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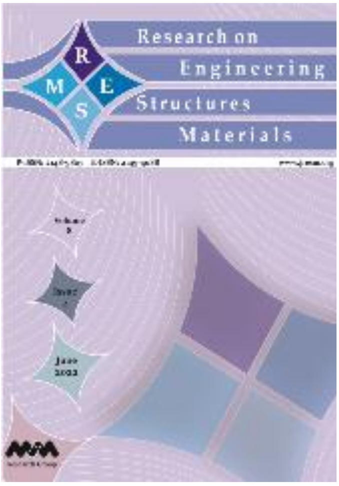

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Research Article

Optimizing cost and strength by utilization of blast furnace slag aggregate and recycled concrete sand in concrete using response surface models

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Abstract

The utilization of waste materials in concrete is crucial for sustainable construction, as it can contribute to environmental conservation and enhance concrete properties. Waste management and sustainable construction poses significant challenges in the construction industry. While numerous studies have focused on environmental conservation, only a limited number have explored the use of Blast furnace slag aggregate (BFSA) as coarse aggregate and recycled concrete sand (RCS) as fine aggregate to optimize cost and concrete properties using response surface models. In this study, response surface methodology (RSM) based on central composite design (CCD) was employed to evaluate the impact of BFSA (0-50%) and RCS (0-100%) replacement parameters on cost, compressive strength. ANOVA was used to verify the accuracy of the generated models. The RSM regression equations demonstrated high R2 values exceeding 0.8 for all responses, indicating that the models could explain variability in the responses. The cost and compressive strength were found to be a suitable relation with BFSA and RCS replacement levels. In conclusion, RSM can help reduce costs by incorporating waste materials into concrete without significantly impacting concrete properties.

1. Introduction

Rapid urbanization and industrialization have led to a continuous increase in the generation rate of construction and demolition (C&D) waste and a corresponding increase in the demand for natural resources [1-3]. Currently, a significant amount of C&D waste is disposed of through dumping and landfilling, which inevitably leads to land occupation and environmental issues. Additionally, there is a high demand for raw materials in the construction industry, leading to a depletion of natural resources [1-2]. Therefore, the reclamation of C&D waste is an essential step towards reducing the end-of-life impacts of structures and reducing their upstream impacts by minimizing the need for the extraction of natural resources [3]. Recycling C&D waste is a growing field, with a particular focus on recycling C&D waste into aggregates as sustainable building materials. The mechanical properties of recycled aggregate concrete (RAC) have been widely investigated, and it has been commonly accepted that the natural coarse aggregates can be replaced with recycled coarse aggregates (RCAs) by up to 30% without sacrificing the overall performance of concrete [4-6]. However, there is still a significant portion of concrete fines that cannot be recycled and reused.

On the other hand, recycled concrete powder (RCP) has also been recycled to replace fines aggregate in mortar or concrete. Existing studies [1,2,7,8] have demonstrated that the inferior properties of RCP mortar are mainly attributed to the higher porosity and water

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absorption of RCP particles. Additionally, the incorporation of RCP affects the particle packing status of aggregates in mortar under dry packing conditions, which is mainly caused by the change of particle size distribution after adding different contents and sizes of RCP particles. The packing status of granular materials can be characterized by the particle packing density, which is defined as the absolute volume to bulk volume ratio of the packed material. Red mud, Fly ash, silica fume (SF), metakaolin, blast furnace slag, and rice husk ash are the industrial by-products that different researchers [9-12] have used as cement replacement to improve concrete strength; due to, latent hydraulic properties, the compressive strength increased at an early stage, and flexural strength at later age showed better results.

In conclusion, recycling C&D waste, including RCP, as a sustainable construction material is a growing field. However, the use of RCP as replacement of sand in mortar or concrete has been found to have negative effects on the properties and microstructures of cementitious materials [13-15]. Further research is necessary to investigate ways to enhance the reactivity of RCP and improve its performance as fine aggregate in concrete is required.

Blast furnace slag is generated as a by-product during the iron-making process. Around 300 kg of molten slag is discharged for every 1000 kg of pig iron produced. The molten slag is cooled using various methods to produce Granulated Blast Furnace Slag (GBFS) , which has high glass content and potential hydration activity when rapidly cooled by water quenching [16,17]. In recent years, GBFS has been extensively used in the cement and concrete industry, as well as in geopolymers, glass ceramics, agricultural fertilizers, and wastewater treatment [18-21]. Several investigations have been conducted on the problem of C&D wastes application to concrete, as reflected in the literature published studies [22-25]. Tam et al. [26] discovered that the presence of recycled fine/coarse aggregate with adhered old mortar can have detrimental effects on the early-age performance, strength development, and long-term performance of concrete. Boudali et al. [27] put forth a proposal suggesting that waste concrete/brick fines, which possess notable quantities of calcium, silicon, and aluminum, can be acquired through the grinding of discarded concrete/brick. These fine particles can subsequently be utilized as an alternative binder or supplementary cementitious material, effectively substituting cement in various construction applications.

According to Li et al. [28], the recycling of construction waste into recycled aggregate results in the generation of 10-20% waste concrete/brick fines. The inclusion of recycled concrete in concrete production can substantially influence the properties of cement. The utilization of recycled concrete as aggregates can have an impact on various aspects of concrete, including workability, compressive strength, splitting tensile strength, flexural strength, water absorption, and air permeability [29,30]. When recycled concrete is utilized as a substitute for natural aggregate, it has the potential to affect the workability of the concrete. This is primarily due to the presence of attached mortar, which can lead to an increased water demand in the mixture. However, through appropriate processing techniques, the amount of attached mortar can be minimized, resulting in an improvement in the mechanical properties of the concrete [31,32].

Every year, the global steel and iron industries generate an excess of 400 million tons of slag, a number that is continuously rising as the demand for steel and iron in diverse sectors continues to grow.

To obtain slag aggregates, smelter slag is crushed or fire-liquid slag melt is treated to produce molten slag aggregates [33]. These aggregates are experiencing growing utilization as binding constituents and fillers in various forms of concrete employed for construction objectives [34]. Synthetic aggregates, like blast furnace slag, are produced by altering the physical and chemical properties of an original material. They can be intentionally created for use as synthetic aggregate or obtained as a by-product from manufacturing and combustion processes. Non-metallic blast furnace slag is formed through a chemical reaction between lime in the flux and the aluminates and silicates found in the ore and coke ash during the smelting process. Different types of blast furnace slag products, including aggregate for road asphalt production, are created using various cooling methods. Bottom ash, a waste product from coal-burning power plants, has the potential to replace specific aggregates used in asphalt pavement. In light of growing environmental concerns, bottom ash is being considered for multiple transportation applications such as embankment fill, roadway fill, sub-base, and base courses.

The utilization of slag as a substitute for cement in concrete production can enhance the properties of cement. Slag possesses pozzolanic properties, meaning it can react with calcium hydroxide to create additional cementitious compounds. Incorporating recycled concrete and slag into concrete production offers a practical and environmentally conscious approach for the construction sector. In recent years, there has been an increasing emphasis on using blast furnace slag (BFS) as a sustainable alternative to natural aggregate in concrete manufacturing. However, despite its popularity, there is a significant disparity between the demand for GBFS (Ground Granulated Blast Furnace Slag) in the cement industry and its supply. Some countries rely on imported GBFS to meet their demands.

The preparation of composite GBFS using solid wastes as raw materials is a viable method, but very few studies have been conducted on this topic, as indicated by a literature search. While some studies [35-37] have demonstrated that the mixture of solid wastes and GBFS offers superior properties, a summary of the specific synergistic effects is lacking. To successfully prepare composite GBFS, the synergistic effect between solid wastes and GBFS needs to be explored. The synergistic effect mainly lies in four aspects, including the alkali, sulfate, and particle filling effects, which significantly promote the hydration of GBFS. In systems consisting of three or more components, multiple synergistic effects are present, resulting in better properties. Therefore, the objective of this review is to provide new insights into using solid wastes to prepare composite blast furnace slag that can replace some or even all of the GBFS. The application of composite GBFS in cement, mortar, and concrete not only effectively addresses the high demand for high-quality GBFS but also improves the utilization rate of other solid wastes and promotes cross-industry cooperation among enterprises.

Abhishek et al. [38] the application of granulated blast furnace slag (GBS) was investigated in both normal vibrated and self-compacting concrete. The study focused on partially replacing the natural coarse aggregate with recycled concrete aggregate (RCA). The results revealed that the GBS-based self-compacting concrete specimens, where the natural coarse aggregate was replaced with recycled coarse aggregate, experienced a reduction in compressive strength exceeding 20%.

The study explored the application of air-cooled blast furnace slag aggregate (ACBFSA) as a substitute for limestone coarse aggregate in ultra-high-performance fiber-reinforced concrete. It was found that ACBFSA can be utilized partially or entirely as a replacement while maintaining crucial properties. However, as the replacement ratios increased, the workability of the concrete decreased [39].

The impact of incorporating Blast Furnace Slag Fine Aggregate (BFSFA) on the resistance to freezing and thawing in a chloride environment was examined. The study found that by utilizing BFSFA with a finer grain size and increasing the proportion of BFSFA in the mixture compared to natural sand, the freezing and thawing resistance was enhanced [40], the researchers investigated the incorporation of washing aggregate sludge (WAS) as an additional component in alkali-activated paste and mortars. The findings of the study revealed several effects of WAS on the material properties. Firstly, the presence of WAS resulted in an extension of the setting time. Additionally, it led to an increase in water absorption and voids content within the paste and mortars. Consequently, the compressive strength was reduced. However, an interesting observation was made during wetting-drying cycles, where WAS demonstrated an efficient enhancement in residual compressive strength. In a study conducted by Alzaza et al. [41], an environmentally friendly construction material was developed by utilizing blast furnace slag (BFS) as a binder and fine aggregate in mortar. To enhance its suitability for construction in cold weather conditions, a calcium silicate hydrate seed accelerator was added. The study revealed that the inclusion of BFS aggregate in concrete led to enhanced resistance against frost and sulfuric acid attack. These findings underscore the potential of BFS as a feasible substitute for natural aggregate in concrete manufacturing. Nevertheless, it is crucial to take into account different factors, including the concrete type and the extent of substitution, as they can impact the properties and potential applications of concrete utilizing BFS.

The aim of this research was to examine the properties and behavior of M25 grade normal concrete by incorporating a blend of recycled concrete sand and blast furnace slag aggregate. The study aimed to identify the most suitable proportions of replacing both fine and coarse aggregates with waste materials in order to decrease the cost and carbon dioxide (CO_2) emissions related to concrete manufacturing.

1.1 Response Surface Methodology

An efficient method is required for optimizing the properties of concrete containing waste materials, as it is an important step towards sustainable construction that reduces the depletion of natural resources and promotes cleaner neighborhoods. Response surface methodology (RSM) has been used to generate models for independent variable optimization, which is a statistical, theoretical, and numerical technique [42,43]. The effect of independent parameters on one or numerous responses is considered by RSM, which employs partial factorial designs like central composite design (CCD) to generate response surfaces for second-order mathematical models. Mathematical models generated using RSM have been observed to be efficient in predicting the properties of concrete containing waste materials [44,45].

Several researchers [46-50] have applied the use of RSM in the optimization of concrete containing waste materials, and it has been found to be an effective method for identifying mixtures that yield the best compromises among the responses. Regression analysis, experimental designs, and recommended statistical tests are generated by RSM employing design of experiment (DOE) software packages such as Minitab and Design Expert [51]. Partial factorial designs used by RSM reduce the number of experiments required compared to full factorial designs, making it a practical method for researchers with limited time and resources [25,45].

A solution to cost-effective conventional concrete production is provided by this study through the use of waste materials such as BFSA (0-50%) as coarse aggregate and RCS (0-100%) as sand replacement in concrete. The performance of concrete containing these waste materials is predicted by mathematical models generated in this study, which optimize their contents, cost, compressive strength. The response surface models generated in this research are distinct from those developed by other researchers and validate the practicability of the generated models. Overall, an efficient method that can bring about a revolution in sustainable construction is the use of RSM in optimizing the properties of concrete containing waste materials, as depicted in Figure 1.

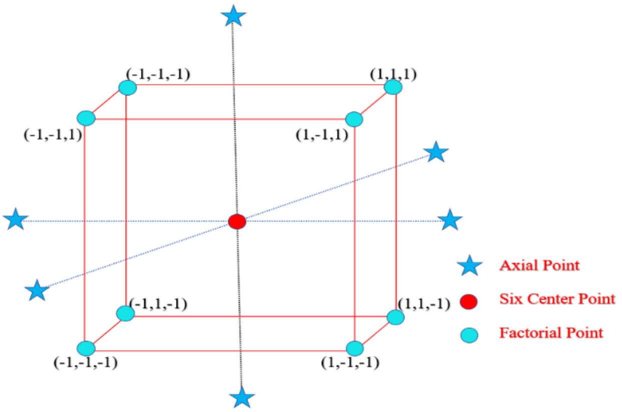


Fig. 1 Central Composite Design (CCD) augmented with hybrid points

In this study, RSM based on CCD was employed to evaluate the impact of two parameters, namely blast furnace slag aggregate (BFSA) and Recycled Concrete sand (RCS) replacement percentages, on four response variables: cost, compressive strength. The range of BFSA was set from 0 to 50%, while RCS was set from 0 to 100%. The response variables were measured for each experiment and used to generate mathematical models that would predict the response variables based on the input parameters.

The generated models were then analyzed using ANOVA (Analysis of Variance) to verify their accuracy [42,45,52]. ANOVA is a statistical method used to determine whether there are significant differences between the means of multiple groups. In this case, ANOVA was used to determine whether the models accurately predicted the response variables based on the input parameters. The results of the study showed that BFSA and RCS replacement percentages had a significant impact on all four response variables. The mathematical models generated from the experimental data showed good agreement with the measured values, as confirmed by the ANOVA analysis. The models were then used to determine the optimal conditions for each response variable. RSM based on CCD proved to be an effective method for evaluating the impact of BFSA and RCS replacement percentages on cost, compressive strength, split tensile strength, and flexural strength [53,54].

The mathematical model generated by the RSM based on CCD for evaluating the impact of BFSA and RCS replacement percentages on the response variables can be expressed in equation 1:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1^2 + \beta_4 X_2^2 + \beta_5 X_1 X_2 + \varepsilon \quad (1)$$

where, Y is the predicted response variable (e.g., cost, compressive strength) β_0 is the intercept term β_1, β_2, β_3, β_4, β_5 are the regression coefficients for linear, quadratic, and interaction terms X_1 and X_2 are the coded values of the independent variables (e.g., BFSA replacement and RCS replacement) ε represents the random error term [55].

By analyzing the CCD experimental design and fitting the data to the model, the regression coefficients (β_0, β_1, β_2, β_3, β_4, β_5) can be estimated, allowing us to predict the response variables for different combinations of BFSA and RCS replacement levels [45].

The mathematical models generated from the experimental data showed good agreement with the measured values and were used to determine the optimal conditions for each response variable. ANOVA analysis was used to verify the accuracy of the models and confirm their validity. This study highlights the potential benefits of using BFSA and RCS in construction materials, as well as the importance of statistical optimization techniques in achieving optimal results.

1.2. Optimization Process

The optimization process for the RSM based on CCD involves finding the optimal values of BFSA and RCS replacement percentages that maximize or minimize the response variable of interest, subject to any constraints that may exist. The initial step in the optimization process involves generating a mathematical model using experimental data and conducting an analysis of variance (ANOVA) to validate the model's reliability. Once the model is confirmed, the subsequent step is to determine the optimal values of the input variables (BFSA and RCS) that will yield the desired response variable (e.g., cost or compressive strength). This can be accomplished through various optimization techniques, including response surface methodology, gradient-based optimization, or genetic algorithms.

One commonly employed technique is to employ a response surface plot, which visually depicts the relationship between the input variables and the response variable. This plot aids in identifying the optimal values. Another approach entails utilizing constrained optimization techniques, where the optimal input variable values are ascertained while considering any applicable constraints. For example, material costs may need to be minimized while fulfilling specific strength requirements, or the strength requirements may need to be met while minimizing the environmental impact of the materials.

Subsequently, the optimal input variable values can be validated by conducting experiments using the predicted values and comparing the results against the model's predictions. If the experimental outcomes align with the model predictions, the optimal values can be considered the final solution. If there is a disparity, it may be necessary to refine the model or conduct additional experiments to obtain a more accurate model.

2. Materials and Methods

2.1. Materials

The researchers in this study utilized 43-grade OPC cement that conforms IS: 8112 [32] standard and BFSA was collected from Ambala city, India. To determine various properties, standard laboratory tests were conducted, including normal consistency (28%), soundness (2.5mm), fineness (2%), initial setting time (126 minutes), final setting time (243 minutes), specific gravity (3.19), and compressive strength (recorded as 26.6 MPa at 3 days, 34.23 MPa at 7 days, and 45.60 MPa at 28 days).

Natural fine aggregate and coarse aggregates were obtained from local markets by the researchers and grading analysis was performed based on Indian standard (IS: 383) [56]. Blast furnace slag aggregate was purchased by the researchers online from the India Mart site and was converted into a coarse aggregate shape using a jaw crusher. The Specifications for the mechanical behavior of ordinary coarse aggregate and BFSA are presented in Table 1.

Feasible use of RCS was achieved by manually crushing 5- to 7-month-old and uncontaminated 150 mm^3 size concrete cubes with a hammer. For the present study, the crushed products were sieved and recombined to obtain the required grading. Table 1 shows the fineness modulus of the recycled aggregate. Concrete casting was carried out using tap water that was purified in this experiment to eliminate harmful substances in compliance with IS: 10500-2012 [57].

Table 1. Specifications for the mechanical behavior of ordinary coarse aggregate and BFSA

Property	Normal coarse aggregate	Blast furnace slag aggregate
Fineness modulus	7.38	7.25
Flakiness index (%)	15.39	7.35
Bulk density(compact) (kg/m^3)	1565	1417
Los Angeles abrasion resistance (%)	22.56	35.45
Impact value (%)	9.60	17.30
Bulk density(loose) (kg/m^3)	1485	1310
Crushing value (%)	20.10	12.53
Elongation index (%)	10.31	18.65
Specific gravity	2.67	2.58

2.2. Experimental Design

The mix design for M25 grade concrete was conducted following the guidelines of the Indian Standard, as presented in Table 1. To generate precise optimum values and analyze a significant amount of experimental data, a Central Composite Design (CCD) within the framework of Response Surface Methodology (RSM) was employed. A total of 13 experimental runs were carried out based on the CCD, which is renowned for its adaptability in determining the number of center points and axial distances.

In this study, a set of 25 concrete mixes was generated using RSM, with varying proportions of cement, sand, RCS (Recycled Concrete Aggregate), BFSA (Blast Furnace Slag Aggregate), and coarse aggregate. The specific quantities used for each mix are outlined in Table 2, adhering to the M25 concrete mix design as specified in IS 456:2000 [58]. The independent parameters considered in the experimentation were BFSA and RCS. The response parameters evaluated in the study were denoted as R1 and R2, representing cost and compressive strength, respectively.

2.3. Experimental Procedure

Experimental designs for all 25 runs with control mix were obtained using Design Expert 13 as shown in Table 2.

Fig. 2 Experimental setup

Table 2. Mix design with replacement in (kg/m^3)

Level	Mix Name.	RCS	BFSA	Cement	FA	RCS	CA	BFSA	Water	Extra water
0	0R0B	0	0	342	711.4	0	1174	0	153.9	0
1	10R5B	10	5	342	640.26	71.14	1115.3	58.7	153.9	1
2	25R5B	25	5	342	533.55	177.85	1115.3	58.7	153.9	1
3	50R5B	50	5	342	355.7	355.7	1115.3	58.7	153.9	1
4	75R5B	75	5	342	177.85	533.55	1115.3	58.7	153.9	1
5	100R5B	100	5	342	0	711.4	1115.3	58.7	153.9	1
1	10R15B	10	15	342	640.26	71.14	997.9	176.1	153.9	2
2	25R15B	25	15	342	533.55	177.85	997.9	176.1	153.9	2
3	50R15B	50	15	342	355.7	355.7	997.9	176.1	153.9	2
4	75R15B	75	15	342	177.85	533.55	997.9	176.1	153.9	2
5	100R15B	100	15	342	0	711.4	997.9	176.1	153.9	2
1	10R25B	10	25	342	640.26	71.14	880.5	293.5	153.9	5
2	25R25B	25	25	342	533.55	177.85	880.5	293.5	153.9	5
3	50R25B	50	25	342	355.7	355.7	880.5	293.5	153.9	5
4	75R25B	75	25	342	177.85	533.55	880.5	293.5	153.9	5
5	100R25B	100	25	342	0	711.4	880.5	293.5	153.9	5
1	10R35B	10	35	342	640.26	71.14	763.1	410.9	153.9	6
2	25R35B	25	35	342	533.55	177.85	763.1	410.9	153.9	6
3	50R35B	50	35	342	355.7	355.7	763.1	410.9	153.9	6
4	75R35B	75	35	342	177.85	533.55	763.1	410.9	153.9	6
5	100R35B	100	35	342	0	711.4	763.1	410.9	153.9	6
1	10R50B	10	50	342	640.26	71.14	587	587	153.9	8
2	25R50B	25	50	342	533.55	177.85	587	587	153.9	8
3	50R50B	50	50	342	355.7	355.7	587	587	153.9	8
4	75R50B	75	50	342	177.85	533.55	587	587	153.9	8
5	100R50B	100	50	342	0	711.4	587	587	153.9	8

The cement, FA, and CA were slowly mixed for two minutes, and water was added to achieve the desired workable consistency. After achieving a suitable mix, the freshly mixed concrete was then transferred into lubricated molds and compacted uniformly using a table vibrator and tested according to Indian standard codes of practice for its compressive strength after 28 of submersion in water at 27°C.

The cube specimens were tested at the age of 28 days in Compression Testing Machine (CTM) after drying at room temperature according to IS: 516-1959 [59], Without impacts and jerks and uniformly, the load was applied, and the failure load taken by each specimen was recorded and the results have been shown in Figure 2. Each independent run involved manual mixing of the concrete containing waste materials with water, ensuring homogeneity in the mix.

3. Results and Discussion

In this section, the results and discussion of the experimental data and the mathematical models for the cost, compressive strength, the analysis includes the validation of the model's using ANOVA and the interpretation of the model coefficients and response surface plots. The optimization process for determining the optimal BFSA and RCS replacement percentages that maximize or minimize the response input variables is also discussed in table 3. Insights into the impact of BFSA and RCS replacement parameters on the properties of construction materials are provided by the results and discussion. The effectiveness of RSM based on CCD for modeling and optimizing construction materials is demonstrated.

Table 3. Input parameter

Factor	Name	Minimum	Maximum	Coded Low	Coded High	Mean	Std. Dev.
A	RCS	0	100.00	-1	+1	52.00	33.32
B	BFSA	0	50.00	-1	+1	26.00	15.94

3.1. Models Fitting

The regression coefficients are estimated by minimizing the sum of squared errors between the predicted values and the actual values of the response variable. The statistical significance of the model as a whole and the individual terms within the model is assessed using the F-test and t-test, respectively.

Table 4. Fit Statistics table for cost and compressive strength

Coefficient	Cost	Compressive Strength
Std. Dev.	0.0007	0.8463
Mean	4122.99	35.07
C.V. %	0	2.41
R^2	1	0.8667
Adjusted R^2	1	0.8334
Predicted R^2	1	0.7853
Adeq Precision	NA	18.5066

After fitting and validating the model, it becomes a powerful tool for predicting the response variable at any given combination of BFSA and RCS replacement percentages within the experimental range. Additionally, the model can be utilized to identify the optimal combination of BFSA and RCS replacement percentages that either maximize or minimize the response variable, while considering any constraints that may be present. This allows for an informed decision-making process, ensuring that the desired outcome is achieved while adhering to specific requirements or limitations.

The Coefficient of Variation (CV%) is a measure of the relative variability of the data. In this table 4, the CV% values for Compressive Strength range from 1.40% to 3.30%. This suggests that the variability in the data for these properties is fairly consistent. However, the CV% for Cost is very low, at 0%. This suggests that the data for Cost is very consistent and has very little variability. All of the Predicted R^2 and Adjusted R^2 values for the various strength properties of the material were in agreement, with the difference between them being less than 0.2 for all cases. The Predicted R^2 of 1.0000 and Adjusted R^2 of 1.0000 for the property of Cost were found to be in agreement, while the Predicted R^2 of 0.7853 and Adjusted R^2 of 0.8334 for compressive strength were also in agreement. Moreover, the Adeq Precision ratio was greater than 4 for all models, indicating that there was adequate signal to noise ratio. This indicates that the models could be effectively used to navigate the design space.

3.2. Coded Factors

Predictions for the response are made based on the given levels of each factor using equations that incorporate coded factors. Typically, the high levels of the factors are represented as +1, while the low levels are represented as -1. The coded equation is advantageous in identifying the relative influence of the parameters by comparing the coefficients associated with each factor. In this study, Tables 5 and 6 present the regression equations in terms of coded factors, which were derived using Response Surface Methodology (RSM) for all responses.

Table 5. Final equation in terms of coded factors

Factor	Cost	Compressive Strength
	3925.7	35.7
A	-172.51	-0.6742
B	-739.62	-10.57
AB		0.2776
A^2		-0.0811
B^2		-13.81

It is worth noting that for a linear interaction between variables and responses, at least one regression coefficient in the model should not be zero. Table 5 displays the final equation obtained from the analysis, expressing the relationship between the coded factors (represented as A and B) and the dependent variable (represented as C). This equation demonstrates how the values of the coded factors are combined to determine the value of the dependent variable.

Table 6. Actual equation in terms of coded factors

Factor	Cost	Compressive Strength
	4837.83	33.3386
RCS	-6.9006	-0.0316
BFSA	-14.792	0.33521
RCS * BFSA		0.00022
RCS^2		-0.0001
$BFSA^2$		-0.0055

The coefficients assigned to the coded factors in this equation determine the magnitude of their impact on the dependent variable. On the other hand, Table 6 presents the actual equation in terms of coded factors for the specific study, providing further details and insights into the relationship between the factors and the dependent variable.

3.3. Cost Optimization

3.3.1. Linear Model Fit Summary and ANOVA Evaluation for Cost

The identification of the response surface model was assisted by the model statistics summary and ANOVA for the linear model for cost, as presented in Table 10 and Table 11, respectively. A perfect correlation in the cost response was observed in the tables. The strength of correlation of the response surface model was determined using model statistics summary, including R2 and adjusted R2.

Table 7. ANOVA for cost

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	3.135E+06	2	1.568E+06	2.822E+12	< 0.0001	significant
A-RCS	1.381E+06	1	1.381E+06	2.486E+12	< 0.0001	
B-BFSA	1.464E+06	1	1.464E+06	2.636E+12	< 0.0001	
Residual	0.0000	23	5.555E-07			
Cor Total	3.135E+06	25				

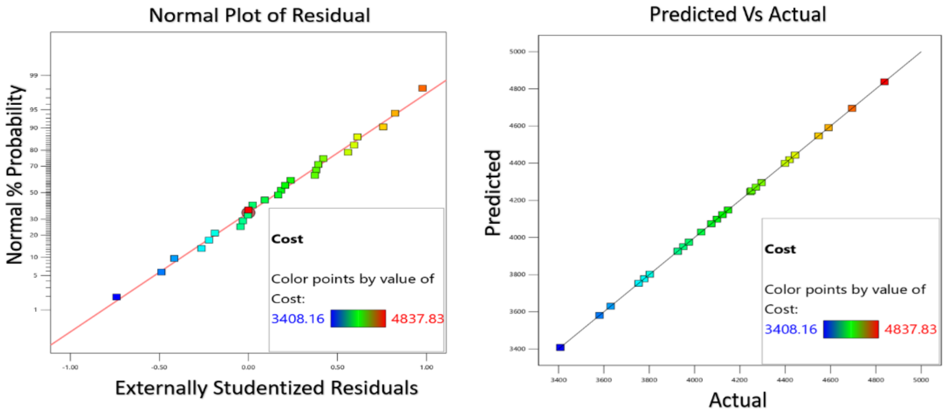
The ANOVA analysis presented in Table 7 demonstrates a highly significant relationship between the factors and the cost variable. The overall model exhibits statistical significance ($p < 0.0001$), indicating its effectiveness in explaining the variation observed in the cost. Both factors, "A-RCS" and "B-BFSA," contribute significantly to the cost variable ($p < 0.0001$). The large F-values and very low p-values indicate that these factors have a substantial impact on the cost. Moreover, the absence of residual variation (error term) suggests a perfect fit of the model to the data.

The ANOVA results provided in Table 7 offer valuable insights into the relationship between the factors and the cost variable. This serves as a solid foundation for further analysis and decision-making. It should be noted that the factors have been coded, and the analysis employs Type III - Partial sum of squares. The significant model F-value, coupled with a very low probability (0.01%) of such a large F-value occurring due to noise, further confirms the model's capability to explain the variation in the dependent variable accurately. Furthermore, the p-values for the model terms indicate their significance. In this case, the coded factors A and B are both significant model terms, with p-values less than 0.0500.

This suggests that these factors have a substantial impact on the dependent variable and should be considered in the analysis. On the other hand, values greater than 0.1000 indicate that the model terms are not significant. If many model terms are insignificant, reducing the model may improve its accuracy. Overall, the analysis provides valuable insights into the significance of the model terms, guiding further analysis and decision-making.

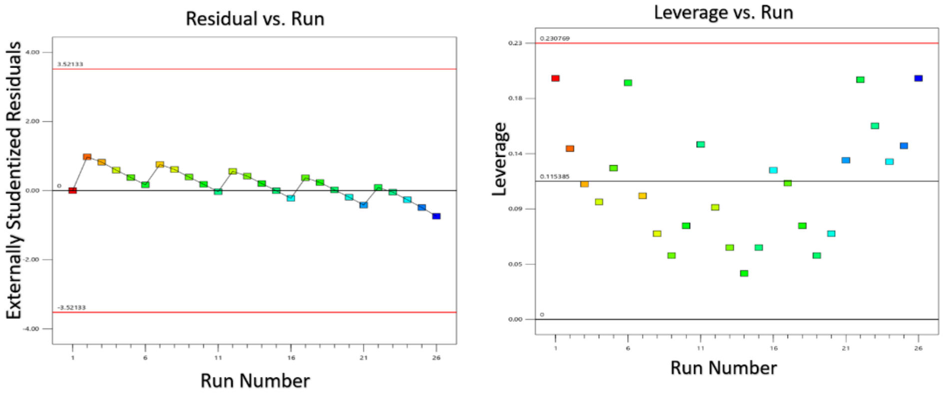
3.3.2. Model Graphs and Diagnostic Findings

Diagnostic findings in Design Expert typically include statistical tests and numerical measures that assess the quality of the model. For example, the adequacy of the model fit to the data can be determined through the lack of fit test, and any patterns or outliers in the data that may indicate problems with the model can be identified using the residual plot.



(a) Normal plot of residual

(b) Predicted vs actual



(c) Residual vs run

(d) Leverage vs run

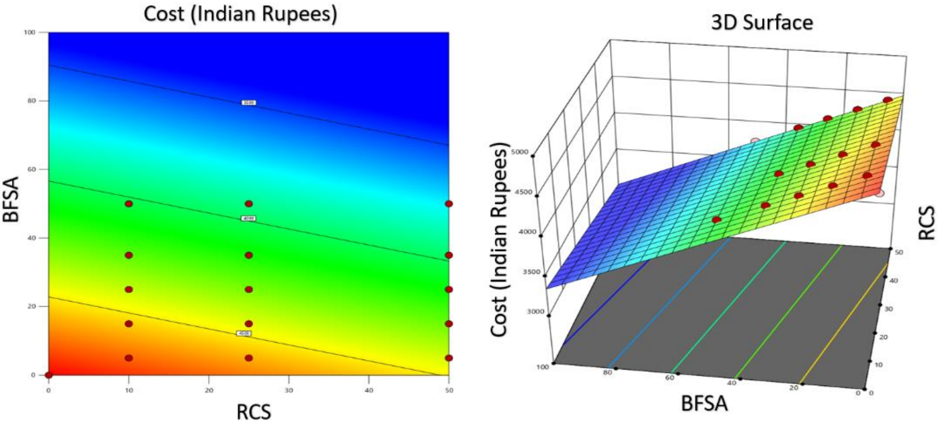
Fig. 3 Model graphs and diagnostic findings of cost

Measures of the model's predictive accuracy, such as the root mean square error (RMSE) or the coefficient of determination (R-squared), can also be included in the diagnostic findings. By examining these model graphs and diagnostic findings, the performance of the statistical model can be assessed, and any necessary adjustments can be made to improve its accuracy and predictive power.

Figure 3a shows that a normal plot of residuals can diagnose problems with a statistical model. Departures from normality in the plot may indicate a mis specified model or missing predictors. Figure 3b depicts a predicted vs actual plot, which compares predicted values to actual values. Deviations from the diagonal line indicate discrepancies between predicted and actual values and can indicate misspecification or missing predictors. Figure 3c shows how a predicted vs actual plot can identify systematic bias or non-linear relationships. Figure 3d depicts how a leverage vs run plot can identify influential observations and evaluate model robustness over time or other variables. If influential observations are found, the model may need re-evaluation or exclusion of those observations. A residual vs run plot can identify trends or cycles in residuals, indicating the need to update the model with additional predictors. These plots can improve a model's accuracy and predictive power. The summary of ANOVA cost is presented in Appendix 1.

3.3.3. Model Graphs of Cost

Model graphs typically include graphical representations of the model, such as contour plots or surface plots, which allow the user to visualize the relationship between the input variables and the response variable.



(a) Contour (b) 3D Surface

Fig. 4. Model graphs of cost

These plots can help identify any nonlinear relationships between the variables and can also help identify any interactions between the variables that may be important for the model. The relationship between cost, BFSA, and RCS can be effectively visualized through contour plots (Figure 4(a)) and 3D plots (Figure 4(b)). Contour plots illustrate lines of constant cost on a grid of BFSA and RCS values, providing a clear representation of how cost varies with different combinations of BFSA and RCS percentages. On the other hand, 3D plots depict the cost on the z-axis, with BFSA and RCS values represented on the x and y axes, respectively. This visualization allows for a comprehensive understanding of how changes in BFSA and RCS impact the cost of the concrete mixture. By examining these plots, it becomes possible to identify regions in the input space where cost is highly sensitive to variations in BFSA or RCS percentages. This information can be used to determine optimal values that minimize cost while still meeting the desired specifications and requirements.

Furthermore, a previous study discovered that when incorporating waste materials as replacements, it was necessary to decrease the mass of BFSA and RCS while increasing the proportion of coarse aggregate. This adjustment in the composition of the concrete mixture resulted in cost optimization. The findings of this study can serve as a valuable reference for decision-making regarding the optimal utilization of waste materials, ensuring a balance between cost-effectiveness and meeting necessary construction criteria.

3.3.4. Linear Model Fit Summary and ANOVA Evaluation for Compressive Strength

The identification of the response surface model was assisted by the model statistics summary and ANOVA for the linear model for Compressive Strength. Table 8 presents the results of the ANOVA analysis for compressive strength. The table shows the sources of variation, sum of squares, degrees of freedom, mean square, F-value, and p-value for each factor. The model was found to be significant with a p-value of less than 0.0001. The factors A-RCS and AB were not significant as their p-values were greater than 0.05. However, the factors B-BFSA and B^2 were found to be highly significant with p-values of less than 0.0001. The factors A^2 was also not significant with a p-value of 0.5110. The residual sum of squares was 14.32, and the total sum of squares was 107.44. A perfect correlation in the Compressive Strength response was observed in tables 8.

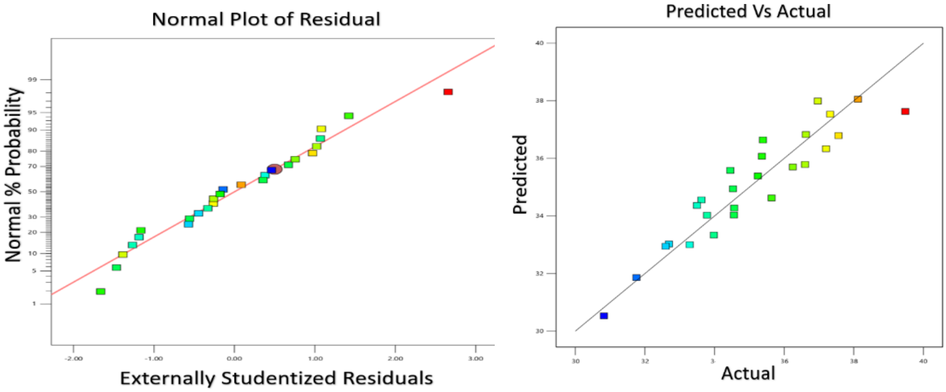
Table 8. ANOVA for compressive strength

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	93.12	5	18.62	26.00	< 0.0001	significant
A-RCS	2.22	1	2.22	3.10	0.0935	
B-BFSA	23.29	1	23.29	32.52	< 0.0001	
AB	0.3740	1	0.3740	0.5222	0.4783	
A^2	0.3208	1	0.3208	0.4480	0.5110	
B^2	40.77	1	40.77	56.93	< 0.0001	
Residual	14.32	20	0.7162			
Cor Total	107.44	25				

3.3.5. Model Graphs and Diagnostic Findings

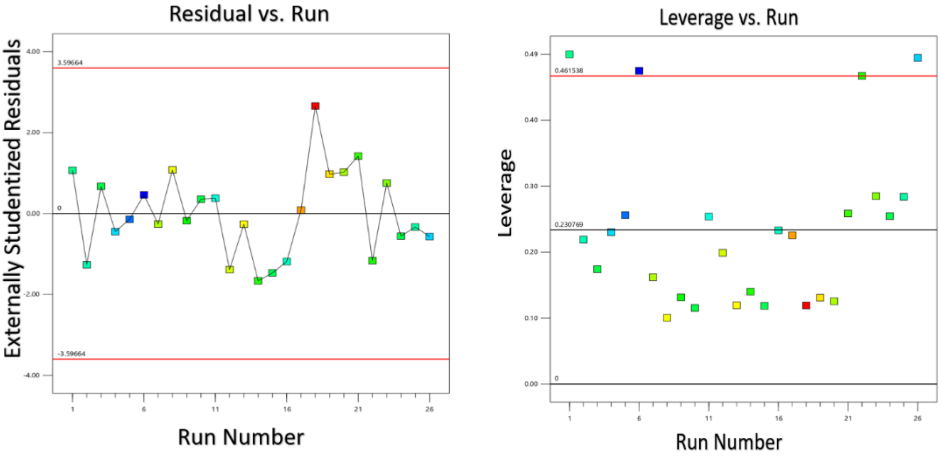
The influence of BFSA and RCS on the compressive strength of concrete is elucidated in Figure 5. In Design Expert, diagnostic findings encompass statistical tests and numerical measures that assess the quality of the model. These findings aid in evaluating the model's fit to the data, with the lack of fit test determining if the model adequately represents the observed data. The residual plot helps identify any patterns or outliers that may indicate potential issues with the model. Additional diagnostic measures such as RMSE (Root Mean Square Error) or R-squared provide insights into the model's predictive accuracy. Analyzing these model graphs and diagnostic findings empowers users to assess the performance of their statistical model and make necessary adjustments to enhance its accuracy and predictive power.

In Figure 5(a), problems with a statistical model can be diagnosed using a normal plot of residuals. Departures from normality in the plot may indicate a mis specified model or missing predictors. Figure 5(b) compares predicted values to actual values using a predicted vs actual plot. Deviations from the diagonal line indicate discrepancies between predicted and actual values and can indicate misspecification or missing predictors. Figure 5(c) demonstrates how a predicted vs actual plot can identify systematic bias or non-linear relationships. Figure 5(d) shows how a leverage vs run plot can identify influential observations and evaluate model robustness over time or other variables. If influential observations are found, the model may need re-evaluation or exclusion of those observations. A residual vs run plot can identify trends or cycles in residuals, indicating the need to update the model with additional predictors. These plots can improve a model's accuracy and predictive power. The summary of ANOVA compressive strength is presented in Appendix 2.



(a) Normal plot of residual

(b) Predicted vs actual



(c) Residual vs run

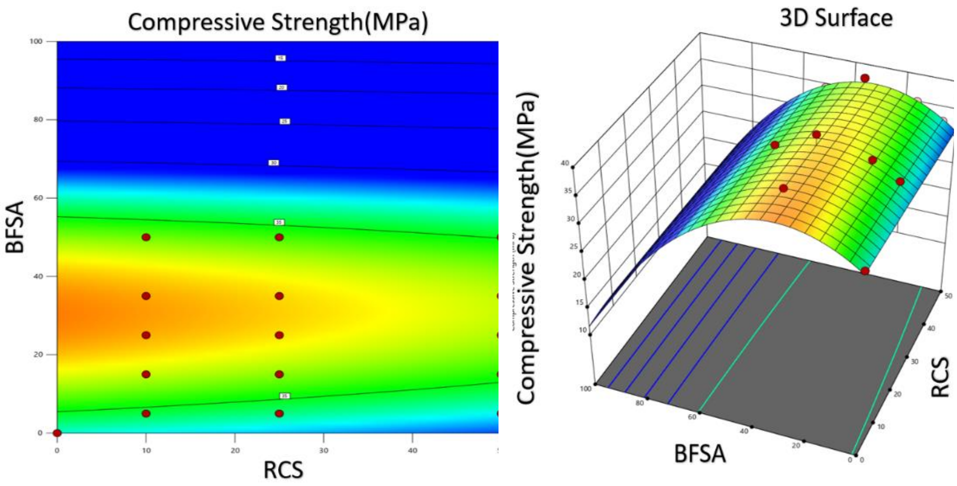
(d) Leverage vs run

Fig. 5 Model graphs and diagnostic findings of compressive strength

3.3.6. Model Graphs of Compressive Strength

Model graphs typically include graphical representations, such as contour plots or surface plots, which allow the relationship between the input variables and the response variable to be visualized by the user. These plots enable the identification of nonlinear relationships between the variables, as well as the identification of any interactions between the variables that may be important for the model.

Figures 6(a) and 6(b) present the visualization of the relationship between Compressive strength, BFSA, and RCS using contour and 3D plots. The contour plot displays lines of constant Compressive strength on a grid of BFSA and RCS, while the 3D plot shows compressive strength on the z-axis and BFSA and RCS on the x and y axes, respectively. By examining the contours or the surface of the plot, it is possible to identify regions of the input space where Compressive Strength is particularly sensitive to changes in BFSA or RCS. This information can be used to identify optimal values of BFSA and RCS that minimize Compressive Strength or to explore the sensitivity of the model to changes in the input variables.



(a) Contour (b) 3D Surface

Fig. 6 Model graphs of compressive strength

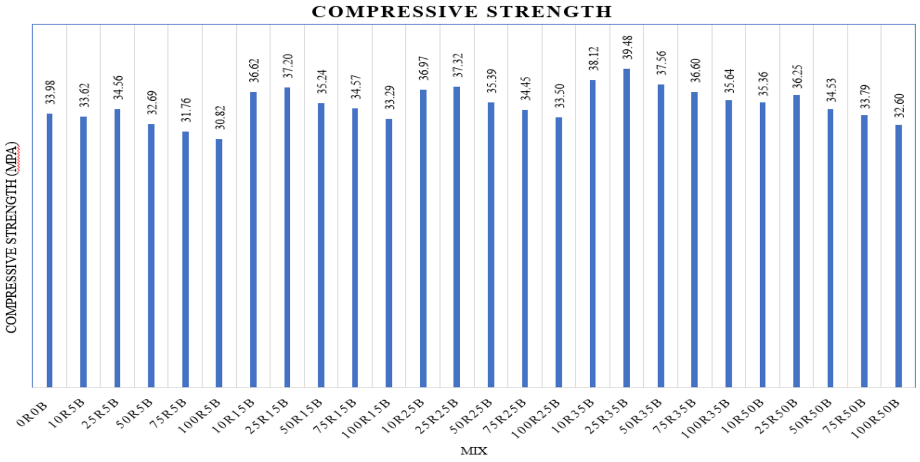


Fig. 7 Compressive strength values for the concrete mixtures

The provided Figure 7 offers a comparison of the percentage replacements of fine aggregate by RCS (Recycled Concrete Sand) and coarse aggregate by BFSA (Blast Furnace Slag Aggregate), along with the corresponding compressive strength values for the concrete mixtures. Analysing the data, several observations can be made regarding the impact of aggregate replacements on compressive strength. when both the fine aggregate replacement by RCS and the coarse aggregate replacement by BFSA remain at a constant percentage of 5%, the compressive strength values vary from 30.82 for the Mix with 100% fine aggregate replacement (100R5B) to 34.56 for the Mix with 25% fine aggregate replacement (25R5B). This indicates that higher replacement percentages of fine aggregate lead to a slight decrease in compressive strength. When, focusing on the replacement of coarse aggregate by BFSA, it can be observed that as the replacement percentage increases from 5% to 25%, the compressive strength generally increases. For instance, the compressive strength rises from 33.62 for the Mix with 5% fine aggregate replacement and 10% coarse aggregate replacement (10R5B) to 37.32 for the Mix with 5% fine aggregate replacement and 25% coarse aggregate replacement (25R25B).

Lastly, considering a higher replacement percentage of coarse aggregate by BFSA (35% and 50%), a decreasing trend in the compressive strength is evident. As the coarse aggregate replacement increases, the compressive strength gradually decreases. For example, the compressive strength drops from 38.12 MPa for the Mix with 35% fine aggregate replacement and 10% coarse aggregate replacement (10R35B) to 32.60 MPa for the Mix with 50% fine aggregate replacement and 100% coarse aggregate replacement (100R50B).

In summary, the data emphasizes the influence of both fine and coarse aggregate replacements on the compressive strength of concrete mixtures. It highlights the importance of carefully selecting and optimizing aggregate replacements to achieve the desired compressive strength in concrete production.

4. Conclusion

In summary, the prescribed limits have a crucial role in determining the permissible ranges for various parameters involved in the evaluation of construction materials. These limits provide essential guidelines for assessing parameters like Compressive Strength and Cost. By establishing lower and upper boundaries for each parameter, these limits ensure that values fall within acceptable ranges and comply with specific criteria or desired standards.

For the Compressive Strength parameter, the acceptable range is defined with a lower limit of 30.822 MPa and an upper limit of 39.48 MPa. These limits serve as benchmarks for evaluating the compressive strength of construction materials, guaranteeing that it meets necessary requirements and ensures quality and durability.

Similarly, the Cost parameter specifies a permissible range of cost values, with a lower limit of 3408.16 INR and an upper limit of 4837.83 INR. Adhering to these limits ensures that the cost remains within reasonable bounds, guiding the evaluation of the financial aspects of the construction project.

When replacing coarse aggregate with BFSA at higher percentages (35% and 50%), a consistent trend emerges, showing a gradual decline in compressive strength. Increasing the percentage of coarse aggregate replacement correlates with a decrease in compressive strength in the concrete mixtures. This trend is evident in cases like the mix with 35% fine aggregate replacement and 10% coarse aggregate replacement (10R35B), where the compressive strength decreases from 38.12 to 32.60 in the mix with 50% fine aggregate replacement and 100% coarse aggregate replacement (100R50B). This observation emphasizes the significant influence of replacing coarse aggregate with BFSA on the mechanical properties of concrete, particularly compressive strength.

Therefore, careful consideration of the percentage of coarse aggregate replacement is crucial to achieve desired properties and performance in concrete applications. By evaluating and determining the appropriate percentage, the mechanical properties of the concrete mix, specifically compressive strength, can be optimized. This ensures that the construction materials meet necessary standards, providing the required structural integrity and overall quality.

References

[1] Pradhan B, Chand S, Chand S, Rout PR, Naik SK. Emerging groundwater contaminants: A comprehensive review on their health hazards and remediation technologies.

Groundwater Sustainable Development 2023;20:100868. https://doi.org/10.1016/j.gsd.2022.100868

[2] Miller BG. 4 - the effect of coal usage on human health and the environment. Clean Coal Engineering Technology. 2011:85-132. https://doi.org/10.1016/B978-1-85617-710-8.00004-2

[3] Pulkit K. Effect of stone slurry & recycled aggregate on properties of concrete waste management. Lap LAMBERT Academic Publication. 2018 Dec.

[4] Kim J. Construction and demolition waste management in Korea: recycled aggregate and its application. Clean Technologies and Environmental Policy. 2021;23(8):2223-2234. https://doi.org/10.1007/s10098-021-02177-x

[5] Marrero M, Puerto M, Rivero C, Freire-Guerrero A, Solís-Guzmán J. Assessing the economic impact and ecological footprint of construction and demolition waste during the urbanization of rural land. Resources, Conservation and Recycling. 2016;117. https://doi.org/10.1016/j.resconrec.2016.10.020

[6] McAllister J. Factors influencing solid-waste management in the developing world. PhD Thesis, Master of Science, Utah State University, Logan, Utah, 5-2015

[7] Russo N, Lollini F. Effect of carbonated recycled coarse aggregates on the mechanical and durability properties of concrete. Journal of Building Engineering. 2022;51:104290. https://doi.org/10.1016/j.jobe.2022.104290

[8] Makul N, Fediuk R, Amran M, et al. Zeyad AM, Murali G, Vatin N, Klyuev S. Use of recycled concrete aggregates in production of green cement-based concrete composites: A Review. Crystals. 2021;11(3). https://doi.org/10.3390/cryst11030232

[9] Zhou C, Chen Z. Mechanical properties of recycled concrete made with different types of coarse aggregate. Construction and Building Materials. 2017;134:497-506. https://doi.org/10.1016/j.conbuildmat.2016.12.163

[10] Grazia D, Trottier C, Dantas SRA, Nagarajun Y, Ziapour R, et al. Influence of recycled concrete aggregate type on rheological behaviour of mixtures proportioned using the equivalent volume method. Recent Progress in Materials. 2022;4(3):1-1. https://doi.org/10.21926/rpm.2203017

[11] Duan Z, Hou S, Xiao J, Li B. Study on the essential properties of recycled powders from construction and demolition waste. Journal of Cleaner Production 2020;253:119865. https://doi.org/10.1016/j.jclepro.2019.119865

[12] Zhu F, Yang C, Miao M. Experimental study on the properties of polyvinyl alcohol fiber reinforced cementitious composites with super early strength. Materials Letters 2023;330:133264. https://doi.org/10.1016/j.matlet.2022.133264

[13] Goergens J, Belli R, Schulbert C, Goetz-Neunhoeffer F. Influence of different CA2/CA-ratios on hydration degree, AH3 content and flexural strength investigated for a binder formulation of calcium aluminate cement with calcite. Cement and Concrete Research. 2023;165:107090. https://doi.org/10.1016/j.cemconres.2023.107090

[14] Yücel HE, Öz HÖ, Güneş M, Kaya Y. Rheological properties, strength characteristics and flexural performances of engineered cementitious composites incorporating synthetic wollastonite microfibers with two different high aspect ratios. Construction and Building Materials 2021;306:124921. https://doi.org/10.1016/j.conbuildmat.2021.124921

[15] Solanke SS, Pawade PY, Ali Khan H. An experimental study on tensile as well as flexural strength of concrete by using sugarcane baggase ash & steel fiber. Materials Today: Proceedings. 2022;60:627-637. https://doi.org/10.1016/j.matpr.2022.02.129

[16] Agarwal A, Ramana G V, Datta M, Soni NK, Satyakam R. Pullout behaviour of polymeric strips embedded in mixed recycled aggregate (MRA) from construction & demolition (C&D) waste - Effect of type of fill and compaction. Geotextiles and Geomembranes. Published online 2023. https://doi.org/10.1016/j.geotexmem.2023.01.004

[17] Abera Y (Shanko) A. Performance of concrete materials containing recycled aggregate from construction and demolition waste. Results in Materials. 2022;14:100278. https://doi.org/10.1016/j.rinma.2022.100278

[18] Bergonzoni M, Melloni R, Botti L. Analysis of sustainable concrete obtained from the by-products of an industrial process and recycled aggregates from construction and demolition waste. Procedia Computer Science. 2023;217:41-51. https://doi.org/10.1016/j.procs.2022.12.200

[19] Bolan S, Padhye LP, Kumar M, et al. Review on distribution, fate, and management of potentially toxic elements in incinerated medical wastes. Environmental Pollution.2023;321:121080. https://doi.org/10.1016/j.envpol.2023.121080

[20] Koelmel J, Prasad V, Velvizhi G, Butti S, Mohan S. Chapter 15 - metalliferous waste in India and knowledge explosion in metal recovery techniques and processes for the prevention of pollution. Environmental Materials and Waste (Resource Recovery and Pollution Prevention). 2016;339-390 https://doi.org/10.1016/B978-0-12-803837-6.00015-9

[21] Ministry of transport. Transport Yearbook 2018. Ministry of Transport. Czech Republic.2018:52.

[22] Zeng Q, Liu X, Zhang Z, Wei C, Xu C. Synergistic utilization of blast furnace slag with other industrial solid wastes in cement and concrete industry: Synergistic mechanisms, applications, and challenges. Green Energy and Resources 2023;1(2):100012. https://doi.org/10.1016/j.gerr.2023.100012

[23] Horii K, Tsutsumi N, Kitano Y, Kato T. Processing and reusing technologies for steelmaking slag. Nippon Steel Technical Report. 2013;805(104):123-129.

[24] Yu P, Wang S, Li Y, Xu G. A Review of Granulation Process for Blast Furnace Slag. MATEC Web of Conferences.2016;68:6007. https://doi.org/10.1051/matecconf/20166806007

[25] Assaad JJ, Mikhael C, Hanna R. Recycling of waste expanded polystyrene concrete in lightweight sandwich panels and structural applications. Cleaner Materials.2022;4:100095. https://doi.org/10.1016/j.clema.2022.100095

[26] Liu H, Li Q, Wang P. Assessment of the engineering properties and economic advantage of recycled aggregate concrete developed from waste clay bricks and coconut shells. Journal of Building Engineering 2023;68:106071. https://doi.org/10.1016/j.jobe.2023.106071

[27] Chen W, Jin R. 7 - Recycled concrete for non-structural applications. Recycled Concrete. Technologies and Performance (Woodhead Publishing Series in Civil and Structural Engineering). 2023:233-263. https://doi.org/10.1016/B978-0-323-85210-4.00006-0

[28] Ul Islam MM, Li J, Roychand R, Saberian M, Chen F. A comprehensive review on the application of renewable waste tire rubbers and fibers in sustainable concrete. Journal of Cleaner Production. 2022;374:133998 https://doi.org/10.1016/j.jclepro.2022.133998

[29] Tam VWY, Butera A, Le KN, Li W. Utilising CO2 technologies for recycled aggregate concrete: A critical review. Construction and Building Materials. 2020;250. https://doi.org/10.1016/j.conbuildmat.2020.118903

[30] Boudali S, Abdulsalam B, Rafiean AH, Poncet S, Soliman A, Elsafty A. Influence of fine recycled concrete powder on the compressive strength of self-compacting concrete (SCC) using artificial neural network. Sustainability (Switzerland). 2021;13(6). https://doi.org/10.3390/su13063111

[31] Li S, Gao J, Li Q, Zhao X. Investigation of using recycled powder from the preparation of recycled aggregate as a supplementary cementitious material. Construction and Building Materials.2021;267. https://doi.org/10.1016/j.conbuildmat.2020.120976

[32] Prakash Singh O, Singh Kulhar K, Choudhary S. Strength studies on concrete containing of recycled coarse aggregate and granite cutting waste as partial replacement of fine aggregate. Materials Today: Proceedings. 2023;76:481-487. https://doi.org/10.1016/j.matpr.2022.11.153

[33] Cominato V, Benavente Canteras F, Andréia Gachet L, Cristina Cecche Lintz R. The effect of granulometry of natural and recycled coarse aggregate on permeable concrete properties. Materials Today: Proceedings. 2022;65:1711-1718. https://doi.org/10.1016/j.matpr.2022.04.717

[34] Spaeth V, Djerbi Tegguer A. Improvement of recycled concrete aggregate properties by polymer treatments. International Journal of Sustainable Built Environment. 2013;2(2):143-152. https://doi.org/10.1016/j.ijsbe.2014.03.003

[35] Sarhan Alyaseen A, Shah S, Solanki R, Daxini B, Alwani YK. Reuse of Improved Recycled Concrete Aggregates (RCA) for Sustainable and Environmental-Friendly Rigid Pavements. IOP Conf. Series: Materials Science and Engineering. 2021. 1145; 012024 https://doi.org/10.1088/1757-899X/1145/1/012024

[36] Yuksel I. Blast-furnace slag. Waste and Supplementary Cementitious Materials in Concrete. Characterisation, Properties and Applications. Woodhead Publishing Series in Civil and Structural Engineering. 2018, :361-415 https://doi.org/10.1016/B978-0-08-102156-9.00012-2

[37] Naresh B, Saravanan M. Experimental study of replacement of cement with ground granulated blast furnace slag. Materials Today: Proceedings. 2022;62:3493-3496. https://doi.org/10.1016/j.matpr.2022.04.302

[38] Salih MA. New geo-polymerization process for high strength alkali-activated binder with palm oil fuel ash and ground granulated blast furnace slag. Proceedings of the National Academy of Sciences. 2015.3:1-15

[39] Owaid HM, Hamid RB, Taha MR. A review of sustainable supplementary cementitious materials as an alternative to all-portland cement mortar and concrete. Australian Journal of Basic and Applied Sciences. 2012;6(9):287-303.

[40] Krishna Murthy H, Brijbushan S, Maneeth PD. An experimental research on partial replacement of river sand by silica sand and partial replacement of cement by GGBS in rigid pavements. International Journal of Recent Technology and Engineering 2019;8(3):4971-4977. https://doi.org/10.35940/ijrte.C5631.098319

[41] Abhishek P, Ramachandra P, Niranjan PS. Use of recycled concrete aggregate and granulated blast furnace slag in self-compacting concrete. Material Today Proceeding. 2020;42:479-486. https://doi.org/10.1016/j.matpr.2020.10.239

[42] Cao Q, Nawaz U, Jiang X, Zhanga L, Ansari WS. Effect of air-cooled blast furnace slag aggregate on mechanical properties of ultra-high-performance concrete. Case Studies in Construction Materials. Jan 2022;16:e01027. https://doi.org/10.1016/j.cscm.2022.e01027

[43] Bilici S, Kabay N, Miyan N, Omur T, Ozkan H. Effect of washing aggregate sludge waste on the properties of alkali-activated blast furnace slag. Journal of Building Engineering. 2023;63(PA):105527. https://doi.org/10.1016/j.jobe.2022.105527

[44] Pulkit K, Saini B, Chalak H, Illikainen M. M Effect of various interface bond tests and their failure behavior on substrate and overlay concrete- A Review. Research on Engineering Structures and Materials.2022:1-22. http://dx.doi.org/10.17515/resm2022.575me1103.

[45] Ahmed T, Ray S, Haque M, Tasnim Nahin T, Ferdous Mita A. Optimization of properties of concrete prepared with waste glass aggregate and condensed milk can fiber using response surface methodology. Cleaner Engineering and Technology. Aug 2022;8:100478. https://doi.org/10.1016/j.clet.2022.100478

[46] Seetharaman R, Seeman M, Kanagarajan D, Sivaraj P, Saravanan I. A statistical evaluation of the corrosion behaviour of friction stir welded AA2024 aluminium alloy. Materials Today: Proceedings 2020;22:673-680 https://doi.org/10.1016/j.matpr.2019.09.066

[47] Chong BW, Othman R, Jaya RP, Li X, Hasan M, Abdullah M. Meta-analysis of studies on eggshell concrete using mixed regression and response surface methodology. Journal of King Saud University - Engineering Sciences. April 2021. https://doi.org/10.1016/j.jksues.2021.03.011

[48] Ali M, Kumar A, Yvaz A, Salah B. Central composite design application in the optimization of the effect of pumice stone on lightweight concrete properties using RSM. Case Study in Construction Material. Jan 2023;18 https://doi.org/10.1016/j.cscm.2023.e01958

[49] Kursuncu B, Gencel O, Bayraktar OY, Shi J, Nematzadeh M, Kaplan G. Optimization of foam concrete characteristics using response surface methodology and artificial neural networks. Constrion and Building Material. Jan 2022;337:127575. https://doi.org/10.1016/j.conbuildmat.2022.127575

[50] Manohar DR, Anbazhagan P. Shear strength characteristics of geosynthetic reinforced rubber-sand mixtures. Geotextiles and Geomembranes. 2021;49(4):910-920. https://doi.org/10.1016/j.geotexmem.2020.12.015

[51] Shi J, Zhao L, Han C, Han H. The effects of silanized rubber and nano-SiO2 on microstructure and frost resistance characteristics of concrete using response surface methodology (RSM). Construction and Building Material. Feb 2022;344:128226. https://doi.org/10.1016/j.conbuildmat.2022.128226

[52] Poorarbabi A, Ghasemi M, Azhdary Moghaddam M. Concrete compressive strength prediction using neural networks based on non-destructive tests and a self-calibrated response surface methodology. Journal of Non-destructive Evaluation .2020;39(4):1-11. https://doi.org/10.1007/s10921-020-00718-w

[53] Hamada HM, Al-Attar AA, Tayeh B, Bin Mat Yahaya F, Abu Aisheh YI. Optimising concrete containing palm oil clinker and palm oil fuel ash using response surface method. Ain Shams Engineering Journal. 2023:102150 https://doi.org/10.1016/j.asej.2023.102150

[54] Guo L, Guo Y, Zhong L. Research on the back analysis and failure mechanism of recycled concrete aggregate meso-parameters based on Box-Behnken Design response surface model. Journal of Building Engineering. Jan 2022;51:104317 https://doi.org/10.1016/j.jobe.2022.104317

[55] Saboo N, Nirmal Prasad A, Sukhija M, Chaudhary M, Chandrappa AK. Effect of the use of recycled asphalt pavement (RAP) aggregates on the performance of pervious paver blocks (PPB). Construction and Building Materials. 2020;262:120581. https://doi.org/10.1016/j.conbuildmat.2020.120581

[56] Sinkhonde D. Generating response surface models for optimisation of CO2 emission and properties of concrete modified with waste materials. Cleaner Materials. June 2022;6:100146. https://doi.org/10.1016/j.clema.2022.100146

[57] Bheel N, Ali MOA, Shafiq N, et al. Utilization of millet husk ash as a supplementary cementitious material in eco-friendly concrete: RSM modelling and optimization. Structures. Feb 2023;49:826-841 https://doi.org/10.1016/j.istruc.2023.02.015

[58] Amiri H, Azadi S, Karimaei M, Sadeghi H, Farshad Dabbaghi. Multi-objective optimization of coal waste recycling in concrete using response surface methodology. Journal of Building Engineering. Oct 2022;45:103472. https://doi.org/10.1016/j.jobe.2021.103472

[59] IS 383-1970. Specification for coarse and fine aggregates from natural sources for concrete. Bureau of Indian Standard. Published online 1970.

[60] IS 10500. Indian Standard Drinking Water Specification (Second Revision). Bureau of Indian Standards. May 2012;IS 10500:1-11

[61] IS: 456. Plain and Reinforced Concrete. Bureau of Indian Standards. Published online 2000.

[62] IS:516. Hardened Concrete -Methods of Test. Bureau of Indian Standards.1959