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STUDY ON SILICA INFUSED RECYCLED AGGREGATE CONCRETE USING DESIGN OF EXPERIMENTS

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Abstract

Recycled Aggregate (RA) generated from the construction industry is used as a material for sustainable construction. The old mortar attached to these aggregates makes it porous and are generally used for low-grade applications. However, by infusing with silica fumes, the properties of recycled aggregate concrete (RAC) can be improved, as the silica fumes get infused into the pores of old mortar attached to it. In this study, the optimum percentage of recycled aggregate that can be used in fresh concrete for higher grade applications was found out. Design of experiments (DoE) was used to optimize percentage of silica fumes and recycled aggregate to achieve optimum properties of concrete. Equations to predict the properties of concrete were also modelled using regression analysis.

Keywords: Concrete, Silica fumes, Recycled aggregate, Design of experiments.

1. Introduction

Sustainable development is an important concept in today's world. Recycled aggregate (RA) which is generated as a waste product of the construction world is identified as a sustainable material and lot of research works are done in this area [1-3]. Generally the application of RA is confined to low-grade applications because of its weak interfacial transition zone [4-6].

Silica fumes enhance the mechanical and micro-structural properties of concrete through pozzolanic reaction and filler effect. Improvement in tensile strength and

Nomenclatures

CCD	Central composite design
DoE	Design of experiments
ITZ	Interfacial transition zone
NMA	Normal mix approach
P	P-value
PRESS	Prediction sum of squares
RA	Recycled aggregate
R-Sq	R-squared
R-Sq(adj)	Adjusted R-squared
R-Sq(pred)	Predicted R-squared
RSM	Response surface method
S	Standard error of the regression
SE Coef	Standard error of coefficient
T	T-value
TSMA	Two-stage mix approach
X_1	Silica percentage
$X_1.X_2$	Pair wise interaction terms
X_1^2, X_2^2	Curvilinear terms
X_2	Recycled aggregate percentage

Abbreviations

IS	Indian Standard

compressive strength of recycled aggregate concrete is observed with the incorporation of silica fumes [7]. Pozzolan-silica fume combinations can improve the strength of mortars more than natural pozzolan or silica fume alone. The increase in strength can be attributed to the improved aggregate-matrix bond resulting from the formation of a less porous transition zone in the silica fume concrete [7, 8].

The mixing approach for recycled aggregate is generally done in two ways, normal mix approach (NMA) and two-stage mix approach (TSMA) [9]. In normal mix approach water is added to the mix in one step whereas in TSMA water is added in two steps. In the first stage the coarse aggregate, fine aggregate and half of water is added and mixed and in second stage, the cement is added to this mixture and then remaining water is added [9]. As the mixing of ingredients in TSMA follows different stages, it gives more homogenous mix when compared to NMA due to denser concrete microstructure and a better improved interfacial transition zone [9, 10].

The structure of recycled aggregate concrete is much more complicated than that of normal concrete. It possesses two ITZs, one between the recycled aggregate (RA) and new cement paste (new ITZ) and the other between the recycled aggregate (RA) and the old mortar attached (old ITZ) [11, 12] (Fig. 1).

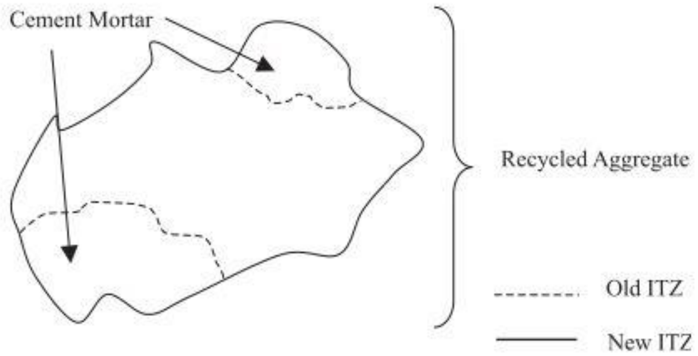

Fig. 1. Interfacial transition zones of RAC [11].

The main objective of the present investigation is to optimize the percentage of recycled aggregate that can be replaced for coarse aggregate and the amount of silica for an economical design. The aspect of economical design can be attained by maximum replacement of coarse aggregate with recycled aggregate without compromising the strength. The work also focuses on optimizing the factors (silica percentage and recycled aggregate) for the required zone of response (workability and strength) using Design of Experiments (DoE).

2. Experimental Program

2.1. Materials

For this study Ordinary Portland cement of 53 grade and amorphous densified grade B silica fume was used. Care was taken so that no lumps were formed during mixing. The basic material properties of fine aggregate, coarse aggregate (virgin and recycled), cement and silica fume are listed in Tables 1 and 2.

Table 1. Basic material properties [13].

Properties	Result
Specific gravity coarse aggregate (Virgin)	1.56
Specific gravity recycled aggregate	1.23
Zone of fine aggregate	Zone II
Specific gravity of fine aggregate	2.10
Specific gravity of cement	3.15

Table 2. Basic properties of silica fume.

Properties	Result
SiO_2 content (%)	91
CaO content (%)	0.3
Specific surface (m^2/kg)	22000
Specific gravity	2.1

2.2. Mix proportions and testing

The concrete was designed as per IS 10262: 2009 [14] for a target mean strength of M50. Mixing proportions were done for 0%, 10%, 20%, 30%, 40%, and 50% by weight replacements of coarse aggregate by RA for both NMA and TSMA. In normal mix approach (NMA) coarse aggregate, fine aggregate, cement and water added respectively and desired concrete mix was obtained. In two-stage mix approach (TSMA) water was added in two steps. In the first step water is added to fine aggregate and coarse aggregate and mixed for 30 seconds. In second step cement was added and then mixed for 30 seconds and then remaining water was added again, mixed for 120 seconds.

The concrete mixture was poured into molds of size 10cm×10cm×10cm to form concrete cubes. The compressive strength of these cubes after 7 day and 28 days curing are measured as per IS 516 (1959) [15].

3. Results and Discussion

3.1. Optimization of recycled aggregate

Concrete is of a three-phase system, comprising of coarse aggregate, fine aggregate in mortar mix and Interfacial Transition Zone (ITZ) between mortar matrix and coarse aggregate. This Interfacial Transition Zone between cement paste and aggregate plays a vital role in concrete. The weakness of interfacial zone inhibits the accomplishment of composite action in normal strength concrete and hence, the interfacial region is generally considered as the 'weak link' in concrete.

The proportions of recycled aggregate were taken as 10%, 20%, 30%, 40% and 50% by weight of coarse aggregate. All the mix proportions of RAC mixed using TSMA and NMA were done with a slump of 75 mm (medium workability) as per mix design. In TSMA adding half of the water during mixing will lead to the formation of thin layer of cement slurry on the surface of recycled aggregates, which permeates into the porous of old cement mortar filling up the old cracks and voids. In order to complete the cement hydration process, the remaining water is added and thus developing a strong Interfacial Transition Zone (ITZ). The water cement ratio of the mix was taken as 0.4, and the cubes of size 10 cm × 10 cm were casted.

The results of compressive strength of Normal Mix Approach (NMA) and Two Stage Mix Approach (TSMA) are tabulated and represented in Fig. 2 corresponding to 7 day strength and in Fig. 3 corresponding to 28 day strength.

From the results presented in Figs 2 and 3, it is observed that the optimum amount of recycled aggregate that can be replaced to attain maximum compressive strength was near to 30% RA for both 7 and 28 days of curing.

The replacement of recycled aggregate using TSMA showed an increase in compressive strength compared with NMA and is shown in Fig. 4. From these results it is evident that the strength of concrete made of TSMA are better than that of NMA for 28 day. Therefore by replacing 30% of coarse aggregate by RA using TSMA was found to be optimum for attaining the maximum compressive strength.

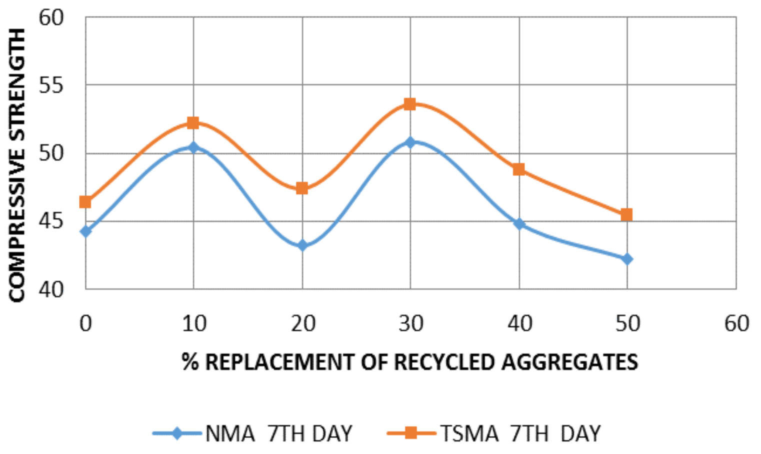

Fig. 2. Compressive strength for different proportions of RAC at 7 days.

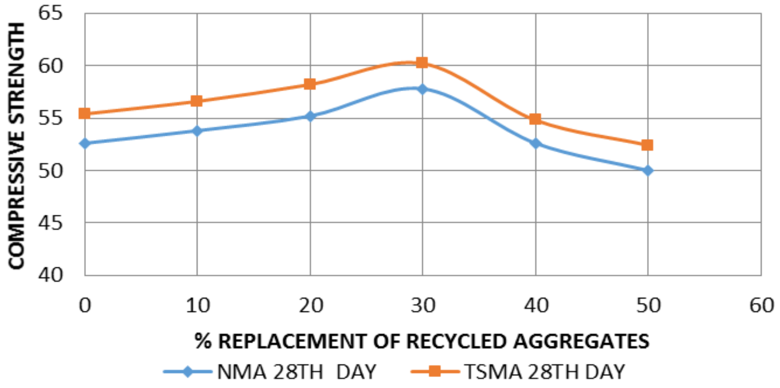

Fig. 3. Compressive strength of different proportions of RA at 28 days.

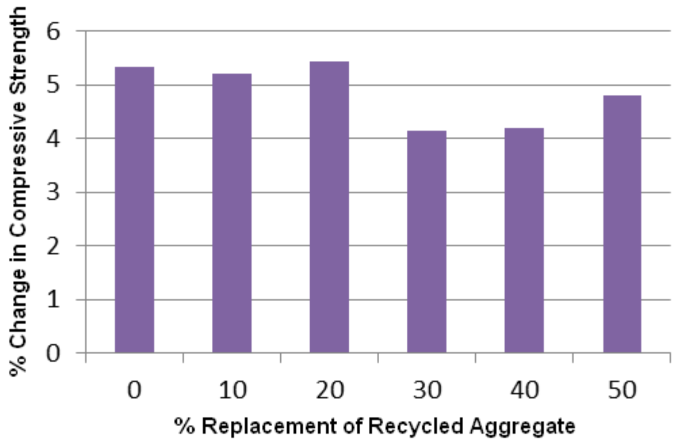

Fig. 4. Percentage change in compressive strength of TSMA with respect to NMA at 28 day.

3.2. Design of experiments

The present investigation focuses on finding the flow properties (workability) and compressive strength of concrete with the replacement of cement by silica fume and coarse aggregate by recycled aggregate. Based on the experimental investigation reported in section 2, optimum amount of recycled aggregates to attain high strength is found to be between 20 to 40 %. Also based on the previous research works the amount of silica content in the concrete is 10 to 30% of cement to attain high compressive strength [7, 8, 16, 17]. Hence in the present investigation RA composition is made between 20 to 40 % of coarse aggregate and silica between 10 to 30 % of cement. Design of Experiments (DOE) is used to get the best possible combination of experiments. To get the maximum information from the minimum number of experiments, it was decided to use response surface methodology (RSM) for the experimental study. RSM also enables to model the various properties of concrete with respect to the percentages of silica and aggregates. A central composite design (CCD) was chosen considering its larger design space and rotatability. A CCD can run sequentially and are very efficient, providing much information on experiment variable effects and, overall experimental error in a minimum number of required runs. In addition to modelling the properties as a function of the factors / variables, it permits optimization of variables to get the desired properties. Compared to a factorial design, the design space in CCD is larger extending beyond the defined variable bounds and the predicted responses at or near the axial points fall within the design region. Generally, the magnitude of prediction error increases geometrically with distance outside the design region and due to this the prediction error is much lesser than other conventional experimental predictions. The values of the variables were provided as the minimum and maximum for generating the CCD design. The response taken for the above selected factors were the compressive Strength (both 7 days and 28 days) and flow percentage. The variation of properties with respect to linear terms (X_1 and X_2), pair wise interaction terms (X_1. X_2) and curvilinear terms (X_1^2 and X_2^2) were investigated. Here X_1 and X_2 refer to silica content and aggregate content respectively. (Refer Eq. (1) Section 3.3). The experimental design for the study was generated using Minitab 17 (statistical software) [18] by considering the nonlinear behaviour of concrete and is listed in Table 3.

Table 3. Design table for experimentation.

Run Order	% of Aggregates	% of Silica
1	30	20
2	30	5.85
3	20	10
4	15.8	20
5	44.1	20
6	20	30
7	30	20
8	40	10
9	40	30
10	30	34.1
11	30	20
12	30	20
13	30	20

3.3. Analysis by design of experiments

Experimental investigations are conducted based on the run order generated in Table 3 for flow percentage, 7 and 28 day compressive strength and presented in Table 4.

Using the experimental results presented in Table 4 regression analysis was performed to predict the compressive strength and flowability of concrete as a function of silica and aggregate and reported in Figs. 5, 6 and 7.

The flow percentage decreases with increase in the percentage of aggregate. The trend is same with nearly equal slope for all the levels of silica (low, middle, high) and hence it can be concluded that the interaction effects are negligible. i.e., the variation of flowability with aggregates is independent of the amount of silica used in the concrete. Similarly, the flowability was found to decrease with increasing silica content. Here also, the variation of flowability with silica content was independent of the amount of aggregates.

Table 4. Experimental results for properties of silica infused recycled aggregate concrete.

Run Order	Percentage Recycled aggregate	Silica Percentage	Flow Percentage	7day Compress-ive Strength	28 day Compress-ive Strength
1	30.0	20.0	69.2	50.2	52.4
2	30.0	5.85	88.0	52.8	55.8
3	20.0	10.0	74.6	55.2	60.6
4	15.8	20.0	71.6	51.6	54.6
5	44.1	20.0	67.4	48.8	50.6
6	20.0	30.0	63.2	46.8	53.2
7	30.0	20.0	69.2	50.2	52.4
8	40.0	10.0	70.6	50.6	51.0
9	40.0	30.0	61.6	47.4	51.8
10	30.0	34.1	59.4	46.2	49.8
11	30.0	20.0	69.2	50.2	52.4
12	30.0	20.0	69.2	50.2	52.4
13	30.0	20.0	69.2	50.2	52.4

When the silica content is in between 20 - 30% the compressive strength is found to decrease with increase in aggregate content, the decrease is steeper when the aggregate level is 20%. But when the aggregate percentage is increased to 40% the compressive strength increases marginally with increase in silica [7].

For both 7 day and 28 day compressive strength decreases with increase in silica percentage irrespective of the amount of aggregate. However the decrease is sharper for lower amount of aggregate. Hence it can be concluded that the variation of compressive strength with amount of aggregates is dependent on the amount of silica or vice versa.

This shows that interaction effects are present between percentage of silica and aggregate, that is, the percentage of silica influences how the percentage of aggregate affect the compressive strength.

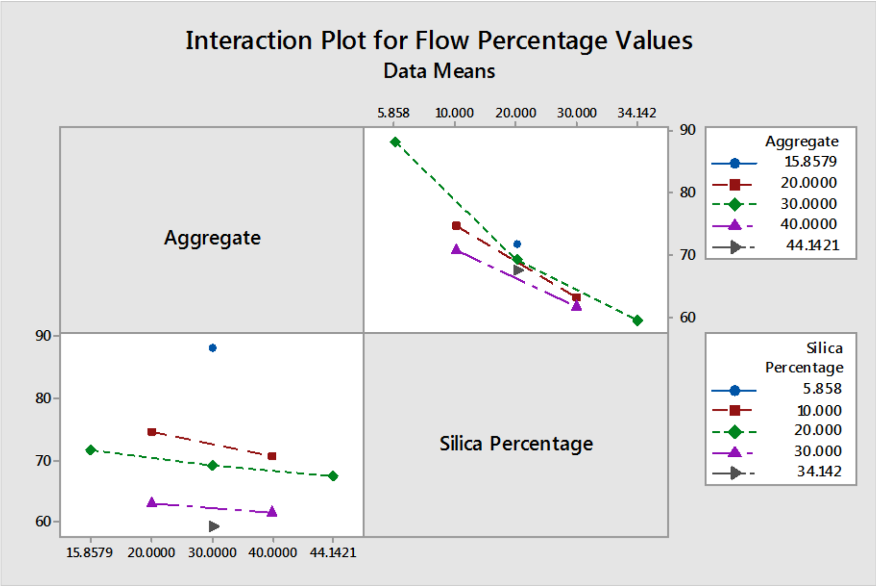

Fig. 5. Interaction plot for flow percentage values.

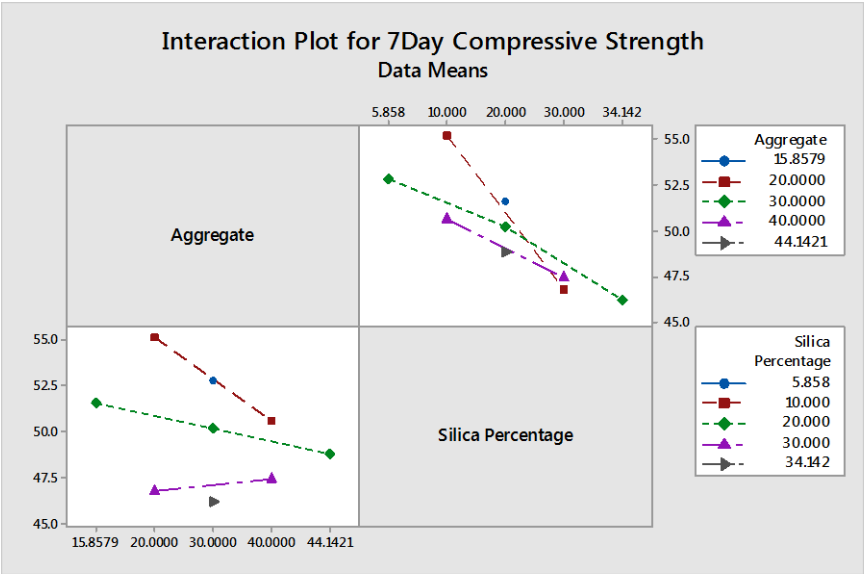

Fig. 6. Interaction plot for 7 day compressive strength.

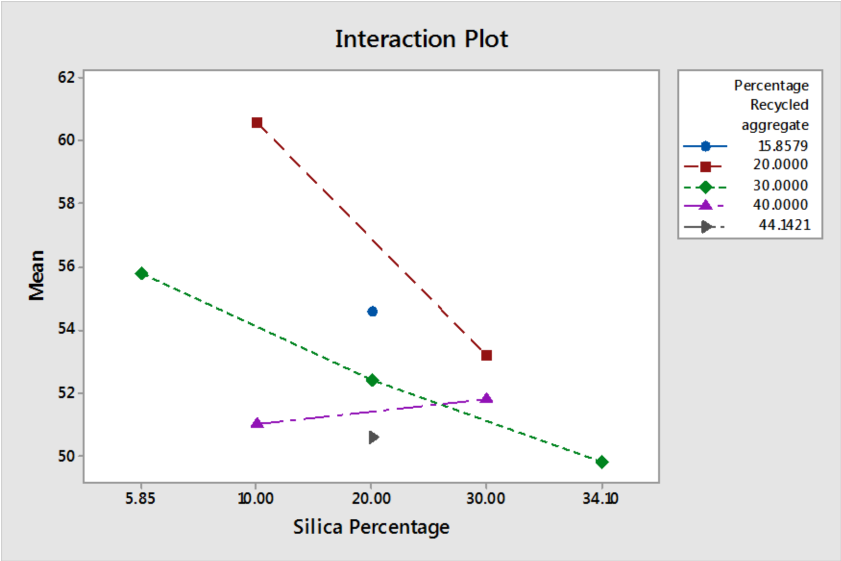

Fig. 7. Interaction plot for 28 day compressive strength.

To develop models to predict the flowability and compressive strength of concrete the experimental data was analysed by response surface regression using second order polynomial equation of the form

$$Y = C_0 + C_1X_1 + C_2X_2 + C_{11}X_1^2 + C_{22}X_2^2 + C_{11}X_1X_2 \quad (1)$$

where X_1 and X_2 represent silica percentage and recycled aggregate respectively.

Minitab package was used for regression analysis and analysis was done using coded units. Coded units are normalized centred representations, -1, 0 and +1 corresponding to the minimum, central point and maximum levels of the X factors respectively. Analysis in terms of coded units ensures orthogonality, a desired statistical property for any DoE. Table 5 illustrates the regression analysis for flowability.

Taking only the coefficient of terms that are significant based on statistical significance level of 0.1, the regression equation for flowability (in terms of actual values of the variables used or uncoded values) was obtained as

$$Flow\ Percentage\ Values\ = 89.5\ - 1.437\ X_1\ + 0.255X_2 \quad (2)$$

The factors with positive coefficient will have a positive effect on the property and those with negative coefficient will decrease the property. As noted from interaction plots it may be seen from the regression equation that interaction effect is significant. When the objective of the experiment is to optimize the properties, it is important to have higher R-squared values, implying that the regression model is a good predictor of the property being considered. The R-squared value of 85.73% for flowability indicates that 85.73% of changes in flowability can be explained by the model given in Eq. (2).

Similar regression analysis was conducted for 7 and 28 day compressive strength and the equations are:

$$7\ Day\ Compressive\ Strength = 65.31 - 0.5267X_1 - 0.3820X_2 - 0.00313X_1^2 + 0.01300X_1X_2 \quad (3)$$

$$28\ day\ Compressive\ Strength = 81.14 - 1.029X_1 + 0.896X_2 + 0.02050X_1X_2 \quad (4)$$

Contour plot is a two dimesional graph that represents emperical relationship between a property and any two variables. Here contour plots are drawn to represent the relationship between the response and the factors. In the present study workability(Fig. 8) and compressive strength (Figs. 9 and 10) are taken as responses.The factors considered here are silica fumes and recycled aggregate.

Table 5. Response surface regression: flow percentage vs. percentage recycled aggregate, silica percentage.

Term	Coefficient in Coded Units	Coefficient in uncoded units	SE Coeff.	*T*	*P*
Constant	69.20	89.540	1.543	44.851	0.000
aggregate	2.051	0.2548	1.725	1.189	0.273
silica	10.77	-14.373	1.725	6.242	0.000
aggregate*aggregate	1.743	-0.0087	2.616	0.666	0.527
silica*silica	2.457	1.2288	2.616	0.939	0.379
aggregate*silica	1.230	0.06150	3.450	0.357	0.732

S = 3.44999 PRESS = 592.475
R-Sq = 85.72% R-Sq(pred) = 0.00% R-Sq(adj) = 75.52%

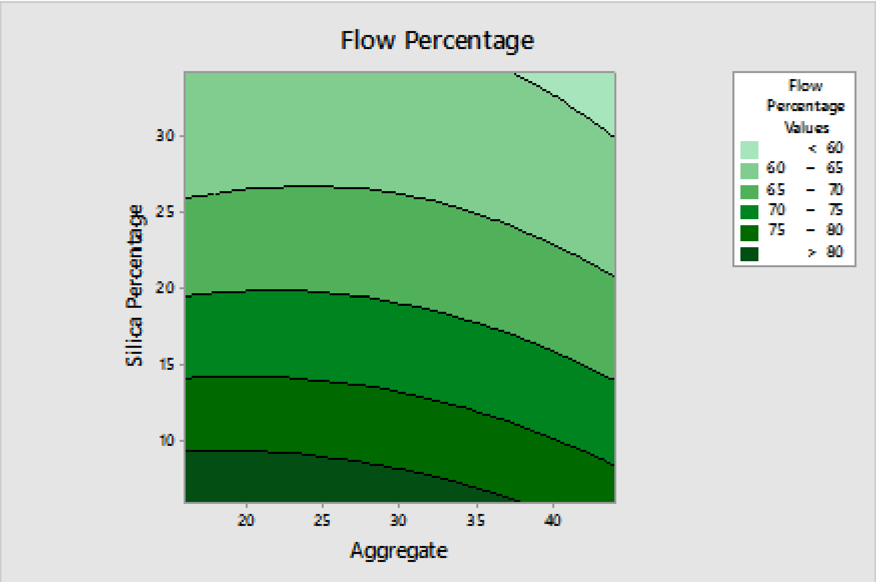

Fig. 8. Contour plots of flow percentage.

From Fig. 8 it is evident that as silica percentage and aggregate percentage increases, flowability decreases.The maximum amount of flowability is obtained when the silica percentage is less than 10% and aggregate is also from lower to middle levels.

Similarly the 7 day and 28 day compressive strength are highest when the silica and aggregate percentages are at lower levels (Figs. 9 and 10).

To optimize the concrete properties, the contour plots of flow percentage, 7day and 28 day compressive strength were overlaid within the applied constraints, listed in Table 6. These constraints were formulated based on the design requirements on fields corresponding to concrete of M50 grade and also considering a suitable factor of safety.

The contour plots for the three properties were overlaid to find the range of factors which gives the desired properties. Such a feasible region in the overlaid contour plot is depicted as white region in Fig. 11. Thus it can be inferred that corresponding to RA between 23 to 33 percentages and silica less than 10 percentages, the required target strength and workability can be achieved.

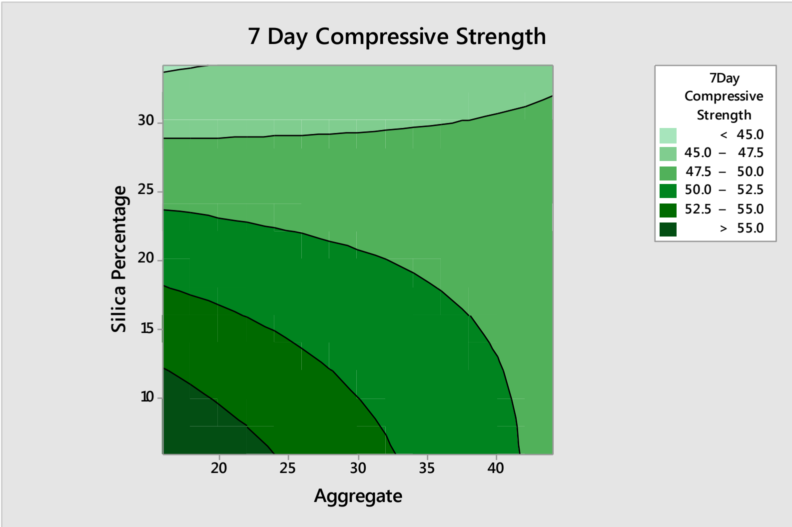

Fig. 9. Contour plots of 7 day compressive strength.

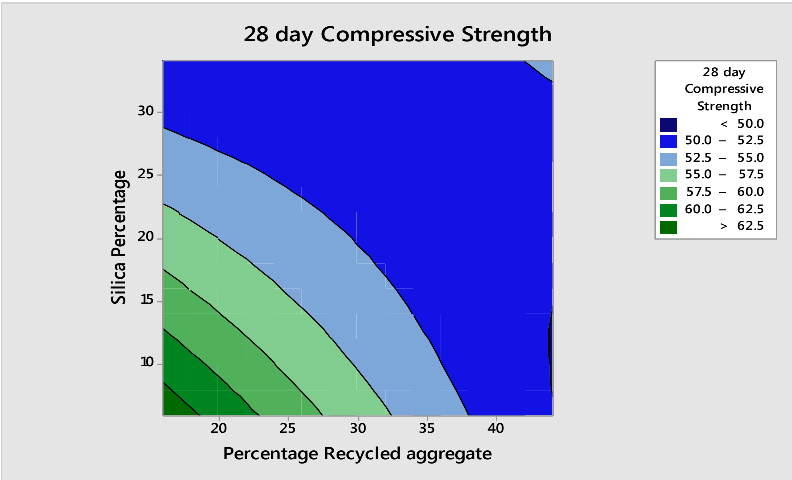

Fig. 10. Contour plots of 28 day compressive strength.

Table 6. Optimisation limits.

Name	Goal	Lower limit	Upper Limit
Compressive strength	Maximize	55 MPa	60 MPa
Flow Percentage	is in range	80%	88%

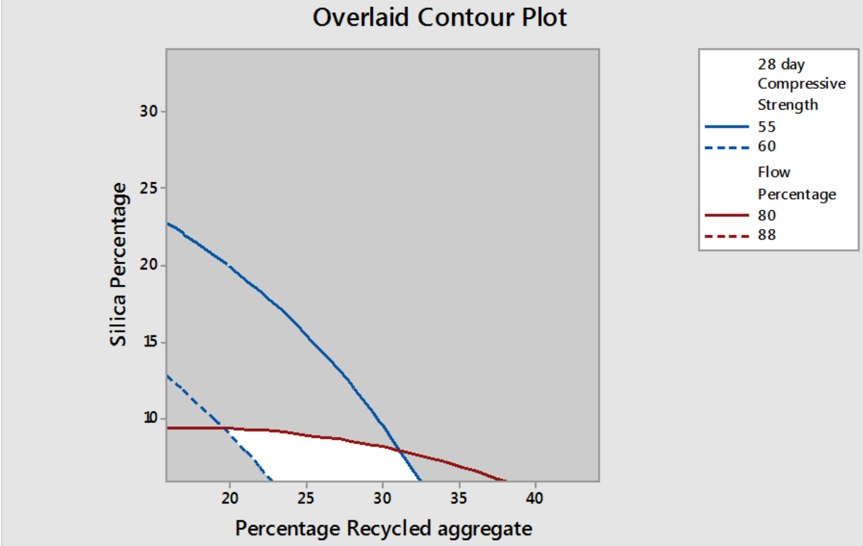

Fig. 11. Overlaid contour plot -28 day compressive strength and flow percentage.

4. Conclusions

This study discusses the effect of recycled aggregate as a replacement to coarse aggregate and the effect of silica as a replacement to cement on both the strength and workability of concrete. RA replacement was incorporated without any compromise on compressive strength. From the study it was found that two stage mix approach gives better results compared with normal mix approach. Design of experiments was performed by taking silica percentage and RA percentage replacement as the factors and the flowability and compressive strength as the responses. Based on the results it was observed that the flow percentage almost decreases with increase in the percentage of aggregate for all percentage of silica variation. The higher amount of silica addition on higher percentage aggregate replacement increases the strength but reduces the workability. This may be due to the pozzolanic and amorphous nature of the silica which increases the strength and water absorption. Based on the contour plot it is observed that the maximum amount of flowability is obtained when the silica percentage is less than 10% and aggregate is from lower to middle levels. The 7 day and 28 day compressive strength are highest when the silica and aggregate percentages are at lower levels.

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