Impact of using Recycled Demolition waste as Aggregates in Steel Fiber Reinforced Self-compacting Concrete on its Sulphate Resistance

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Abstract: The objective of performing this study was to estimate the impact of replacement of natural aggregates (NAs) with the recycled demolition waste aggregates (rDWAs) on the sulphate resistance of steel fiber-reinforced self-compacting concrete (FRSCC). In this regard, 13 laboratory experiments were conducted and analyzed using central composite design (CCD) in combination with response surface methodology (RSM). The sulphate resistance was evaluated in the form of % reduction in compressive strength (CS) of the FRSCC samples after 28 days, 90 days and 120 days. It was revealed that after 28 days, 90 days and 120 days the % reduction in CS was 97%, 14.85% and 8.6% more than the control samples, respectively. Also, the % reduction in CS of the FRSCC samples showed a linear relation with both the process parameters i.e., % replacement of NAs with rDWAs and % dosage of steel fibers. The findings of this study are expected to encourage the reuse of rDWAs in FRSCC-based structures.

Keywords: Recycling, waste management, self-compacting concrete, central composite design, optimization.

1. Introduction

Infrastructure development is one the most important factors that influence the comprehensive development of any nation. Construction materials such as, cement, aggregates, sand etc., are some of the extensively used materials in the infrastructure. Considering their importance and vast use, continuous innovations are being made in these materials with an objective of improving their properties and applications. In this way, the fiber-reinforced self-compacting concrete (FRSCC) has been invented that could improve various properties of the conventional concrete and also eliminated the use of vibrators [3]. Therefore, significant increase in the global use of SCC could be reported. However, several environmental and societal implications are associated with the generation and consumption of SCC-
based structures some of which are, excessive water consumption, waste generation, emission of pollutants etc [1–4].

In order to, eliminate the issues related to FRSCC-based construction, efforts are being made to replace the natural aggregates (NAs) with recycled demolition waste aggregates (rDWAs) [5,6]. It is expected that such efforts can assist in fulfilling the various sustainable development goals (SDGs) set by United Nations such as, SDG 3, SDG 8, SDG 12 and SDG 13. Also, the replacement of the NAs with the rDWAs was reported to sustain the properties of conventional FRSCC. Further, rDWAs were reported to show substantial affinity with the steel FRSCC. However, limited studies have estimated the impact of rDWAs on the sulphate resistance (SR) of the FRSCC [7,8].

Therefore, this study highlights the impacts of replacing the NAs with the rDWAs in the steel FRSCC, on its sulphate resistance ability. In this context, the samples of steel FRSCC with different proportions of rDWAs and steel fibers (SFs) were designed and analyzed for estimating the impacts on its SR after 28 days, 90 days and 120 days. Further, in order to optimize the results, the combination of central composite design (CCD) and response surface methodology was used. It is expected that the findings of this analysis will assist in encouraging the use of rDWAs in the FRSCC-based structures [9,10].

2. Materials and methods

2.1. Constituents of concrete

The basic constituents of the FRSCC, used in present study, were ordinary portland cement (OPC) of 43-grade, natural aggregates (NAs): fine and coarse, rDWAs: coarse, fly ash, superplasticizer, water and SFs. The NAs, comprising fine and coarse aggregates, were procured from a local quarry [11,12]. The demolition waste was collected from a demolition site located in S.A.S. Nagar Mohali, Punjab, India. Fly ash was used as an admixture and it was bought from ACC Ltd., Ropar, Punjab, India. The polycarboxylate type superplasticizer was used and bought from Oswal Chemical Ltd., Chandigarh, India. Similarly, tap water was used for preparing all the solutions. The various properties of these constituents are mentioned Table 1 & 2.

| S.No. | Property          | Units     | Values                      |
|-------|-------------------|-----------|-----------------------------|
|       |                   |           | Cement | Fine Aggregates | Coarse Aggregates | Fly ash |
| 1     | Blaine's Fineness | m²/kg     | 352    | -              | -                | -       |
| 2     | Specific gravity  | g cm⁻³    | 3.09   | 2.3            | 2.7              | 2.76    |
| 3     | Consistency       | %         | 33     | -              | -                | -       |
| 4     | Initial setting   | min       | 52     | -              | -                | -       |
| 5     | Final setting     | min       | 256    | -              | -                | -       |
| 6     | Bulk density      | kNm⁻³     | -      | 17             | 15.1             | -       |
| 7     | Void ratio        | -         | -      | 0.499          | 0.467            | -       |
| 8     | Fineness modulus  | -         | -      | 2.87           | 6.91             | -       |
| 9     | LOI               | -         | -      | -              | -                | 3.11    |
| 10    | Blaine's Fineness | m²g       | -      | -              | -                | 2.6     |

Table 1. Physical properties of constituents of FRSCC

| Sieve size (in mm) | Passing percentage |
|--------------------|--------------------|

Table 2. Size distribution and physical properties of the fine aggregates
2.2. Preparing the FRSCC samples

Hooked shaped steel fibers (SFs) were used for reinforcing the SCC. The various properties of SFs are, tensile strength = 1378 N mm$^{-2}$, average length = 29 mm, average width = 0.45 mm, aspect ratio = 58 and density = 8 kg m$^{-3}$. The samples of FRSCC were designed as per the specifications of IS 456-2000 and the observations made in Okamura and Ozawa (1995). In this way, the M30 grade samples for FRSCC of different shaped, as per the requirement of the experiment, were designed. The various constituents of the mix design were: cement = 440 kg m$^{-3}$, fine aggregates = 953 kg m$^{-3}$, coarse aggregates = 764 kg m$^{-3}$, fly ash = 98 kg m$^{-3}$, superplasticizer = 9 kg m$^{-3}$ and water = 199 L m$^{-3}$. The mixture of FRSCC prepared in this way was poured into the moulds which were left undisturbed till their curing starts [11–14].

2.3. Experimental design and testing

The design of experiments was done with an objective of assessing the impacts of process parameters i.e., dosage of rDWA s and SFs, on sulphate resistance of the FRSCC samples. As per the CCD approach, total 13 experiments were designed and five levels of the process parameters were decided, as mentioned in Table 3.

| S.No. | Process parameters | Coded Values |
|-------|-------------------|--------------|
| 1     | rDWA (%)          | -1.41  -1  0  +1  +1.41 |
| 2     | Steel fibers (%)  | 0  0.35  0.70  1.05  1.4 |

| Fine aggregates | Coarse aggregates |
|-----------------|-------------------|
| 21              | 99                |
| 14.8            | 95.25             |
| 12.1            | 60.45             |
| 10.3            | 40.15             |
| 7.11            | 7.25              |
| 5.21            | >90               |
| 3.15            | 75-90             |
| 1.12            | 40-74             |
| 0.54            | 15-39             |
| 0.18            | 0-15              |

Further, the samples, designed as per the Table 3, were analyzed for assessing its sulphate resistance. The sulphate resistance was assessed as per the specifications set by ASTM C1012, C1012M – 15. In this case, the sulphate resistance of FRSCC was estimated in the form of % loss in compressive strength of the FRSCC after 28 days, 90 days and 120 days of contact with sodium sulphate solution. Statistical analysis of the findings was performed using Design Expert software [15,16]. This association between the process and response parameters can be presented using Eq. (1):

$$Y = c_0 + c_1X_1 + c_2X_2 + c_3X_3 + c_{12}X_1X_2 + c_{13}X_1X_3 + c_{23}X_2X_3 + c_{11}X_1^2 + c_{22}X_2^2 + c_{33}X_3^2$$  (1)

Where, $X_1$ and $X_2$ are the response parameters; $Y$ represents the process parameters and $c_i$ denotes the coefficients which are self-valued by the software. The models were further accuracy-checked using analysis of variance (ANOVA) and regression analysis. After assessing the credibility of the models, response surface plots were generated and optimization was done.

3. Results and discussion
3.1. Model equations and statistical analysis

The association between the process and response parameters was developed and its described in Eq. (2) through Eq. (4).

\[
Y_1 = 2.14 + 0.33X_1 + 0.23X_2 \\
Y_2 = 3.64 + 0.64X_1 + 0.35X_2 \\
Y_3 = 5.49 + 1.14X_1 + 0.55X_2
\]

Where, \(Y_1\) to \(Y_3\) represents the % loss of CS of FRSCC samples after staying in contact with sulphate solution for 28 days, 90 days and 120 days, respectively [17,18]. The given equations made it evident that the process parameters showed positive and linear association with the response parameters. Further, the predicted values of response parameters using the model equations are shown in Table 4.

| S.No. | Process parameters | Experimental Responses | Predicted Responses |
|-------|--------------------|------------------------|---------------------|
|       | \(X_1\) | \(X_2\) | \(Y_1\) | \(Y_2\) | \(Y_3\) | \(Y_1\) | \(Y_2\) | \(Y_3\) |
| 1     | 0     | 1.41 | 2.4  | 4    | 6.4  | 2.5  | 4.13 | 6.27 |
| 2     | 0     | -1.41| 1.6  | 2.6  | 3.7  | 1.82 | 3.12 | 4.71 |
| 3     | 0     | 0    | 2.2  | 3.7  | 5.4  | 2.13 | 3.64 | 5.49 |
| 4     | -1    | 1    | 2.1  | 3.5  | 5.2  | 2.04 | 3.34 | 4.90 |
| 5     | -1    | -1   | 1.8  | 3    | 4.8  | 1.58 | 2.65 | 3.79 |
| 6     | 0     | 0    | 2.2  | 3.7  | 5.4  | 2.13 | 3.64 | 5.49 |
| 7     | 0     | 0    | 2.2  | 3.7  | 5.4  | 2.13 | 3.64 | 5.49 |
| 8     | 1.41  | 0    | 2.5  | 4.2  | 6.8  | 2.61 | 4.55 | 7.11 |
| 9     | 0     | 0    | 2.2  | 3.7  | 5.4  | 2.13 | 3.64 | 5.49 |
| 10    | 1     | 1    | 2.7  | 4.7  | 7.2  | 2.69 | 4.63 | 7.19 |
| 11    | -1.41 | 0    | 1.4  | 2.4  | 3.3  | 1.67 | 2.73 | 3.88 |
| 12    | 1     | -1   | 2.3  | 4.4  | 7    | 2.24 | 3.93 | 6.08 |
| 13    | 0     | 0    | 2.2  | 3.7  | 5.4  | 2.13 | 3.64 | 5.49 |

Further, the comparison of the predicted and experimental values of the response parameters was done and are shown in Fig. 1. Also, in order to establish the credibility of the models, the findings were analyzed using ANOVA and its results are described in Table 5. From Fig. 1 and Table 5, it can be seen that a significant association existed between the process and response parameters as at confidence interval of 95%, the coefficient of regression \(R^2\) for all the response parameters was almost equal to 1.
Fig. 1. Regression plots for different properties

Table 5. Findings of ANOVA-based analysis

| Source       | 28 days P-Values | 90 days P-Values | 120 days P-Values | df |
|--------------|------------------|------------------|-------------------|----|
| Model        | <0.0001          | <0.0001          | <0.0001           | 5  |
| $X_1$        | 0.0003           | 0.0002           | 0.0004            | 1  |
| $X_2$        | 0.0002           | 0.0002           | 0.0002            | 1  |
| $X_1X_2$     | 0.3867           | 0.2473           | 0.1275            | 1  |
| $X_1^2$      | 0.0004           | 0.0008           | 0.0006            | 1  |
| $X_2^2$      | 0.0013           | 0.0005           | 0.0012            | 1  |
| Lack of fit  | 0.0002           | 0.0004           | 0.0001            | 3  |
The findings of ANOVA also made it evident that the p-value in case of all the model equations were <0.0001 which signifies their high credibility. Also, it can be seen that the response parameters showed maximum association with the process parameters i.e., $X_1$, $X_2$, $X_{12}$ and $X_{22}$. Only these parameters were used for further analysis and rest were not used for further statistical analysis.

### 3.2. Response surface plots and optimization

After establishing the credibility of model equations, the software was used further to generate the response surface plots.

**Fig. 2.** Response surface plots

After analyzing the impacts of process parameters on response parameters, the optimized conditions were assessed and are mentioned in Table 6.

#### Table 6. Optimized conditions for response parameters

| Response parameters | Units | Outcomes at optimized conditions i.e., rDWAs = -0.73 and SF = 0.46 | Control specimen |
|---------------------|-------|---------------------------------------------------------------|------------------|
| 28 days             | %     | 1.99                                                          | 1.01             |
| 90 days             | %     | 3.33                                                          | 2.9              |
| 120 days            | %     | 4.91                                                          | 4.52             |

### 3.3. Sulphate resistance

The results shown in Fig. 2, Table 4 and Table 6, show that with the increase number of contact days of FRSCC samples with the sulphate solution. Moreover, after 120 days, the % loss in CS of the FRSCC samples was almost 8.6% more than that of the control samples. Similarly, the % loss in CS of the FRSCC samples for 28 days and 90 days was 97% and 14.85% greater than the control samples, respectively. Therefore, it can be implied that with the increase in the number of contact days, the comparative % decrease of the CS of FRSCC samples and controlled FRSCC samples is reducing. It is well-established that on increasing the number of curing days, the strength of concrete increases due to formation of C-S-H bond. However, on keeping the concrete in contact with sulphate solution, the formation of C-S-H bonds is reduced in earlier stages and therefore, the % decrease in CS of the FRSCC samples was observed more prominent in 28 days as compared to 120 days.

The % reduction in CS of the FRSCC samples showed a linear association with the addition of steel fibers and rDWAs. The decrease in CS of the FRSCC samples can be attributed to the breakage of the C-S-H structure in the concrete matrix of FRSCC samples. On contacting the FRSCC samples with sodium sulphate solution, the carbon molecules of C-S-H bond is replaced with sodium molecules. In this way, the pozzolanic molecules providing strength to the FRSCC samples are eliminated and consequently, the CS of FRSCC samples decreases.

### 4. Conclusions
From the findings of this study, it can be concluded that the rDWAs can act as a potential replacement of NAs in FRSCC-based civil engineered structures, without significantly impacting its sulphate resistance. It was observed that after keeping the FRSCC samples in contact with sodium sulphate solution for 120 days, the % loss in its CS was only 8.6% greater than the control samples. Also, the % replacement of NAs with rDWAs and % dosage of SFs showed linear relation with the % loss in CS of the FRSCC samples. CCD and RSM based optimization process also proved efficient in developing a model to estimate the % loss in CS without conducting extensive laboratory experiments.

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