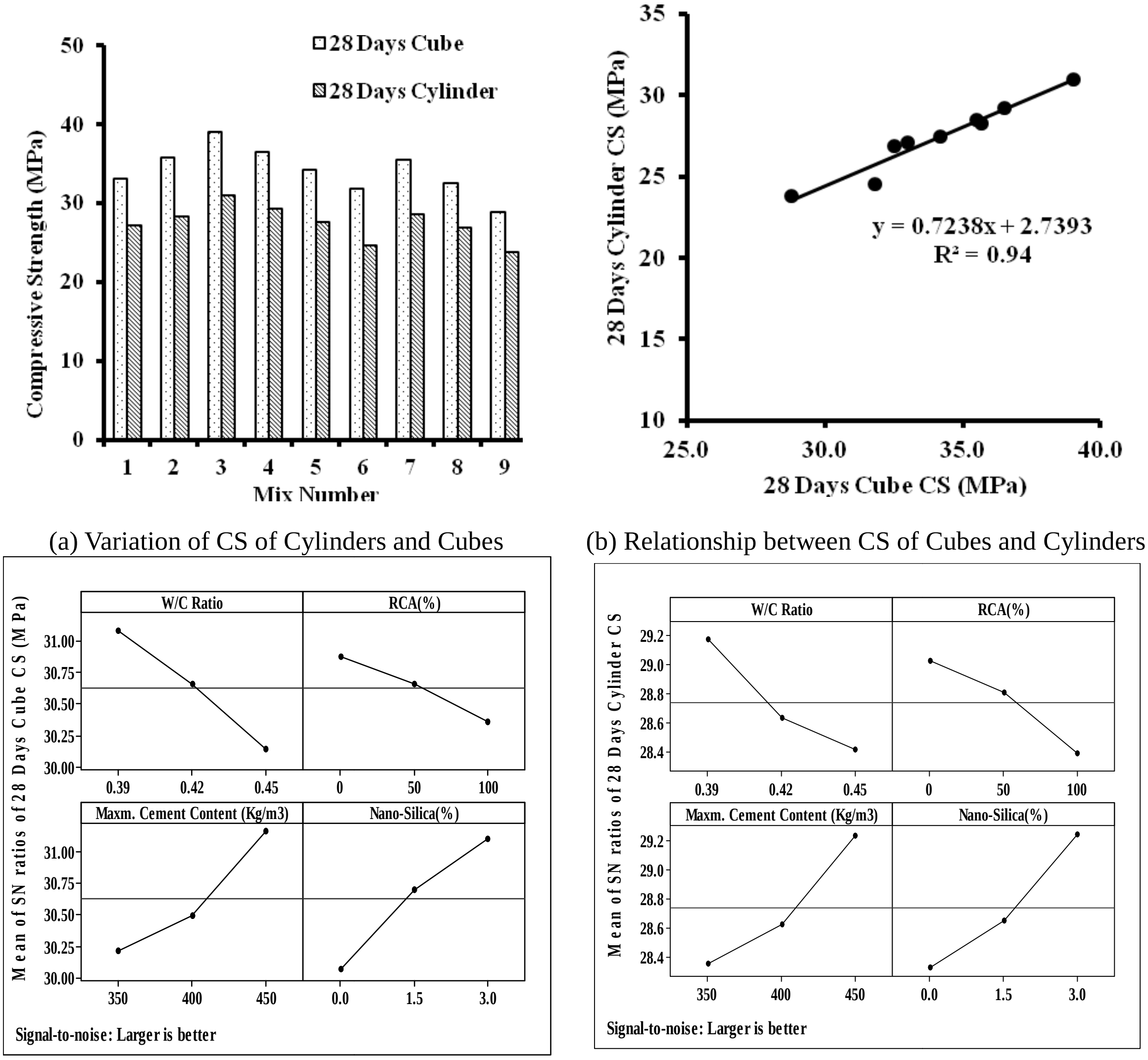
2.3 Preparation, casting and testing of specimens

The concrete mixes were designed as per the quantity of materials given in Table 4. However, depending upon the amount of RCA in a particular mix, the correction for water absorption was made. The required amount aggregates and cement was thoroughly mixed at a low speed for 2 min in a concrete rotary mixture. The required amount of NS was added to the water with consideration of the quantity of water present in colloidal NS. After that, the mixture of NS and water was slowly poured in and stirred at a low speed for another 2 min to achieve desired workability. Concrete specimens were removed from molds after 24 h and thereafter curing was done under water for duration of 28 days at normal temperature and humidity conditions. The CS was determined on standard cubes of size 150 mm and cylindrical specimens of 150 mm Φ× 300 mm height using 3000 kN compressive testing machine in accordance with BIS (IS: 516-1959). Modulus of Elasticity (E) of concrete mixes was determined using cylindrical specimens of 150 mm Φ× 300 mm height in accordance to ASTM C 469 (2002). The split Tensile Strength (STS) Test of concrete after 28 days was performed on cylindrical specimens of 150 mm Φ× 300 mm height according to the procedure given in BIS (IS 5816 1999). The Flexural Tensile Strength (FTS) test was conducted on prisms of size 100×100×500 mm in accordance with BIS (IS 516 1959). Ultrasonic pulse velocity (UPV) test was performed in accordance with BIS (IS: 13311 (Part 1) 1992) using TICO ULTRASONIC INSTRUMENT, supplied by PROCEQ SA, Switzerland. The rebound number (RN) test was performed in accordance with BIS (IS: 13311 (Part 2) 1992) using Schmit Hammer (TYPE ND) supplied by supplied by PROCEQ SA, Switzerland. Statistical analysis of the experimental results have been carried out using MINITAB software @ 16 for the determination of the importance of each selected factors for its contribution towards the optimization of the behavior of concrete. The Analysis of Variance (ANOVA) has been carried out to determine the relative significance and effect on responses. In this study Taguchi Method stresses the importance of studying the responses variation using the SN ratio, resulting the maximization of quality characteristics variation due to the controllable factors with the concept of the “Larger-the Better”.

3. Results and discussion

3.1 Compressive strength

The variation of compressive strength of cubes and cylinders for all nine number of mixes are presented in Fig. 2(a). However, it is observed that the 28 days CS of cube are higher than that cylinders is due to the size effect phenomenon of specimens, which states that increase in the aspect ratio leads to decease in CS (Neville 2012). However, the experimental values of individual mix could not be compared with another mix as in each mix each individual parameter is kept at different level. Fig. 2(b) shows the relation between the 28 days cubes and cylinder CS of all mixes. It was found that liner correlation exists and the coefficient of determination is found to be 0.94 that indicates about the existence of strong correlation between the two parameters. The main effects plot for S/N ratios for the 28 days CS of cubes and cylinders with consideration all the factors are presented in Fig. 2(c)-(d) respectively. It can be seen that the response 28 days CS improves with increases with increase in the factors maximum cement content and NS(%).This observed enhancement in CS with increase in addition of NS is mainly because of densification of



(a) Variation of CS of Cylinders and Cubes (b) Relationship between CS of Cubes and Cylinders

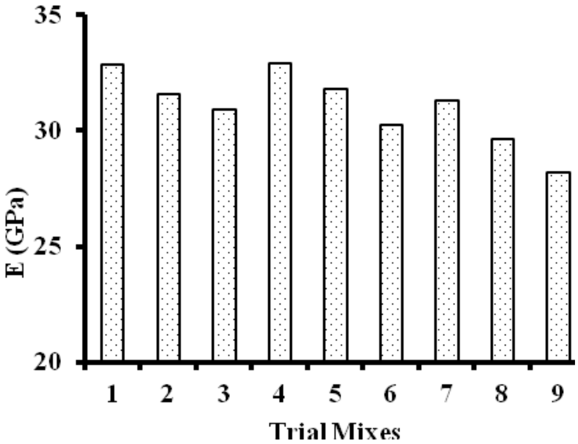
(c) Plots for S/N ratios of CS of cubes (d) Plots for S/N ratios of CS of cylinders

Fig. 2 Analysis of results of compressive strength

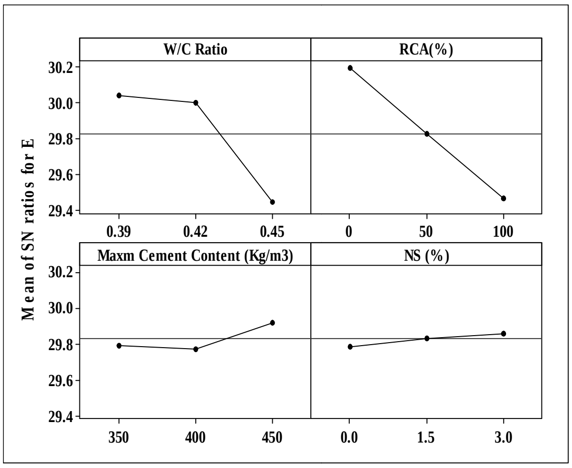
concrete with removal of voids present in concrete (Pacheco-Torgal *et al*. 2010). Furthermore, the improvement of CS with increase in cement content is due to increase in binding material, which improves the bonding between cement mortars and aggregates (Neville 2012). However, 28 days CS reduces with increase in W/C ratio and RCA(%).The reduction in 28 days CS with increase in RCA(%) is due to the degradation of concrete quality with the incorporation of RCA whose properties are inferior to virgin aggregates (de Juan and Gutiérrez 2009). Moreover, the reduction of 28 days CS with increase in W/C ratio is attributed the fact that increase in W/C ratio weakens the mortar matrix subsequently affecting the CS of concrete (Neville 2012). The influences of the factors are ranked based on a parameter called Delta, which is the difference between the maximum responses to the minimum response. It is observed that all the factors are significantly affecting the response 28 days CS, however, it is found that the effect of factor NS(%) is having rank one whereas the factor RCA(%) is having rank 4. The optimal value of 28 days CS is achieved when water cement ratio is kept at 0.39 (level 1), RCA at 0% (level 2), Maximum cement content at 450 kg m-3 (level 3), and percentage of Nano-silica at 3% (level 3) i.e. at A1B1C3D3.

3.2 Modulus of elasticity

Fig. 3(a) shows the variation of Modulus of Elasticity (E) for nine numbers of mixes. From the main effect plot for SN ratio of E is shown in Fig. 3(b). The figure depicts that the factor RCA(%) is at rank one then followed by water cement ratio, Maximum cement content and NS (%) at rank 4. The incorporation of pozzolanic materials has no significance influence on E value, as E value of concrete is dependent on characteristics of aggregates.



(a) Variation of modulus of elasticity (E)



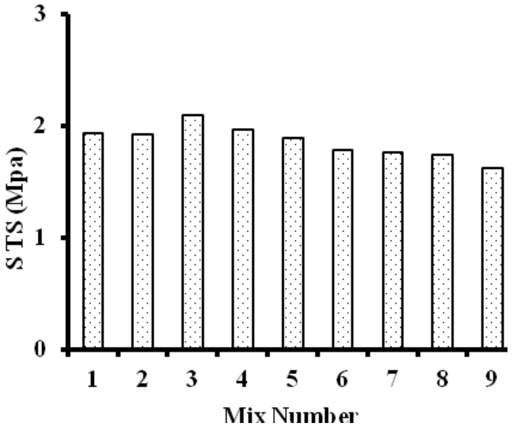
(b) S/N ratios of modulus of elasticity (E))

Fig. 3 Analysis of results of modulus of elasticity

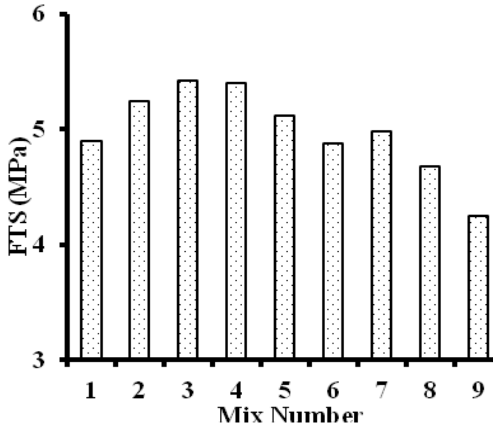
Therefore, the factor NS(%) is ranked at last among all selected factors. Moreover, the optimal performance is at water cement ratio of 0.39 (level 1), replacement of RCA at 0% (level1), Maximum cement content at 450 kg/m3(level 3) and replacement of Nano-silica at 3% (level 3) i.e. at A1B1C3D3.

3.3 Tensile strength

Figs. 4(a)-(b) represents the graphical variation of Split and flexural Tensile Strength of nine numbers of mixes at 28 days respectively. The variation of these results depends upon several factors and levels of these factors



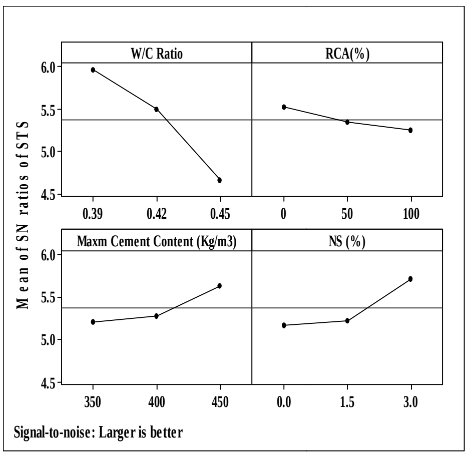
(a) Variation of STS



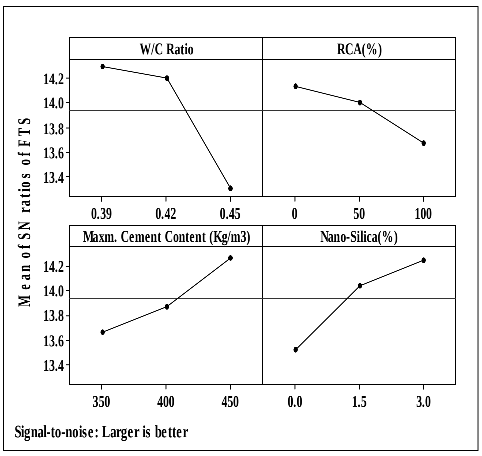
(b) Variation of FTS

Fig. 4 Analysis of results of tensile strength

From the delta analysis of plots for SN ratios of STS presented Fig. 5(a), it is found that W/C ratio is at rank one followed by NS (%), Maximum cement content and RCA(%) at rank 4. Moreover, it can be found that from analysis of SN ratio of STS the optimal performance is at water cement ratio of 0.39 (level 1), RCA at 0% (level1), Maximum cement content at 450 kg m-3 (level 3) and Nano-silica at 3% (level 3) i.e. at A1B1C3D3. The measured experimental results of FTS are analyzed statistically and plots of main effect for SN ratio values are shown in Fig. 5(b). Based on the delta value calculated from the, W/C ratio is at rank one followed by NS (%), Maximum cement content and RCA (%) at rank 4. From the main effect plot for SN ratio of flexural strength the optimal performance is at water cement ratio at 0.39 (level 1), RCA at 0% (level1), Maximum cement content at 450 kg m-3 (level 3) and NS at 3% (level 3) i.e. at A1B1C3D3.

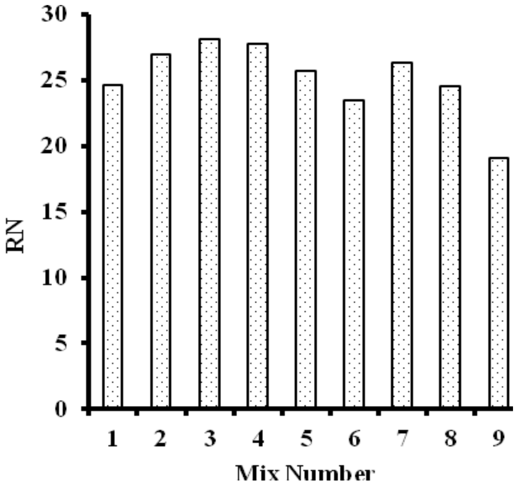


(a) Plots for S/N ratios of STS

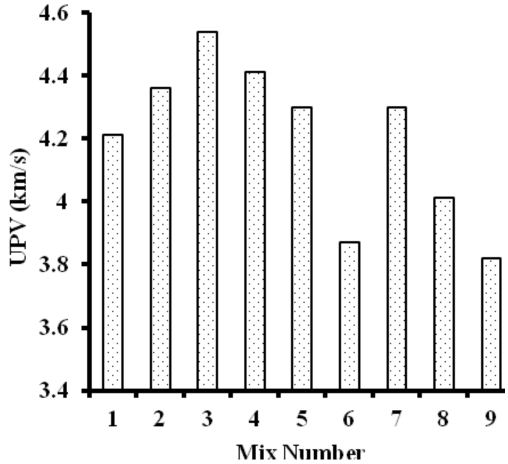


(b) Plots for S/N ratios of FTS

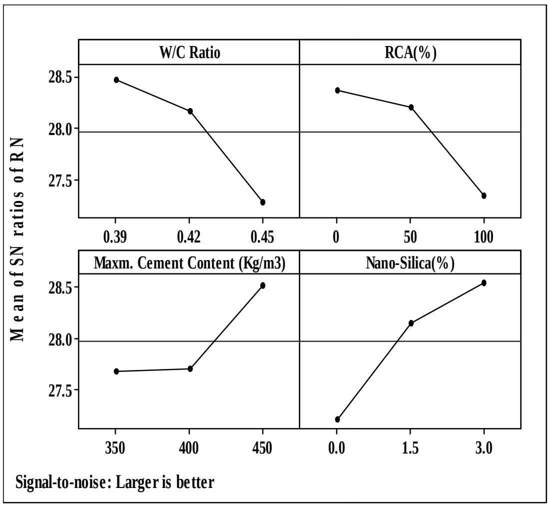
Fig. 5 Plots for S/N ratios of tensile strength



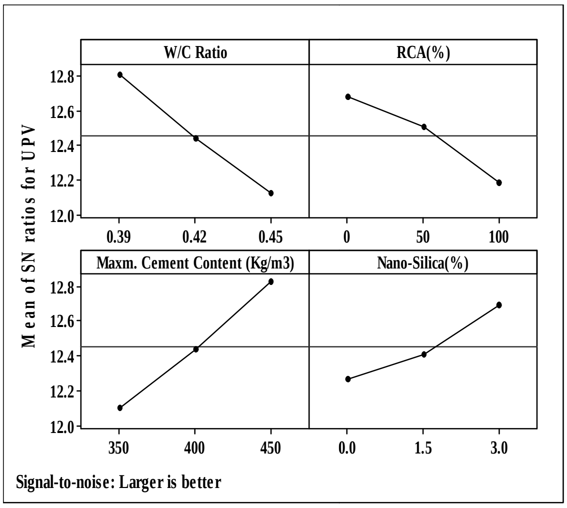
(a) Variation of RN



(b) Variation of UPV



(c) Plots for S/N ratios of RN

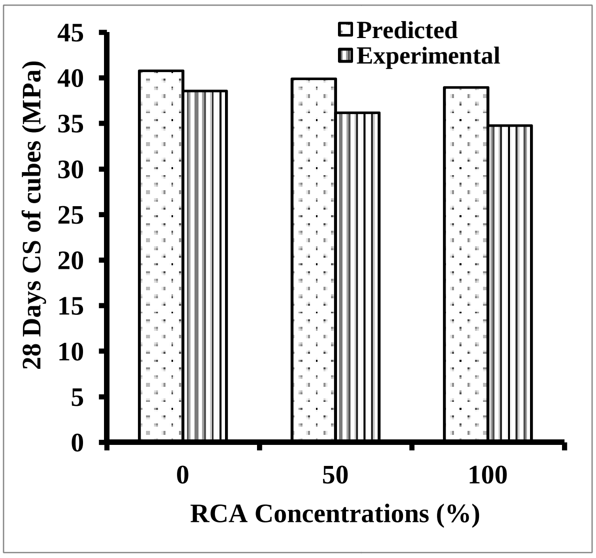


(d) Plots for S/N ratios of UPV

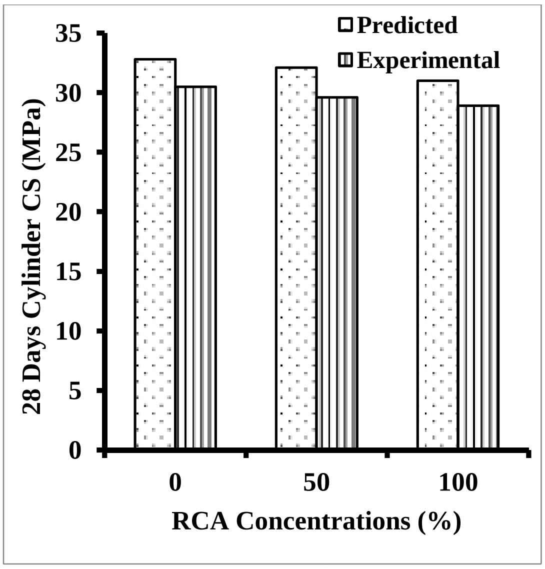
Fig. 6 Analysis of results of non-destructive test

3.4 Non-destructive test

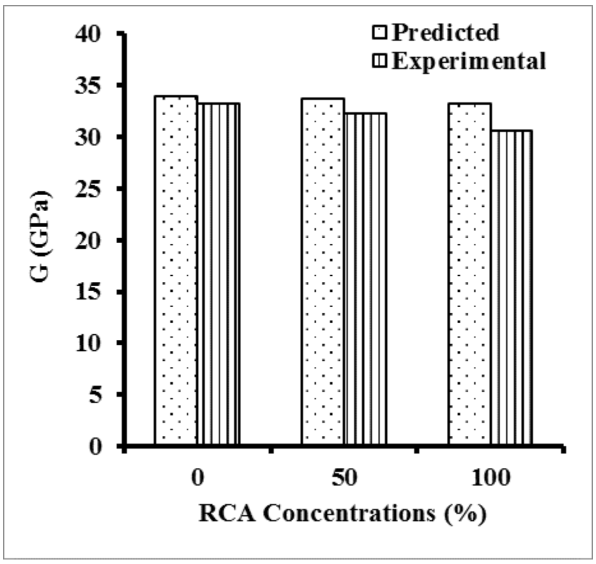
Fig. 6(a)-(b) illustrate variation of test results of Rebound Number (RN) and Ultrasonic Pulse Velocity (UPV) of concrete respectively. From the main effect plot for S/N ratio of RN shown in Fig. 6(c), the factor NS(%) is at rank one followed by water cement ratio, RCA (%) and Maximum cement content at rank 4. This type of behavior of RN of concrete with the incorporation of NS could be attributed to the fact that addition NS reduced the porosity of concrete mixes by filling the voids. Therefore, the RN of concrete increases with increasing NS(%). It is also found that the optimal performance of concrete is at W/C of 0.39 (level 1), RCA(%) at 0% (level1), Maximum cement content at 450 kg m-3 (level 3), and NS(%) at 3% (level 3) i.e. at A1B1C3D3. From the delta analysis of the main effect plot for S/N ratio of UPV shown in Fig. 6(d), the optimal performance is at water cement ratio of 0.39 (level 1), RCA (%) at 0% (level 1), Maximum cement content at 450 kg m-3 (level 3) and NS (%) at 3% (level 3) i.e. at A1B1C3D3. It is observed that the factor maximum cement content at rank one followed by water cement ratio, RCA (%) and Nano-silica (%) is at rank four. In this case, the delta value is very less than one for every case.



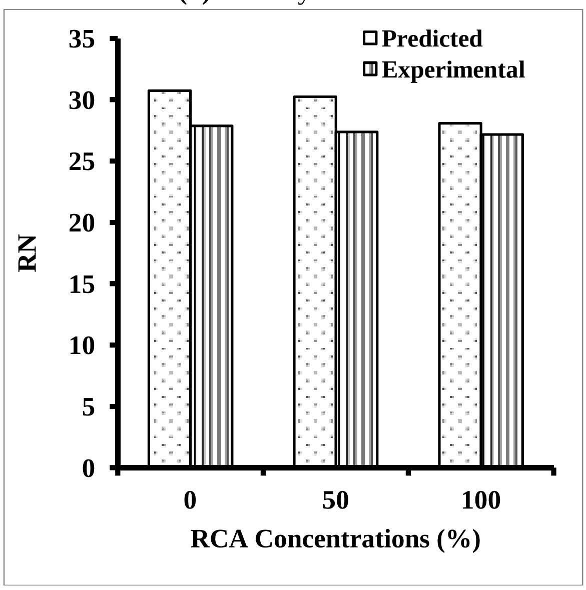
(a) CS of cubes



(b) CS of cylinders

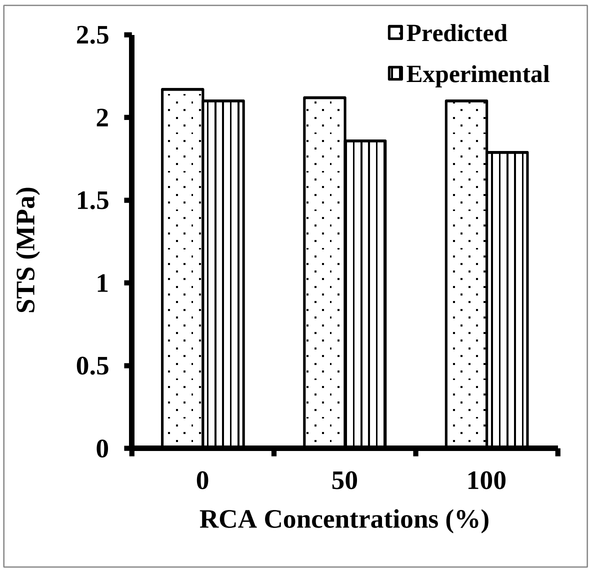


(c) Modulus of Elasticity

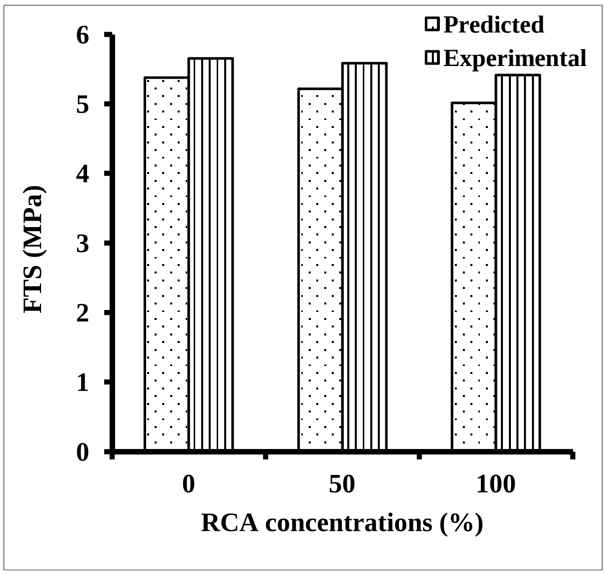


(d) Rebound Number

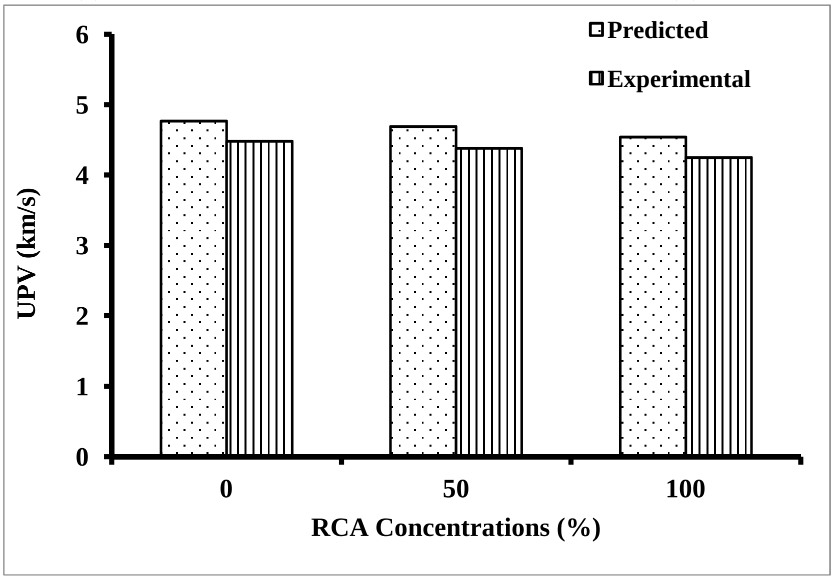
Fig. 7 Comparative study of predicted and experimental results



(a) STS



(b) FTS



(c) UPV

Fig. 8 Comparative study of predicted and experimental results

4. Verification experiments

From the above analysis it can be conclude that in most of the cases Nano-silica (%) and water-cement ratio are the effective factors for most of the responses. To study behavior of RAC, concrete mixes are designed with maximum cement content as 450 kg m-3, W/C ratio-0.39, NS-3% and RCA (%) as 0%, 50% and 100% . These are as follows

- Mix no. I: W/C ratio-0.39, RCA-0%, Cement Content-450 kg m-3, NS-3%
- Mix no. II: W/C ratio-0.39, RCA-50%, Cement Content-450 kg m-3, NS-3%
- Mix no. III: W/C ratio-0.39, RCA-100%, Cement Content-450 kg m-3, NS-3%

Experiments for aforementioned three mixes have been conducted and the results for various parameters have been determined. The experimental results are interpreted and those are compared with results predicted by Taguchi analysis. Fig. 7 and 8 shows the comaprion of experimental and predicted results of the parameters. It can be seen that both results are close to each other, which gives confimation about the accurarcy of model.

The comparison study of results of verification experiments and predicted values by Taguchi model for the selected mix proportions concludes that the error between the experimental values and the predicted values are within the acceptable limits.

5. Conclusion

This present investigation has proposed the Taguchi method for assessment of optimal mixture with multiple responses for concrete containing RCA and NS. Water/cement ratio, recycled coarse aggregate(%), maximum cement content (kg m-3) and Nano-Silica(%) are selected as control factors with responses compressive strength, split tensile strength, flexural tensile strength, modulus of elasticity, rebound number and ultrasonic pulse velocity. Experimental results are analyzed using ANOVA and the summery of the analysis are discussed below:

- Statistical analysis of 28 days CS indicates that all the selected factors are significantly affecting the test results. However, among all factors W/C ratio and NS(%) are more significant factors than other two factors.
- Analysis of the split tensile strength results indicates that the effect of control factor W/C ratio is ranked one and then NS(%) is ranked two which suggests that W/C ratio and NS (%) have more influence factors compared to other two factors. Similar type of observation is also found in case of flexural strength results. However, the analysis of elastic modulus test results illustrates the factor RCA(%) is found to be most significant among all other factors.
- Non-destructive test results are analyzed and significance each factor is determined. The influence of W/C ratio and NS(%) are also confirmed from the analysis. The ANOVA study depicts that W/C ratio and NS (%) are dominant factors in most cases.
- Verification experiments have been conducted to compare performance of the selected mix proportions and it is found that the error between the experimental values and the predicted values are within the acceptable limits.

References

ASTM C 469 (2002), *Standard test method for static modulus of elasticity and Poission's ratio Concrete in Compression*, Annual Book of ASTM Standards, Pennsylvania, USA.

Berndt, M.L. (2009), "Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate", *Constr. Build. Mater.*, **23**(9), 2609-2613.

Berra, M., Carassiti, F., Mangialardi, T., Paolini, A.E. and Sebastiani, M. (2012), "Effects of nanosilica addition on workability and compressive strength of Portland cement pastes", *Constr. Build. Mater.,* **35**, 666-675.

Chang, C.Y., Huang, R., Lee, P.C. and Weng, T.L. (2011), "Application of a weighted Grey Taguchi method for optimizing recycled aggregate concrete mixture", *Cem Conc Comp.*, **33**(10), 1038-1049.

Coelho, A. and de Brito, J. (2011), "Distribution of materials in construction and demolition waste in Portugal", *Waste Manage Res,* **29**(8), 843-853.

De Juan, M.S. and Gutiérrez, P.A. (2009), "Study on the influence of attached mortar content on the properties of recycled concrete aggregate". *Constr. Build. Mater.*, **23**(2), 872-877.

Del Río Merino, M., Gracia, P.I. and Azevedo, I.S.W. (2010), "Sustainable construction: construction and demolition waste reconsidered", *Waste Manage Res.*, **28**(2), 118-129.

Elhakam, A.A., Mohamed, A.E. and Awad, E. (2012), "Influence of self-healing, mixing method and adding silica fume on mechanical properties of recycled aggregates concrete", *Constr. Build. Mater.,* **35**, 421-27.

Hao, J.L., Hills, M.J. and Tam, V.W. (2008), "The effectiveness of Hong Kong's construction waste disposal charging scheme", *Waste Mange Res*, **26**(6), 553-558.

Hosseini, P., Booshehrian A. and Madari, A. (2011), Developing concrete recycling strategies by utilization of nano-SiO2 Particles, *Waste and Biomass Valor,* **2**(3), 347-355.

IS 1331 (1992), *Indian Standard Non-Destructive Testing of Concrete-Method of Test: Part 1 Ultrasonic Pulse Velocity*, Bureau of Indian Standards, New Delhi, India.

IS 1331 (1992), *Indian Standard Non-Destructive Testing of Concrete-Method of Test: Part 2 Rebound Hammer*, Bureau of Indian Standards, New Delhi, India.

IS 2386 (1963), *Methods of Test for Aggregates for Concrete*, Bureau of Indian standards, New Delhi, India.

IS 383 (1970), *Specification for Coarse and Fine Aggregates*, Bureau of Indian standards, New Delhi, India.

IS 5816 (1999), *Indian Standard Splitting Tensile Strength of Concrete-Method of Test*, Bureau of Indian Standards, New Delhi, India.

Limbachiya, M., Meddah, M.S. and Ouchagour, Y. (2012), "Use of recycled concrete aggregate in fly-ash concrete", *Constr. Build. Mater.,* **27**(1), 439-449.

Lin, K.L., Wu, H.H., Shie, J.L., Hwang, C.L. and Cheng, A. (2010), "Recycling waste brick from construction and demolition of buildings as pozzolanic materials", *Waste Manage Res.,* **28**(7), 653-659.

Lin, Y.H., Tyan, Y.Y., Chang, T.P. and Chang, C.Y. (2004), "An assessment of optimal mixture for concrete made with recycled concrete aggregates", *Cem Concrete Res.,* **34**(8), 1373-1380.

Minitab v16 (2010), Minitab Inc.

Montgomery, D.C. (2012), *Design and Analysis of Experiment*, John Wiley and Sons Inc., New York, USA.

Mukharjee, B.B. and Barai, S.V. (2014), "Influence of nano-silica on the properties of recycled aggregate concrete", *Constr. Build. Mater.,* **55**, 29-37.

Neville, A.M. (2012), Properties of Concrete, Pearson Education India, New Delhi, India.

Olivia, M. and Nikraz, H. (2012), "Properties of fly ash geopolymer concrete designed by Taguchi method", *Mater and Design,* **36**, 191-198.

Ozbay, E., Oztas, A., Baykasoglu, A. and Ozbebek, H. (2009), "Investigating mix proportions of

high strength self compacting concrete by using Taguchi method", *Constr. Build. Mater.*, **23**(2), 694-702.
Pacheco-Torgal, F., Miraldo, S., Ding, Y. and Labrincha, J.A. (2013), "Targeting HPC with the help of nanoparticles: An overview", *Constr. Build. Mater.*, **38**, 365-370.
Poon, C.S., Kou, S.C. and Lam, L. (2002), "Use of recycled aggregates in molded concrete bricks and blocks", *Constr. Build. Mater.*, **16**(5), 281-289.
Qing, Y., Zenan, Z., Deyu, K. and Rongshen, C. (2007), "Influence of nano-silica addition on properties of hardened cement paste as compared with silica fume", *Constr. Build. Mater.*, **21**(3), 539-545.
Rakshvir, M. and Barai, S.V. (2006), "Studies on recycled aggregates-based concrete", *Waste Manage Res.*, **24**(3), 225-233.
Rao, M., Bhattacharya, S.K. and Barai, S.V. (2009), "Influence of field recycled coarse aggregate on properties of concrete", *Mater. Struct.*, **44**(1), 1163-1167.
Roy, R.K. (2001), *Design of Experiments Using the TAGUCHI Approach: 16 Steps to Product and Process*, john wiley and sons Inc., New York, USA.
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.
Tam, V.W. and Tam, C.M. (2009), "Parameters for assessing recycled aggregate and their correlation", *Waste Manage Res.*, **27**(1), 52-58.
Tam, V.W., Kotrayothar, D. and Loo, Y.C. (2009), "On the prevailing construction waste recycling practices: a South East Queensland study", *Waste Manage Res.*, **27**(2), 167-174.
Turkmen, I., Gul, R. and Celik, C. (2008), "A Taguchi approach for investigation of some physical properties of concrete produced from mineral admixtures", *Build. Envir.*, **43**(6), 1127-1137.

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