MULTI-RESPONSE OPTIMIZATION OF SCC INCORPORATING INDUSTRIAL WASTES USING TAGUCHI BASED GREY RELATIONAL ANALYSIS

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In the search for sustainable development in the field of the construction sector, scientific advancements in the use of alternative materials in Self-Compacting Concrete (SCC) are of primary interest among researchers. The present study also attempted to use industrial waste materials such as Fly Ash (FA), Cement Kiln Dust (CKD), and Ecosand (ES) in the preparation of SCC, optimizing their mixture formulation using Taguchi-based Grey Relational Analysis (GRA). Batch optimization trials were conducted using a Taguchi L_9 orthogonal array with different replacement levels of CKD (5%, 10%, 15%), FA (25%, 30%, 35%), and ES (10%, 20%, 30%) in SCC. Fresh properties, including slump flow, T500 time, V funnel time, L box passing ratio, and J ring step height, as well as hardened properties like compressive strength, flexural strength, and split tensile strength, were considered as responses. The Taguchi-based GRA results revealed an optimized mixture composition of 53 kg/m^3 CKD, 184 kg/m^3 FA, and 84 kg/m^3 ES. Furthermore, a confirmation test was carried out to validate the model, and the error percentage was found to be less than 10%. ANOVA results indicated that the influencing parameters followed the order of CKD > ES > FA. Based on these findings, Taguchi-based GRA can be considered an ideal tool for optimizing concrete mixes.

Keywords: *multi-response optimization, Taguchi based GRA, SCC, Industrial wastes, CKD, ecosand*

1. Introduction

Self Compacting Concrete (SCC) is concrete that was proposed by Okamura in 1986. It is a highly flowable concrete that fills every corner of formwork uniformly and entirely by its weight without segregation, encasing reinforcement without vibration and maintaining homogeneity. Construction of concrete structures using SCC has gradually increased in India during the last few years which include bridges, atomic power plants, dams, metros, etc. It is achieved by minimizing coarse aggregate, increased paste volume, less water/powder ratio, more superplasticizer, and addition of viscosity-modifying admixtures. To reach self compactability, high contents of fines are needed, which further enlarges the cement content. This eventually increases the cost of SCC compared to conventional concrete. To reduce the cement consumption, industry wastes are introduced into play as cement replacement materials and make concrete sustainable. Fly ash is a waste generated from coal thermal power plants. The role of fly ash in making brick and concrete is dominant. Investigations have shown that SCC mix performs well by replacing cement with fly ash up to 35 - 45% by weight of cement, it improves the fresh properties of SCC [1-2]. Utilisation of flyash in SCC substantially reduces the amount of superplasticizer required [3].

Self-Compacting Concrete (SCC) is a concrete concept initially proposed by Okamura in 1986. It represents a highly flowable form of concrete that uniformly fills every corner of formwork solely through its weight, preventing segregation, enveloping reinforcement without requiring vibration, and maintaining homogeneity. The use of SCC in constructing concrete structures in India has gradually risen over the past few years, encompassing applications such as bridges, atomic power plants, dams, metros, and more. This achievement is realized through techniques like minimizing coarse aggregate, increasing paste volume, reducing the water-to-powder ratio, adding more superplasticizer, and incorporating viscosity-modifying admixtures. Attaining self-compactability necessitates a higher content of fines, which consequently escalates the cement content and, subsequently, the cost of SCC compared to conventional concrete.To mitigate cement consumption, industrial waste materials are introduced as replacements for cement, promoting concrete sustainability. Fly ash, a byproduct generated from coal thermal power plants, plays a dominant role in the production of bricks and concrete. Research investigations have indicated that SCC mixes perform admirably when cement is partially replaced with fly ash, typically ranging from 35% to 45% of the weight of cement [1-2]. This not only enhances the fresh properties of SCC but also substantially reduces the amount of superplasticizer required [3].

Cement Kiln Dust (CKD), as the name implies, is dust collected from the rotary kiln during cement manufacturing. The characteristics of CKD vary depending on the plant, including the type of dust collection system, kiln type, raw feed, and fuel type [4]. CKD contributes to air and land pollution; therefore, it finds application in the manufacturing of glass, bricks, mortar, and concrete [5]. Additionally,

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it serves purposes such as soil stabilization, wastewater treatment, and various agricultural uses.Numerous studies have been conducted to partially replace cement with CKD in Self-Compacting Concrete (SCC). CKD functions as a filler to produce medium-strength SCC [6] and serves as a supplementary cementitious material in fiber-reinforced SCC, with its behavior thoroughly examined [7]. Experimental results have indicated that SCC mixes containing 20% CKD as a cement replacement exhibit the highest mechanical strength when compared to normal concrete mixes [8]. Furthermore, CKD enhances the toughness of rubberized SCC [9]. The utilization of CKD allows for the partial replacement of cement, promoting the development of sustainable, high-strength, and high-performance SCC [10].

For decades, river sand has served as the primary fine aggregate in Self-Compacting Concrete (SCC). However, due to the escalating demand and the growing scarcity of river sand, the search for viable alternatives has commenced. Potential substitutes for river sand encompass manufactured sand (M sand), industrial wastes (specifically certain forms of bottom ash and slag), and recycled aggregates [11 - 13]. Among these alternatives, high-quality M sand stands out as the most promising replacement for river sand. Achieving the required flow characteristics of SCC necessitates an increased paste volume [14]. M sand, characterized by an abundance of fines, contributes significantly to the improvement of the paste in SCC. Experimental results have firmly established that the successful utilization of M sand as a fine aggregate in SCC is indeed feasible.The incorporation of M sand in concrete has witnessed a substantial surge in popularity over recent decades. Meanwhile, Ecosand has found utility in concrete as a partial substitute for traditional sand [15,16]. Ecosand, a byproduct known as Dolomite-silica waste, is obtained during the semi-wet cement manufacturing process. Recent research has explored the microwave characterization of Ecosand for applications in Electromagnetic Interference shielded construction [17]. Furthermore, Ecosand has exhibited potential as a filler material for stabilizing clay soils against swelling and shrinkage [18]. Nevertheless, there is a conspicuous absence of reports regarding the use of Ecosand in SCC as a fine aggregate replacement.

Design of experiments (DOE) is one of the branches of applied statistics that primarily focuses on planning, conducting, analyzing, and interpreting a set of controlled trials to assess the factors influencing the magnitude of the dependent variable(s). DOE is considered one of the most powerful statistical analyses, applicable to a variety of engineering problems. In the 1950s, Genichi Taguchi developed an effective, simple, and organized approach known as the Taguchi method, which provides valuable insights into factor interactions and serves optimization purposes. This method employs well-balanced orthogonal arrays with the fewest necessary trials.

Tertiary blended self-consolidating mortar was optimized based on compressive strength using the Taguchi method [19]. The Taguchi technique was employed to investigate the effects of viscosity, shear regime, and coarse aggregate maximum size on the stability of SCC air voids [20]. Taguchi techniques were utilized for optimizing SCC with high volumes of fly ash, focusing on fresh properties and compressive strength [21]. High-strength SCC was designed using the Taguchi method [22]. Flexural and fracture behavior of recycled aggregate SCC beams were selected for study through Taguchi analysis [23]. High-performance SCC with alkali-activated slag was investigated using Taguchi design [24]. Fiber-reinforced SCC with fly ash and nano-silica was optimized using Taguchi design [25]. The Taguchi approach, including the Best Worst method, was employed to optimize high-strength SCC [26]. Taguchi's method has also been applied to determine the best mix proportions for Polymer Concrete, Geopolymer Concrete, Self Curing Concrete [27], and Fiber-Reinforced Concrete. It is particularly well-suited for single-response problems.

In practical applications, multi-response problems require more efficient techniques for Multi-objective optimization. Some studies have combined the Taguchi method with other methods to optimize multi-response problems. The combination of Taguchi with TOPSIS, for example, can be used to identify the optimum mix for high-strength SCC [28]. Other research has integrated Taguchi and GRA to design and optimize mortar and concrete. They applied weighted GRA and the Taguchi method to achieve optimum recycled aggregate concrete [29] and combined Taguchi and GRA methods to obtain the best-performing mixtures in plastering work made with Palm Oil Fuel Ash [30]. The Taguchi-based GRA method was employed to optimize mortars containing steel scale [31]. In another study, [32] optimized geopolymer concrete for multi-responses using Taguchi and GRA. Additionally, the Hybrid RSM-PCA-GRA method has proven effective in determining the optimal mixture proportions for industrial byproducts-based concrete [33]. However, the Taguchi-GRA method has not yet been applied to SCC mixtures incorporating industrial waste. Thus, in this current research, we aim to fill this knowledge gap by using the multi-response optimization method for SCC mixtures that incorporate industrial waste. In this study, CKD and Fly ash are used as partial replacements for cement, while Ecosand partially replaces M sand in the SCC mixture. The primary objective of this paper is to determine the optimal combination of the mixture using Taguchi-Grey relational analysis. The parameters selected for the study include the percentages of CKD replaced, Fly ash replaced, and Ecosand replaced, while the fresh properties and hardened properties of SCC serve as the responses.

2 Experimental studies

2.1. Design and analyses of experiments.

In this study, we adopt the Taguchi method to design the experiment, selecting the Taguchi L9 orthogonal array. We calculate the Signal-to-Noise (S/N) ratios for the responses and utilize the Grey Relational Analysis (GRA) to optimize the results. Additionally, we perform ANOVA analysis on the Grey relational grade to determine the most significant parameter.

2.1.1. Taguchi based Design of Experiments

The Taguchi method provides greater insight into the interaction of factors and serves the purpose of optimization. This method adopts a well-balanced orthogonal array with the fewest possible trials. In the present study, the L_9 orthogonal array proposed by Taguchi was utilized to optimize the SCC mixture by considering the composition of three vital factors: CKD (A), Fly ash (B), and Ecosand (C), each at three levels (Table 1). For this controlled set of trials, eight quality responses were investigated, namely slump flow (SF), T500 time (T500), V funnel time (VF), L box passing ratio (PR), J ring step height (SH), compressive strength (CS), split tensile strength (TS), and Flexural Strength (FS).

Table 1

Levels of the Screened Factors

Designation	Factor	Level 1	Level 2	Level 3
A	CKD (%)	5	10	15
B	Fly ash (%)	25	30	35
C	Ecosand (%)	10	20	30

Taguchi employs the use of the S/N ratio as a single indicator that accounts for the magnitude of the mean and standard deviation of the trial results to define the relative importance of these factors on the quality responses.

2.1.2 Grey Relational Analysis (GRA)

Grey relational theory was first proposed by Deng in 1982. GRA is best suited for considering multiple responses simultaneously and generating a comprehensive index to represent the assessment of these responses. To perform GRA, raw data preprocessing is an essential prerequisite to address scaling and polarization issues among the observed responses. Raw data matrix, D, can be expressed as shown in Eq. (4).

$$D = \begin{bmatrix} y_0(1) & y_0(2) & \dots y_0(n) \\ y_1(1) & y_1(2) & \dots y_1(n) \\ y_2(1) & y_2(2) & \dots y_2(n) \\ y_3(1) & y_3(2) & \dots y_3(n) \\ \dots & \dots & \dots\ \dots \\ y_m(1) & y_m(2) & \dots y_m(n) \end{bmatrix} \tag{4}$$

Where, y_0 is the reference matrix dataset and y_1 to y_m are the comparison datasets. Every dataset is to contain n number of responses and $y_i(j)$ representing the computation of ith series on jth response. Further, this raw data can be pre-processed by using Eqs. (5) – (6) depending on the expected case

Eq. (5) is chosen for smaller-the-better case.

$$r_i(j) = \frac{\max(y_i(j), i=1,2,\dots,n) - y_i(j)}{\max(y_i(j), i=1,2,\dots,n) - \min(y_i(j), i=1,2,\dots,n)} \tag{5}$$

Eq. (6) is chosen for larger-the-better case.

$$r_i(j) = \frac{y_i(j) - \min(y_i(j), i=1,2,\dots,n)}{\max(y_i(j), i=1,2,\dots,n) - \min(y_i(j), i=1,2,\dots,n)} \tag{6}$$

Where $r_i(j)$ is the normalized value of ith response variable in the jth experiment ,$\Delta_{0i}(j) = | r_o(j) - r_i(j) |$. Their variance can be defined as the difference matrix, δ which can be illustrated as in Eq. (7).

$$\delta = \begin{bmatrix} \delta_{01}(1) & \delta_{01}(2) & \dots\ \delta_{01}(n) \\ \delta_{02}(1) & \delta_{01}(2) & \dots\ \delta_{01}(n) \\ \dots & \dots & \dots\ \dots \\ \delta_{0m}(1) & \delta_{0m}(2) & \dots\ \delta_{0m}(n) \end{bmatrix} \tag{7}$$

Further, the grey relational coefficient (GRC), ε_{0i} (j) can be expressed as

$$\varepsilon_{0i}\,(\mathrm{j}) = \left[\frac{\delta_{min} + \rho\ \delta_{max}}{\delta_{0i}(\mathrm{j}) + \rho\ \delta_{max}}\right] \tag{8}$$

Where, ρ is the coefficient of identification, whose magnitude is ranging from 0 to 1 and usually considered as 0.5. $\delta_{\min}$ and $\delta_{\max}$ are the minimum deviations and maximum deviations of each response variable. Measure of GRC provides the degree of closeness among the pre-processed data and the matrix, ε, can be illustrated as in Eq. (10).

$$\varepsilon = \begin{bmatrix} \varepsilon_{01}(1) & \varepsilon_{01}(2) & \dots\varepsilon_{01}(n) \\ \varepsilon_{02}(1) & \varepsilon_{01}(2) & \dots\varepsilon_{01}(n) \\ \dots & \dots & \dots\ \dots \\ \varepsilon_{0m}(1) & \varepsilon_{0m}(2) & \dots\ \varepsilon_{0m}(n) \end{bmatrix} \tag{9}$$

Eventually, the Grey Relational Grade (GRG), g_{0i} is defined as the sum of weighted GRC to assess the significance of comparison series which can be computed using the following expression.

$$g_{0\mathrm{i}} = \sum_{j=1}^{n} w'(j)\, \varepsilon_{0i}\,(\mathrm{j}) \tag{10}$$

Where, w’(j) refers to the normalized weightage assigned to jth response and hence, $\sum_{\mathrm{j}=1}^{\mathrm{n}} \mathrm{w}'(\mathrm{j})$ equals unity

Fig. 1 -Ecosand

2.1.3. Analysis of Variance (ANOVA)

ANOVA is one of the statistical tools which can be use to determine strongly influencing factors affecting the quality responses among the studied factors.

2.2. Materials

OPC 53 grade concrete, with a specific gravity of 3.15, and potable water conforming to IS standards were used for producing the concrete samples. In this investigation, a Poly Carboxylate Ether (PCE)-based superplasticizer was utilized. Class F Fly ash, collected from a thermal power plant and having a specific gravity of 2.15, was incorporated. CKD and Ecosand were sourced from nearby cement plants and are displayed in Figure 1 and Figure 2. The chemical composition of CKD and Fly ash is presented in Table 2. The specific gravity of CKD is 2.4. The grain distribution of fine aggregates is illustrated in Figure 3. The specific gravity of both M sand and Ecosand is 2.65 and 2.66, respectively. Ecosand falls within Zone IV grading as per IS 383:2016 [34]. For concrete, the fine aggregate must conform to Zone II specifications. Mixing a small percentage of Ecosand with M sand helps satisfy the Zone II limits specification. To enhance passing ability, the coarse aggregate size is limited to 12.5 mm.

Table 2

Chemical Composition of CKD and Fly Ash

Compound	Cement Kiln Dust(%)	Fly ash(%)
SiO_2	13.7	55.38
Al_2O_3	3.5	25.32
Fe_2O_3	2.6	5.20
CaO	45.2	3.32
MgO	0.7	2.02
Na_2O	-	0.12
K_2O	-	0.60
SO_3	-	1.90
LOI	6.5	2.50

Fig.2 - CKD

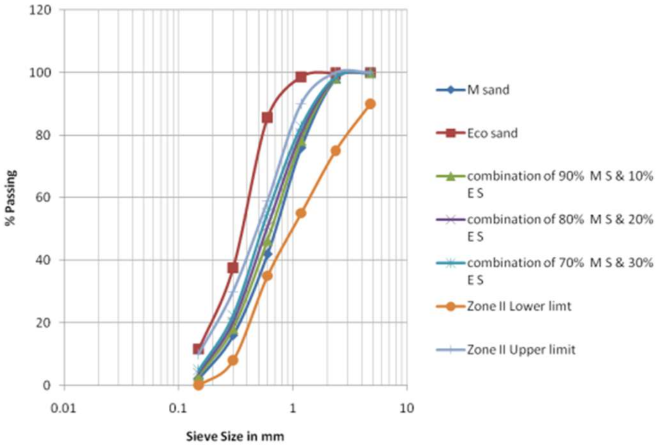

Fig. 3 - Particle size distribution of fine aggregates

2.3. Mix Proportion

In the present study, Self-Compacting Concrete (SCC) is composed of cement, CKD, fly ash, fine aggregate, Ecosand, coarse aggregate, water, and superplasticizer. The proportions of CKD (5%, 10%, 15%) and Fly ash (25%, 30%, 35%) as cement replacement materials, and Ecosand (10%, 20%, 30%) as a fine aggregate replacement material, are varied. A powder-type SCC mixes was developed for this research study, following the EFNARC Guidelines. Nine SCC mixes were created for the L_9 orthogonal array, following the Taguchi method, with a water-to-powder (w/p) ratio (by volume) of 1.02. The quantities of coarse aggregate, water, and superplasticizer remained constant throughout the study. The optimal percentage of superplasticizer was determined using the marsh cone test. The mix proportions for the SCC mixes are detailed in Table 3, and pan mixers were employed to mix the concrete, following the procedures depicted in Figure 4.

2.4. Test methods

2.4.1. Fresh state concrete tests

Fresh property tests were conducted for all the SCC mixtures, including slump flow, T500 time, V-funnel

Table 3

Mix proportions for SCC mixes

Mix ID	Cement Kiln Dust (A)	Fly Ash (B)	Ecosand (C)	CA	M Sand	Eco Sand	Water	Cement	CKD	Fly Ash	S.P
				Kg/m^3	Kg/m^3	Kg/m^3	Kg/m^3	Kg/m^3	Kg/m^3	Kg/m^3	Kg/m^3
M1	5	25	10	785	757	84	196	387	28	138	3.86
M2	5	30	20	785	673	168	196	354	27	163	3.86
M3	5	35	30	785	589	252	196	321	27	187	3.86
M4	10	25	20	785	673	168	196	354	55	136	3.86
M5	10	30	30	785	589	252	196	322	54	161	3.86
M6	10	35	10	785	757	84	196	290	53	184	3.86
M7	15	25	30	785	589	252	196	323	81	134	3.86
M8	15	30	10	785	757	84	196	291	79	159	3.86
M9	15	35	20	785	673	168	196	260	78	182	3.86

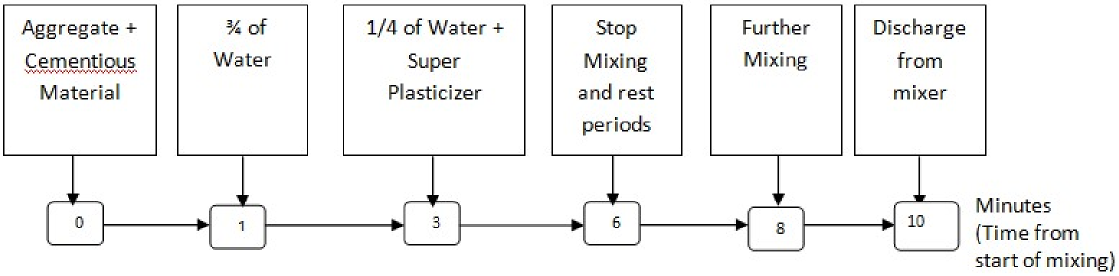

Fig. 4 - Mixing Procedure

time, L-box, and J-ring tests, following EFNARC standards. The slump flow test was used to evaluate the flowability of the concrete mix, while T500 indirectly measured the viscosity of the concrete. The V-funnel test assessed the filling ability, while passing ability was evaluated using the L-box and J-ring tests

2.4.2. Hardened state concrete tests

All casted specimens were cured for 28 days. Test for determining the compressive strength, split tensile strenght and flexural strength were carried out as per IS 516: 2021 standards [35]. For measuring the compressive strength, cube specimens of size 100 mm x 100 mm x 100 mm were casted. Cylindrical specimens of 100 mm diameter and 200 mm height were casted for the measurement of split tensile strength. Prism size 500 x 100 x 100 mm were casted to evaluate the flexural strength.

3. Result and Discussion

3.1. Experimental Results

3.1.1. Fresh Properties

3.1.1.1 Slump flow

Table 4 reveals that all mixes, except for mix M7, fall within the EFNARC limits for slump flow (i.e., 650 mm to 800 mm). The highest slump flow was achieved by specimen M6, with 10% CKD replacement, 35% Fly Ash replacement, and 10% Ecosand replacement. This result can be attributed to the higher quantities of CKD and Fly ash in this mix. Conversely, the lowest slump flow was recorded for M7 specimens, featuring 15% CKD replacement, 25% Fly Ash replacement, and 30% Ecosand replacement. It is worth noting that SCC mixtures incorporating 15% CKD and 30% Ecosand exhibited reduced flowability.

Table 4

Experiment Results

Mixes	Slump Flow	T_{500} time	V Funnel time	L-box	J-ring (Step height)	Compressive Strength	Split Tensile Strength	Flexural Strength
	mm	sec	Sec	Passing ratio	mm	N/mm^2	N/mm^2	N/mm^2
1	665	8	11	0.8	8	46	3.8	5.23
2	695	9	11	0.9	9	38.83	3.93	4.67
3	695	5	8.5	0.9	9.5	41.37	3.52	4.93
4	685	8	11	0.8	10	44.37	4.06	5.3
5	695	7	10	0.9	9	46.9	3.81	5.4
6	715	5	8	1	8	40.5	3.59	4.94
7	610	8	13	0.8	10	40.87	3.79	4.78
8	650	6	9	0.8	9.5	41.37	3.47	4.8
9	655	7	10	0.8	10	40.8	3.48	4.71

CKD introduces a fluidizing effect in the mixtures [6] up to 10%. Beyond this threshold, an increase in CKD content leads to reduced flowability due to increased water absorption [10]. Slump flow increases with a higher percentage of fly ash because fly ash, with its spherical morphology, acts as a ball-bearing, facilitating flow. Additionally, slump flow increases with an increased percentage of Ecosand, up to 20%, due to the low frictional resistance of Ecosand, which further enhances the workability of the concrete."

3.1.1.2 T500 time

From Table 4, it is evident that the T500 time for all mixes, ranging from 3.9 seconds to 4.8 seconds, falls within the limits defined by EFNARC guidelines (i.e., 2 seconds to 5 seconds). Notably, T500 time was lower for M6 mixes, featuring 10% CKD replacement, 35% Fly Ash replacement, and 10% Ecosand replacement, among the nine mixes, owing to the higher fly ash content. A lower T500 time indicates an enhancement in flowability.Conversely, T500 time was higher for M2 mixes, with 5% CKD replacement, 30% Fly Ash replacement, and 20% Ecosand replacement. T500 time tends to decrease as the percentage of fly ash increases. This behavior can be attributed to the smooth and spherical geometry of fly ash particles.

3.1.1.3 V-funnel flow time

V-funnel flow time for all the mixes is found to fall within the range of 8-12 seconds, in accordance with EFNARC Guidelines, except for mix M7, as shown in Table 4. The highest V-funnel flow time was recorded for mix M7, featuring 15% CKD replacement, 25% Fly Ash replacement, and 30% Ecosand replacement. Conversely, the lowest V-funnel flow time was observed in mix M6, with 10% CKD replacement, 35% Fly Ash replacement, and 10% Ecosand replacement, primarily due to the higher percentage of fly ash. It's worth noting that the trend in the variation of V-funnel flow time is similar to that of T500 time.

3.1.1.4 Passing ability

L-box (Passing ratio) and J ring (step height) were used to evaluate the SCC's capacity to flow through tight gaps between reinforcing bars without segregation or blockage. In Table 4, it can be observed that all nine mixes evaluated in this study exhibit a good ability to traverse tight passages between reinforcing bars, with the passing ratio H2/H1 ranging from 0.8 to 1, meeting the necessary EFNARC standards. Among all nine mixes, the M6 mix, containing 10% CKD replacement, 35% Fly Ash replacement, and 10% Ecosand replacement, achieved the highest passing ratio. This increase in passing ratio is attributed to the spherical form of fly ash particles. However, it's important to note that the agglomeration of powders after a certain level of replacement may increase particle friction, thereby reducing passing ability. Additionally, the M6 mix yielded the highest J-ring (step height) values.

3.1.2. Hardened Properties

From Table 4, it is evident that M1 mix, with 5% CKD replacement, 25% Fly Ash replacement, and 10% Ecosand replacement, exhibited the highest compressive strength. On the other hand, M9 mix, featuring 15% CKD replacement, 35% Fly Ash replacement, and 20% Ecosand replacement, had the lowest compressive strength. This suggests that as the amount of CKD increases, the compressive strength of the SCC mixes decreases.

This decrease can be attributed to the fact that, as the percentage of CKD increases, the porosity of the cement paste also increases, thus reducing the overall strength. In comparison to fly ash and Ecosand, variations in CKD content have a more significant impact on compressive strength. Fly ash is used in SCC primarily to enhance the workability of concrete, with minimal influence on the early strength of the concrete. For optimization purposes, only the 28-day strength is considered. Additionally, it is observed that an increase in the percentage of Ecosand leads to a slight decrease in compressive strength. The results of split tensile strength and flexural strength also indicate a similar trend to that of compressive strength

3.2. Statistical analysis and Process Optimization

3.2.1. Taguchi based GRA

Computation of GRG is essential for determining the influence of factors on the experimental observations and prioritizing them. Furthermore, the mean GRG is calculated for each level, considering different factors. GRG was calculated by assigning equal weightage to all responses. Subsequently, the ranking, or the Grey Relational Order, was assigned to the nine experimental runs based on the GRG values presented in Table 5. Mix 6 (CKD-10%, FA-35%, Eco Sand-10%) is ranked first among the nine considered mixes, with a large Grey relational grade of 0.785. It represents the optimal mix among the nine tested.The average GRG for all parameters and the optimum levels of each factor are identified and marked (*) in Table 6. Fig. 5 illustrates the mean Grey relational grade of CKD, FA, and Ecosand. The highest mean GRG values were found for the following combination of factors: CKD – 5% (Level 1), FA – 35% (Level 3), Ecosand – 10% (Level 1), as shown in Fig. 5. A higher mean GRG indicates that a mix made with this combination will perform better in all of the SCC attributes that have been tested. It was observed that CKD is the most significant factor, ranked 1 in Table 6, among the three parameters.

Table 5

Grey relation grade

Mix ID	GRG	Rank
M1	0.714	2
M2	0.606	4
M3	0.613	3
M4	0.485	6
M5	0.552	5
M6	0.785	1
M7	0.368	9
M8	0.457	7
M9	0.411	8

Table 6

Average GRG for each level of different parameters

Parameters	Level 1	Level 2	Level 3	Max - Min	Rank
CKD (A)	0.644*	0.608	0.412	0.232	1
Fly Ash (B)	0.522	0.538	0.603*	0.081	3
Ecosand (C)	0.652*	0.501	0.511	0.151	2

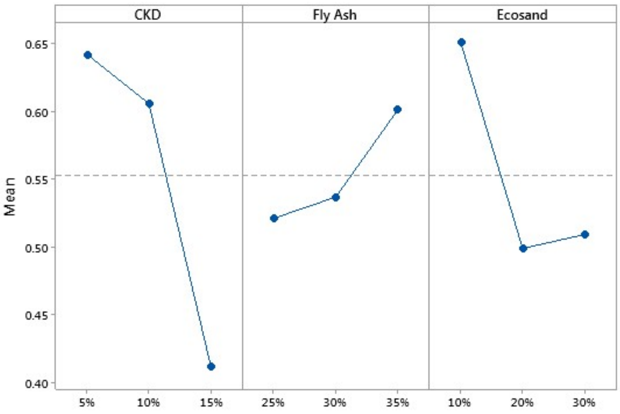

Fig. 5 - Mean Grey relational grades of different parameter

3.2.2. Analysis of variance (ANOVA)

In the present study, statistical measures such as ANOVA are employed to identify significant correlations among the studied factors and to determine the weightage of the percentage contribution of those factors to the responses. The magnitudes of GRG have been taken into consideration for the analysis of variance, and the results are presented in Table 7. It appears that the composition of CKD is the most influential factor among the three parameters, contributing the highest percentage.

Table 7

ANOVA Results

Source	DF	Adj SS	Adj MS	F value	% Contribution
CKD	2	0.09346	0.04673	13.38	60.57
Fly Ash	2	0.01096	0.00548	1.57	7.10
Ecosand	2	0.0429	0.02145	6.14	27.80
Error	2	0.00699	0.00349		4.53
Total	8	0.1543			100.00

3.2.3. Confirmation test

The statistically analyzed results are validated through a confirmation test. If the determined optimal process parameters are already available in any of the nine experimental runs, there is no need for the confirmation test. The present study found an optimal level of CKD – 5% (Level –

Table 8

Validation of optimum mixture

Responses	Predicted Results	Experimental Results	Percentage of Prediction Error
Slump flow (mm)	719.72	738	2.48
T500 time (seconds)	4.124	4	3.10
V funnel time (seconds)	7.845	7.6	3.22
L-box (Passing Ratio)	0.937	1	6.30
J ring (Step Height,mm)	8.127	7.5	8.36
Compressive Strength(N/mm^2)	42.763	42.9	0.32
Tensile Strength (N/mm^2)	3.70705	3.8	2.45
Flexural Strength (N/mm^2)	4.6833	4.8	2.43
GRG	0.79	0.925	

1), FA – 35% (Level – 3), Ecosand – 10% (Level 1), which is not present in any of the experimental runs; therefore, a confirmation test is required. An experiment was conducted using the optimum mix to evaluate its performance. The experimental results of the optimized mix are presented in Table 8. The optimized mix consists of Cement - 290 kg/m^3, Cement Kiln Dust - 53 kg/m^3, Fly ash - 184 kg/m^3, Coarse Aggregate - 785 kg/m^3, M – sand - 757 kg/m^3, Ecosand - 84 kg/m^3, and superplasticizer - 3.86 kg/m^3. The predicted GRG value of the optimized mix is 0.79, which is the highest among all the mixes in Table 5 and is close to the experimental result GRG 0.928. This indicates that the optimized SCC mix outperforms all other mixes in terms of both fresh and hardened properties. The percentage of error between experimental and predicted values in the confirmation test is calculated, and values less than 10% for all responses are shown in Table 8, concluding that the Taguchi method has sufficient capacity and accuracy for parametric optimization.

4. Conclusions

This study optimizes SCC mixes produced with different levels of CKD, Fly ash, and Ecosand using the Taguchi-based GRA method. The following conclusions can be drawn based on experimental and statistical studies: Fresh properties of all mixes satisfied EFNARC guidelines, except for M7 mix (15% CKD, 25% Fly Ash, 30% Ecosand). This indicates that CKD, Fly Ash, and Ecosand can be effectively used in producing SCC.

- The optimized mix, determined through the Taguchi-based GRA method, consists of 290 kg/m^3 of Cement, 53 kg/m^3 of Cement Kiln Dust, 184 kg/m^3 of Fly ash, 785 kg/m^3 of Coarse Aggregate, 757 kg/m^3 of M-sand, 84 kg/m^3 of Ecosand, and 3.86 kg/m^3 of superplasticizer.
- From the Taguchi-based GRA analysis and ANOVA, it was observed that fresh properties and hardened properties were significantly affected by Cement Kiln Dust, followed by Ecosand and Fly ash.
- Taguchi-based grey analysis multi-response optimization techniques save materials and reduce the cost of laboratory research.

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