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Optimization and Stochastic Modelling of Process Parameters to Predict Eco-Friendly and Sustainable Concrete Using Recycled Aggregate

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Abstract

Environmental sustainability is mandating technologically supported eco-friendly alternatives in an attempt to uncover a plethora of possibilities. A critical stage towards attaining an environmentally sustainable product involves formulating and assessing the product by adopting appropriate technology or formula. In the current research, an eco-friendly blend containing recycled aggregates was analyzed and monitored using the Grey Relational Grade (GRG) analysis in the Taguchi optimization technique. Three influencing parameters, involves water/cement ratio, volume ratio of recycled coarse aggregate, and incubation days (curing days), were selected to investigate the grey relational grade analysis based on two responses (compressive strength and split tensile strength). Data were collected on 7, 14, and 28 days of curing (incubation) to determine the ideal combination of recycled aggregate concrete. SEM examination after compression tests revealed the presence of microcracks and tiny pores, demonstrating that recycled aggregate has the same direct impact as recycled aggregate concrete. The GRG method predicted an optimal combination (Run 07) of A1B1C3 (25% recycled aggregate, 0.2 W/C ratio, and 28-day incubation time). To validate the model's adequacy, a validation experimental run based on run 07's conditions (A1B1C3) was performed. ANOVA analysis indicated that incubation days were found to be an influential factor in GRG.

Keywords: *Construction/Demolition waste; Sustainable building; Recycled aggregates; Taguchi method; Grey Relational Grade.*

Introduction

The development of infrastructure in India is expanding at a breakneck pace, integrating numerous individuals with diverse backgrounds from different geo-demographics. Sustainable development in the production of commodities/products is becoming an essential prerequisite rather than an option. In India, the construction sector directly and indirectly employs 35 million skilled and unskilled workers. In the years ahead, there will be an urgent need for more than one billion housing units due to increasing numbers of people, economic growth, and infrastructure expansion. The construction industry is a highly decentralized and disorganized sector as a result of gaps in and differences in best practices. The construction hotspots of

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these landfills of construction waste comprise concrete, bricks, stones, tiles, solid cement, ceramics, wood, plastic, glass, insulating materials, asbestos materials, etc. Concrete is an amalgamated product comprising cement, particles, and water. One of the imminent, critical, and pivotal issues facing the building sector has been reported in recent decades to be the shortage of naturally occurring supplies. Novel strategies are being investigated to alleviate the environmental and social problems stemming from the production of substantial amounts of garbage during construction. Using waste brick fines (WBF) and waste concrete fines (WCF) in place of cement and sand is one such method (Syamsunur et al., 2023). Another appealing strategy with respect to environmental issues and economies involves the reuse of building and demolition debris and rubble in the creation of recycled aggregate concrete. Literature has reported modest variation-based physio-chemical properties among natural concrete aggregate (NCA) and recycled concrete aggregates (RCA) (Abdur Rob & Srivastava, 2022). Due to the viability of employing recycled aggregate for the manufacturing of environmentally conscious building materials, initiatives are necessary to enhance the effectiveness of handling reused aggregate, thereby enabling huge-scale manufacturing with lesser variability. In order to generate an eco-friendly composition with sufficient durability in the cured stage, recycled concrete could potentially be taken into consideration as a competing material. But in addition to the economic advantages linked to minimal gas emissions, using recycled materials as substitutes for natural aggregates also has beneficial impacts on the environment (Bhat, 2021). The quest for technology-based scientific solutions is being concentrated on in order to identify a way towards a sustainable environment. As a result, the demand for establishing such essential infrastructure facilities is extremely high, and at the same time, the management of unused, leftover demolition and construction (C&D) debris poses a severe concern (Anderson & Darling, 1952). The foremost drawbacks of recycled aggregate concrete are its insufficient ability to absorb water and its reduced mechanical, structural, and resilience properties, which constitute the primary impediment to switching from natural to recycled aggregates (Anderson & Darling, 1952). Investigators investigated the manner in which recycled aggregate influences the tensile and compressive strengths of concrete. Compressive strength is essential for ensuring quality (Aslam, 2020), while tensile strength is important for durability (Ball et al., 2019). These two critical parameters are influenced by various variables such as the variety of cement, W/C ratios, moisture percentages, curing period, and recycled aggregate replacement ratios (Bamshad et al., 2023). Real-time data demonstrate that the OFAT (One-Factorial-At a Time) approach were proven to be man-power dependent, robust, expensive, and material-intensive. Conventional optimization techniques such as full factorial and fractional factorial designs involve expensive and time-consuming experimental operational conditions (IS 5816, 1999). In order to estimate the compressive strength and tensile strength of concrete with minimal process time and economics, Taguchi based statistical techniques based on empirical data could serve as an advantage over exhaustive investigations (Byeon & Park, 2023; Chaabene et al., 2020). Taguchi methodology was employed in construction industry to optimize and address various problems/issues such as, concrete mechanical property (Chen et al., 2017), identifying crushing parameters (Franch et al., 2015), geopolymer concrete (Gao et al., 2021), composite materials (Girish et al., 2019; Prasanna et al., 2017), recycled aggregates (Gurway & Gadge, 2023), industrial wastes (Hair et al., 2011), and ceramic waste (Hakeem et al., 2023).

The Taguchi design is a crucial technique in various fields, including manufacturing and research, as it reduces human labor and directs the selection of important elements. It uses a wide range of controllable and modifiable components, and has been shown to be efficient in data optimization, particularly in mechanical and civil engineering fields (Aabid, 2023). Taguchi technique employs an orthogonal array and performs signal-to-noise ratio analysis to navigate the space by minimizing experimental durations, costs and providing reliable results based its mean value, S/N ratio and error on overall response (IS 516, 1959; Mohammed Zayan et al., 2021). The ANOVA analysis facilitates in identifying the contributing variable towards the desired response (Joglekar & May, 1987). There has been little development among the scientific research and development on optimization strategies with minimal number of operational procedures and repetitions. In order to develop strong, resilient, and long-lasting concrete materials meeting the current infrastructural specifications, new products have to be developed through experimenting with different types of materials. The objective of the work is to achieve maximum mechanical properties with minimal recycled aggregate replacement by adopting the Taguchi approach and optimize the operating conditions for a concrete blend using M30 cement. S/N ratio and Grey Relational Grade (GRG) analysis method adopted in this approach deciphers the inter-relations among the factors influencing the mechanical properties with Materials and methodst.

Materials and Methods

Materials

Recycled aggregate was collected from local construction and demolition site (Kattankulathur, Tamil Nadu, and India). The debris was collected and segregated to achieve a homogenous maximum size (20mm). These uniform recycled aggregates were employed for making all the concrete mixes. The recycled aggregate was used to partially replace natural coarse aggregate in the concrete. Natural river sand with maximum size of 4.75 mm was used as the fine aggregate in the concrete. Ordinary Portland Type I cement was used as the binder for making the concrete.

Mix Proportioning

Grade 30 (M30 grade) concrete was designed, mixed, and produced in the laboratory. The concrete was selected to investigate the compressive and tensile strength and validate the mechanical properties of the reinforced concrete structures time-dependent creep and shrinkage phenomena as per standard recommendations. The recycled aggregate was used to partially substitute coarse aggregate. The proportion of replacement is 15%, 20% and 25% by volume. The water-to-cement ratio (W/C) varied to 0.20, 0.25 and 0.3. The specimen was casted as per standards and cured for 7, 14 and 28 days. The proportion of the variations is summarized in Table 1.

Table 1. Levels, Ranges and Variables Used in Design Matrix.

S.No	Variable	Units	Low level	Mid-level	High-level	Low level	Mid-level	High-level
1	Replacement ratio	No units	-1	0	1	15	20	25
2	W/C ratio	No units	-1	0	1	0.20	0.25	0.30
3	Incubation period	Days	-1	0	1	7	14	28

Taguchi Method

Taguchi multi-objective optimization basis was applied to optimize the mixed recycled aggregate concrete (Lam et al., 2023). Three parameters such as water/cement ratio, volume ratio of recycled coarse aggregate, and incubation days (curing days), were selected as input variables to generate L9 orthogonal design matrix using Minitab 18 (Free trail). The levels and ranges of the three variables is represented in Table 1. The signal to noise ratio (S/N) to analyse response variation. The standard deviation is inversely related to the mean and the S/N ratio is used as an alternative to the standard deviation, as the ratio of the mean to the standard deviation. Taguchi method considers three conditions, the larger the better", "the smaller the better", and "on-target, minimum-variation" with respect to the target (goal) (Le Lee & Wong, 2023). In our study, the Taguchi approach detects various categories of optimal levels based on each response, enabling to optimised under larger is better (compressive strength, tensile strength situations respectively. In order to maximise the experimental response, optimization was carried out by calculation and normalizing of S/N ratio, determining Grey Relational Coefficient (GRC), Grey Relational Analysis (GRA) and then grading the results using GRG (Lee & Wong, 2023). The GRG serves as a statistically important relationship grade for every sequence of trials. The influential parameter was identified using analysis of variance (ANOVA). The optimum conditions were predicted, and validation experiment were performed at the recommended conditions to warrant the predicted results. The precision of response is impacted by the grey relational grade, where greater values are regarded as the overall best relationship grade. Figure 1 represents the Taguchi optimization process. The Taguchi orthogonal design (with coded and uncoded values) with response is presented in Table 2.

Figure 1. The Taguchi Optimization Process.

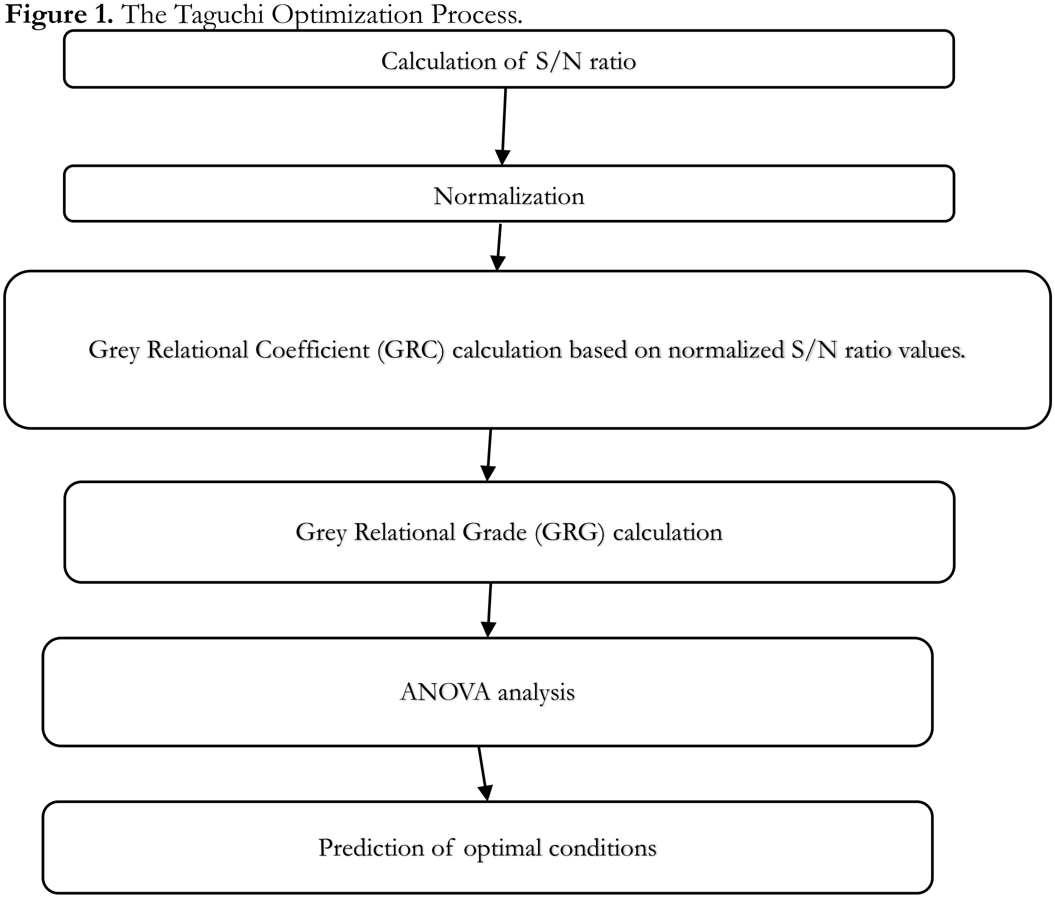


Table 2. The Taguchi Orthogonal Design (With Coded and Uncoded Values) With Response.

Run	Replacement ratio	W/C ratio	Incubation (Days)	Replacement ratio	W/C ratio	Incubation (Days)	Compression strength	Tensile strength
1	1	1	1	15	0.2	7	24.01	3.77
2	1	2	2	15	0.25	14	28.78	5.1
3	1	3	3	15	0.3	28	35.09	5.69
4	2	1	2	20	0.2	14	32.86	5.49
5	2	2	3	20	0.25	28	41.36	5.75
6	2	3	1	20	0.3	7	27.56	4.23
7	3	1	3	25	0.2	28	45.25	5.72
8	3	2	1	25	0.25	7	27.94	3.89
9	3	3	2	25	0.3	14	33.42	5.24

Assessment of Mechanical Properties

Grade 30 (M30 grade) concrete was designed, mixed, and produced in the laboratory. The concrete was selected to investigate the compressive and tensile strength and validate the mechanical properties of the reinforced concrete structures time-dependent creep and shrinkage phenomena as per standard recommendations.

Compression Test

Compression tests were performed as per the standard recommendations of IS 516 (1959). Standard cubes (150 × 150 × 150 mm) molds were used for casting the concrete samples.as per the combinations represented in the Taguchi L9 orthogonal design matrix (Table 1). The cubes were cured in water for 28, 56 and 90 days before testing for compressive strength. A Universal testing machine (UTM) of 2000 kN capacity was used for the testing. The peak load that causes failure to occur (crushing) was obtained and used to calculate the compressive strength of the concrete using Eq. 1.

$$F_{ck} = \frac{P}{\mathrm{A}} \qquad (1)$$

Where, Fck =compressive strength (N/mm2), P = ultimate crushing load (N), A =section area (mm2)

Tensile Strength

Tensile strength testing was performed as per the standard recommendations of (IS 5816, 1999). Standard cylinders (150 × 300 mm) Molds were used for casting the concrete as per the combinations represented in the Taguchi L9 orthogonal design matrix (Table 1). The concrete samples then cured for a period of 28, 56 and 90 days before testing for tensile strength. A UTM of 2000 kN capacity was used for the testing. The peak load that caused tensile failure to occur was recorded from the machine. Eq. 2 was then used to calculate the tensile strength of the casted cylinders.

$$\mathrm{F}_{S} = \frac{2P}{\pi \mathrm{LD}} \qquad (2)$$

where, FS = tensile Strength in N/mm2, P = load (N), D = diameter of the cylinder specimen (mm), L = length of the cylinder specimen (mm)

Scanning Electron Microscope Analysis

Scanning electron microscope of the recycled aggregate reinforced concrete images were imaged using High Resolution Scanning Electron Microscope (HRSEM) (FEI Quanta FEG

200) at SRM university NRC facility. SEM assists us to the insights of structural arrangement, structural surface fractures, crack patterns, flaws, and contaminants.

Results

Taguchi Optimization – Grey Relational Grade Analysis

The outcomes of the present investigation demonstrate that an experimental approach built around the Taguchi technique may be utilized effectively to identify the ideal circumstances (within the scope of elements and their levels investigated) for enhancing the optimal maximum (compression strength and tensile strength) final response. The ideal circumstances for every single parameter would be identified employing the average effects of factors from the S/N ratio studies (Table 3) (Li et al., 2012). The mean response corresponds to the average value for all operating input parameters estimated at different levels. In Table 4 and Figure 2, the main effects due to mean values of compression strength and tensile strength for all parameters at levels 1, 2, and 3 are indicated. Correspondingly, the main effects due to the average S/N ratios across all three variables (compression strength and tensile strength) at different levels are assessed and summarized in Table 4 and Figure 3.

Figure 2. The Main Effect Plot of Response (GRG) Based on mean.

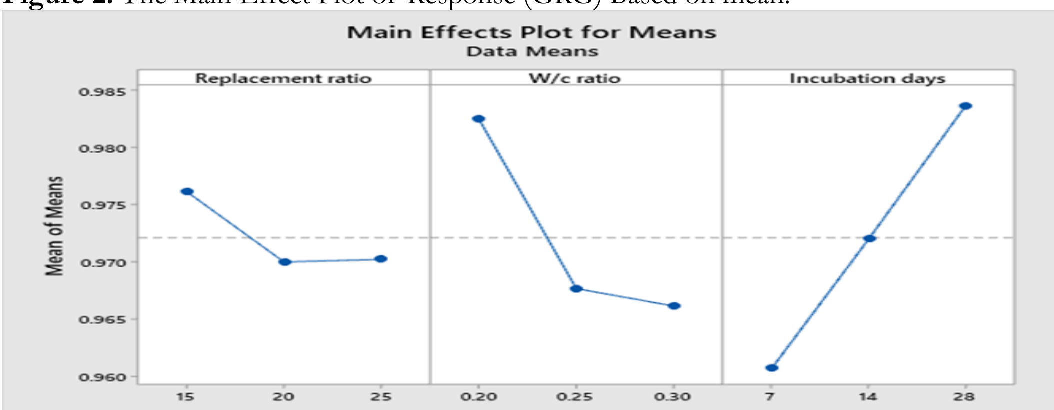
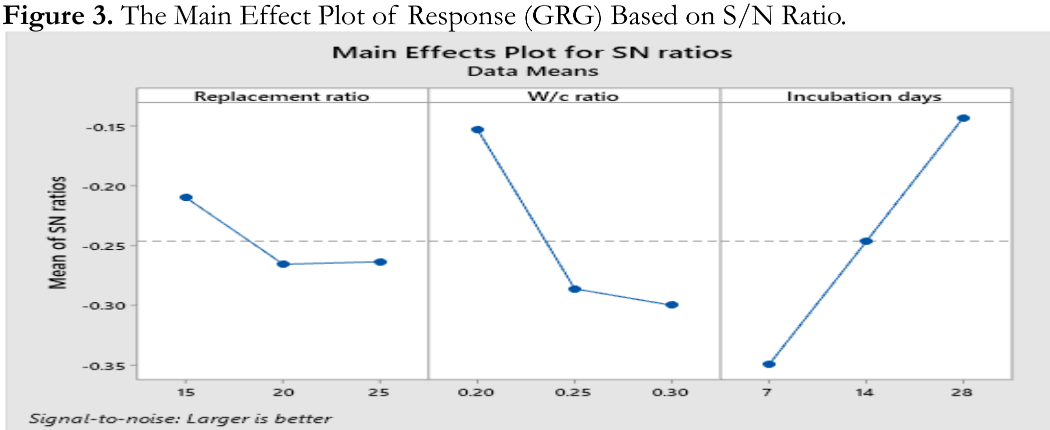


Figure 3. The Main Effect Plot of Response (GRG) Based on S/N Ratio.



Based on the results, the compression strength and tensile strength are all at their highest levels in the incubation days (A), immediately followed by the replacement ratio (B) and the W/C ratio (C). Based on S/N ratio for individual responses, it was found that influencing factor was found to be incubation days in all responses. Incubation days (C) were found to be the lowest, followed by replacement ratio (B) and W/C ratio (C), as determined by delta rank. The influence of the parameters on response is presented in Figure 2 and Figure 3 in rank order (Delta), with incubation time (days), replacement ratio, and W/C ratio being the most significant. The difference between the greatest and lowest average response values corresponds to the delta value for every parameter. With the increase of the ratio of recycled aggregate in the concrete, there is decrease in the response. However, W/C ratio does not have significant impact on the response.

Regarding the S/N ratios of all responses (compression strength and tensile strength), incubation days have the highest impact, followed by the replacement ratio and W/C ratio. Basically, the higher the grey relational grade depends on many reaction parameters. From the results, it was found that as the replacement ratio increased from 25% to 75%, the S/N ratio decreased. A similar pattern of decrease in the S/N ratio is observed in the W/C ratio. Scientific literature report that the compressive strength is inversely related to the W/C ratio, as the W/C ratio increases the compressive strength and split tensile strength is decreased through Abram's generalization law (Liao et al., 2020). The S/N ratio increased with increase in the incubation days (Liu et al., 2023). S/N ratio of incubation days has profound impact on the response. The estimated grey relationship grade that has been determined to be the best at 0.988 (Run 7), which has a higher than the average grade over the nine trials. As a result, by using the existing methodology, response has been substantially enhanced. Based on GRG analysis, run 01 for further experimental studies. The final arbitrary predicted combination based on GRG was found to be A1B1C3. The highest S/N ratios are selected for every variable to predict the optimal scenario and to perform confirmation tests. The predicted conditions were found to be similar to run 07 in the design matrix, i.e., replacement ratio at level 01, W/c ratio at level 01 and incubation days at level 03. Moreover, as both predicted run and experimental run are similar, no validation experiment is required. But to validate model adequacy, a validation experimental run was performed based on run seven conditions (A1B1C3). It was found that the compression strength and the tensile strength increased by 1.70% and 1.57% respectively. Studies conclude that there has been good agreement between the predicted and the experimental run. Figure 2 and Figure 3 represent the main effect plot of response (GRG) based on means and S/N ratio.

Table 3. Caption of the Table. S/N ratio, Normalization, Grade and Rank of the Response.

Run	**S/N ratio**		**Normalization**		**Grey Relational Coefficient**		**Grade**	**Rank**
	Compression	Tensile	Compression	Tensile	Compression	Tensile		
1	33.112	15.148	0.030	0.065	0.976	1.000	0.982	3
2	28.925	11.799	0.001	0.000	0.957	0.956	0.967	7
3	30.480	14.387	0.013	0.053	0.964	0.991	0.979	4
4	30.333	14.791	0.012	0.060	0.964	0.996	0.978	5
5	32.332	15.193	0.025	0.066	0.973	1.000	0.984	2
6	28.806	12.527	0.000	0.017	0.956	0.967	0.948	9
7	33.112	15.148	0.030	0.065	0.976	1.000	0.988	1
8	28.925	11.799	0.001	0.000	0.957	0.956	0.952	8
9	30.480	14.387	0.013	0.053	0.964	0.991	0.971	6

Table 4. The Main Effect of Process Parameters on Mean and S/N Ratio Responses.

Response	Effect of process parameters on mean responses				Effect of process parameters on S/N ratio (responses)			
Compression strength	Level	Replacement ratio	W/C ratio	Incubation days	Level	Replacement ratio	W/C ratio	Incubation days
	1	33.16	34.58	25.23	1	30.15	30.54	28.02
	2	32.48	32.33	31.69	2	29.99	30.03	30.00
	3	35.17	33.91	43.90	3	30.72	30.29	32.84
	Delta	2.69	2.25	18.67	Delta	0.73	0.51	4.82
	Rank	2	3	1	Rank	2	3	1
Tensile strength	Level	Replacement ratio	W/C ratio	Incubation days	Level	Replacement ratio	W/C ratio	Incubation days
	1	4.867	5.007	3.870	1	13.62	13.85	11.75
	2	5.050	4.913	5.277	2	13.94	13.71	14.44
	3	4.950	4.947	5.720	3	13.78	13.78	15.15
	Delta	0.183	0.093	1.850	Delta	0.32	0.14	3.39
	Rank	2	3	1	Rank	2	3	1
GRG	Level	Replacement ratio	W/C ratio	Incubation days	Level	Replacement ratio	W/C ratio	Incubation days
	1	0.9761	0.9825	0.9607	1	-0.2100	-0.1530	-0.3496
	2	0.9700	0.9677	0.9720	2	-0.2657	-0.2863	-0.2468
	3	0.9702	0.9661	0.9837	3	-0.2636	-0.3001	-0.1430
	Delta	0.0061	0.0164	0.0230	Delta	0.0557	0.1471	0.2067
	Rank	3	2	1	Rank	3	2	1

Regression Analysis

Regression analysis was performed to identify the linear relationship among the input parameters and the response (Moghadam et al., 2023). Linear regression models have been established for all grades of response. After the first nine experiments, regression models of the responses were developed for predicting optimal conditions at all three levels of replacement ratio, w/c ratio, and incubation days. Eq. 3, Eq. 4, and Eq. 5 represents the linear regression for the three responses (compression strength, tensile strength, and grade) based on three variables, i.e., replacement ratio, w/c ratio, and incubation days respectively. Based on regression analysis (Eq. 3 and Eq. 4), it was observed that replacement ratio and incubation days were found to have positive influences, whereas W/C ratio was found to have a negative impact on the response (Compression and tensile strength). In case of grade analysis (Eq. 5), incubation days had positive influence on the response, whereas replacement ratio and w/c ratio had negative impact.

$$F_{ck} = 18.78 + 0.0401^{*}\mathrm{R} - 6.7^{*}\frac{\mathrm{W}}{\mathrm{C}} + 0.8868^{*}\text{Incubation days} - - - (3)$$

$$F_{S} = 3.72 + 0.00167^{*}R - 0.60^{*}\frac{W}{C} + 0.0800^{*}Incubation\ days - - - - (4)$$

$$G = 1.0077 - 0.000592^{*}R - 0.1641\frac{W}{C} + 0.01059^{*}\text{Incubation days} - - - (5)$$

G = Grade, R = Replacement ratio, W/C = water to cement ratio, C = Incubation days

Forward regression analysis was performed to identify the most influencing parameter towards the response (Grade). Eq. 6 represents the final optimized equation.

$$G = 0.9959 - 0.1641^{*}\frac{W}{C} + 0.01059^{*}\text{Incubation days} - - - (6)$$

Where Fck = Compressive strength in N/mm2, FS = Tensile strength in N/mm2, G = Grade.

Analysis of Variance (ANOVA)

In the orthogonal studies, the average impact of each variable is assessed using a statistical framework called Analysis of Variance (ANOVA). A commonly used method for confirming the relative impact of every procedure variable on intended outputs is the ANOVA approach. A one-way ANOVA analysis was used to observe the impact of every trial component on the variables. It assists in quantifying the relevance of operational factors' effects on specific outcome attributes. In order to determine the ideal controllable process variables and precisely manage the manufacturing procedure's factors, this research uses the Taguchi technique to study the mechanical and chemical properties of concrete prepared using recycled aggregate (Hakeem et al., 2023). In case of compression and tensile strength, incubation days were found to be statistically significant in both mean and S/N ratio. It was observed from the ANOVA table (Table 5) that, incubation days of the compression strength and tensile strength based on S/N ratio was reported to be statistically significant (0.026 and 0.03). Statistically parameters such as R2, and adjusted R2 were found to be greater than 80% in case of compression and tensile strength (in both mean and S/N ratio). An effective and improved model for steering into the model suggests that correlation coefficient (R2) value greater than 0.8 and close to 1.0 supports model adequacy (Mustapha et al., 2021; Neeraja & Sharma, 2023). Statistically, R2 values relates the target and the response (Preethi et al., 2015). ANOVA helps to decipher the percentage contribution of each and every variable on the response (Rajprasad & Pannirselvam, 2020a). It was observed from ANOVA analysis that the percentage contribution of compression strength (94.05 %), tensile strength (98.49 %) and grade (50.284) respectively and it was concluded that the incubation days was found to be most influencing factor based on percentage contribution towards utilization of recycled aggregate. Pareto analysis also validated that the incubation days to be most influencing parameter among the three factors (Figure 4). The Pareto chart provides a visual representation of the Pareto principle. When outcomes are observed, it is typical for researchers to discover that 20% of the potential causes account for about 80% of the occurrences (Rajprasad & Pannirselvam, 2020b).

Figure 4. Pareto Analysis of the Response on the GRG.

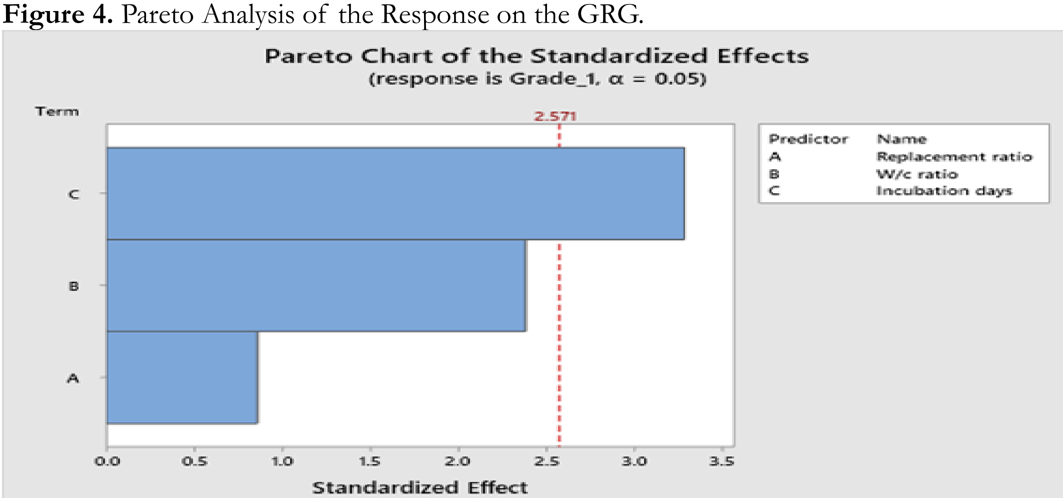


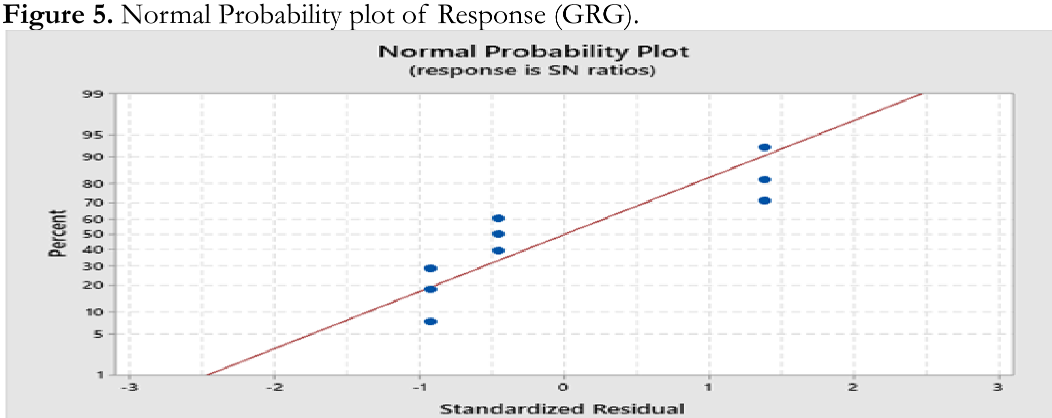
Table 5. ANOVA Table of the Response.

S/N ratio				
Source	DF	SS	F	P
Replacement ratio	2	0.8875	0.93	0.517
W/C ratio	2	0.3894	0.41	0.709
Incubation days	2	35.2294	37.05	0.026*
Error	2	0.9508		
Total	8	37.4570		
Source	DF	SS	F	P
Replacement ratio	2	0.05056	2.35	0.298
W/C ratio	2	0.01342	0.62	0.616
Incubation days	2	5.59776	260.50	0.004*
Error	2	0.02149		
Total	8	5.68322		
Source	DF	Seq SS	F	P
Replacement ratio	2	0.000073	0.33	0.752
W/C ratio	2	0.000493	2.23	0.309
Incubation days	2	0.000795	3.60	0.217
Error	2	0.000221		
Total	8	0.001581		
Statistical parameters		R2	Adj R2	S
Compression test		97.46	89.5	0.6895
Tensile strength		99.69	98.75	0.1747
Grade		86.04	44.14	0.015
*Statistically significant at 95% confident limit				

Normal Probability Plot

Based on the statistical studies, it was demonstrated that the residuals are typically located on the straight line, attributing that the values are dispersed within the 95% confidence level interval (Rashid et al., 2020). Normal probability plot is used to identify the pattern of distribution of the data, i.e., normally distribution. A straight line in the normal residual plot illustrates the statistically significant nature of a model's coefficients, and the correlation of the experimental and predicted outcomes was observed (Reddy & Naqash, 2019). The normality assumption is verified using the Anderson Darling (AD) test (Shaikh & Nguyen, 2013). The experimental data is close to the fitted line for all of the answers, the AD statics values (A2 value – 0.46) and the (p-value = 0.200) for our study was more than 0.05, suggesting that the data has a normal distribution (Shaji & Radhakrishnan, 2003). Based on Grubb's test, no outlier was detected at the 5% level of significance (Singh et al., 2015). Figure 5 represents the normal probability plot of the response (Grade).

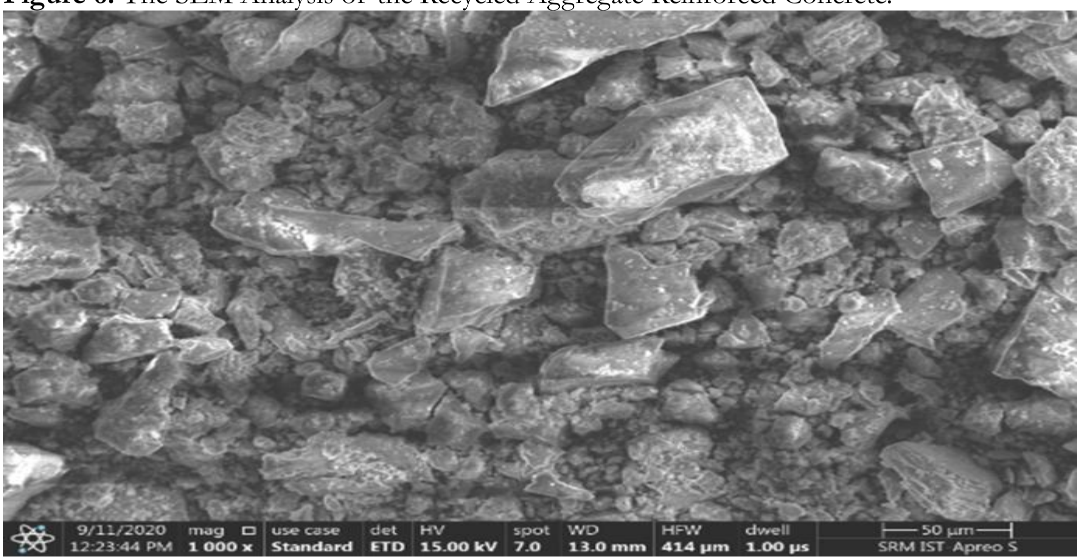
Figure 5. Normal Probability plot of Response (GRG).



Normal Probability Plot

SEM imaging was carried out after compression tests to investigate the microstructural behaviour of the sample (Run 7 containing 25% recycled aggregate, 0.2 water/cement ratio and 28 days incubation period), as Inter Transition Zone (ITZ) influences the mechanical properties of recycled aggregate concrete (RAC) (Stephens, 1974). SEM analysis indicated the presence of microstructures and an ITZ zone in the recycled aggregate-reinforced concrete. Recycled aggregate recycling involves its direct influence on the microstructure of the concrete components, resulting in microcracks, porousness, and weakening of the ITZ zones, subsequently leading to compromises on the aggregate microstructure, engineering qualities, and durability of the concrete. Recycled aggregate mortar contains tiny cracks and pores, facilitating water retention. Literature reported that the presence of voids in the old mortar, attributed to carbonation, ultimately modified and improved the microstructure because the presence of carbon dioxide reacts with calcium hydroxide to form calcium carbonate, thereby filling the voids and pores in the mortar (Sundaramoorthy & Ravindran, 2019). Figure 6 represents the SEM analysis of the recycled aggregate reinforced concrete.

Figure 6. The SEM Analysis of the Recycled Aggregate Reinforced Concrete.



Conclusions

Developing and evaluating an ecologically friendly concrete mix by employing recycled aggregate and adopting an optimal technique or formulation is a crucial step towards creating a concrete mix. Recycled broken concrete (RCA) has wide applications in concrete that provide value addition by maximising environmental and economic benefits. Organic natural aggregate can be substituted out with RCA concrete in many constructions. Nevertheless, RCA's contradictory characteristics may make it challenging to implement in fresh concrete. Due to its denser microscopic architecture, a long-term curing could assist in the development of calcium carbonate solids in the ITZ regions during carbonation treatment, thereby enhancing the efficiency of RCA concrete. SEM analyses were carried out after compression tests at the appropriate days to obtain microstructural insights. Image analysis revealed presence of microcracks and pores, warranting the fact that the recycled aggregate directly influence on the microstructure. Taguchi optimisation and Grey Relational Analysis is applied in almost all process to cater the needs of construction industries. There is persistent research to developing a short-term, efficient, and effective process to achieve maximal mechanical and durability properties of recycle aggregate reinforced concrete. The Grey Relational Analysis (GRA) technique was used to optimise the multiple response characteristic procedure. On analysing the GRG, it has been identified that A1B1C3 is the optimum arbitrarily predicted combination. The highest S/N ratios have been selected for each factor in order to predict an optimal condition and perform validation studies. The design matrix revealed that the expected circumstances were similar to run 07, with a replacement ratio at level 1, a W/C ratio at level 1, and incubation days at level 3. Furthermore, since the experimental run and predicted run are similar, no additional verification experiment is required. However, a validation experimental run based on run 07 circumstances (A1B1C3) was carried out to verify the model's appropriateness. In accordance with the results of an ANOVA analysis, the percentage contributions of compression strength, tensile strength, and grade have been calculated to be 94.05%, 98.49%, and 50.284%, respectively, and it was established that the incubation days were the factor with the greatest significance in terms of percentage contributions towards the use of recycled aggregate. The marketplace is expanding as a result of increasing consumer appetite for environmentally friendly building materials and efforts to minimise waste in the construction sector. The upcoming marketplace will focus on the viability of employing recycled coarse aggregate in new concretes that have comparable or superior strength grades and reducing the impact of recycled aggregate concrete's decreased properties through the development of an appropriate composition in the near future.

Use of AI Tools Declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of Interest

The authors declare no conflict of interest.

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