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Research Article

Prediction of the mechanical properties of concrete incorporating simultaneous utilization of fine and coarse recycled aggregate

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Abstract: The mechanical properties of concrete were optimized using response surface methodology (RSM) and fuzzy logic. The aggregate portion of the concrete was replaced with recycled aggregate to address the environmental problems caused by building demolition wastes. The essential key factors that influenced the suitability of recycled aggregate in concrete applications are the compressive strength (CS), flexural strength (FS), and the split tensile strength (STS). The experiments were designed with nine combinations of two input factors (percentage of coarse and fine recycled aggregates) at different levels 30, 60, and 100%. Furthermore, optimization techniques were used to determine the strong correlations between the variables and the mechanical parameters. Such optimization techniques helped to identify the optimistic maximum strength for replacing 44% coarse and 65% fine recycled aggregate. Using RSM, the maximum strength results were found to be: CS at 7, 28, 56, and 90 days were 23.61, 35.04, 40.02, and 43.63 N/mm^2, respectively, FS 3.6 N/mm^2 and STS 2.0 N/mm^2. The maximum strength parameters were found using fuzzy logic: CS at 7, 28, 56, and 90 days were 23.5, 35.8, 41, and 46.7 N/mm^2, respectively, FS 4.13 N/mm^2 and STS 1.97 N/mm^2. Such optimization can be carried out to lower the material wastage, energy consumption, and expenses for the production.

Keywords: recycled aggregates, construction and demolition waste, optimization, response surface methodology, fuzzy logic.

1. Introduction

Construction and demolition waste (CDW) management has become complex task for both developing and established nations. The developed countries have been paying attention to the generation of CDW for the past 20 years and have passed legislation to stop unlawful dumping, but proper recycling techniques and detailed improvement plans have not yet been studied in detail (Turkyilmaz et al., 2019). Every year, the estimated generation of CDW worldwide would be around 1.3 billion tons. In the United States, the generated amount of CDW in 2018 was more than twice the municipal solid waste, according to estimates from the “United States Environmental Protection Agency” (US EPA, 2020). In China, 30 to 40% of all waste were building demolition waste. The recycling percentage of CDW in China was approximately 5%, and the remaining CDW was typically thrown away in landfills or dumped randomly. The main barriers to CDW recycling are an inadequate management strategy, a lack of advancements in recycling technology, a limited market for recovered CDW products, and an inexperienced recycling market infrastructure. These obstacles have made it extremely difficult to use CDW in a cyclic manner (Huang et al., 2018). The accumulation of CDW in India had been estimated to be nearly 150 million tons in 2020, and the average recycling rate was only 1%. Some cities, such as Chennai and Mumbai produced 2500 tons of CDW daily in 2017, as reported by the "Central Pollution Control Board of India" (Jain, 2021). Most countries allowed the usage of CDW in concrete production; also, Bureau of Indian Standards permitted the CDW utilization with specific guidelines. However, there are still some limitations for using such materials in the new structural concrete. In order to fill the gap in the various standards, further research is necessary to bring a sustainable future to the construction sector. Thus, the current study aimed to ascertain whether the aggregates from CDW might be used in structural concrete to make a sustainable environment for future generations.

Construction and demolition debris is a composite mixture with an uncertain property, which must be processed to create new sustainable aggregates with suitable characteristics for concrete production. The constituents of recycled aggregate include broken glass, bricks, granite, mosaic, broken concrete, and natural aggregates (Pacheco & de Brito, 2021). The recycling capacity of CDW plants are increasing year by year worldwide. The first CDW recycling facility was opened in India in 2009 at Burrari. The facility has the capability of recycling CDW 2000 tons per day (TPD). Similar facilities with capacities of "1100, 550, 300, 200, 500 and 75 TPD" are situated in "Ranikhera, Shastripark, Gujarat, Andhra Pradesh, Telangana, and Madhya Pradesh", respectively. In addition, the plans for recycling facilities are proposed in "Ghumanhera, Libaspur, Kapashera, Bakkarwala, Panaji, Coimbatore, Kannur, Mallasandra, Anjanapura, Wagholi, Fathullaguda, and Kapuluppada" (Swarna K. et al., 2022). While seeing the statistics of recycling capacity in India, approximately 8000 TPD building demolition wastes were generated in major cities in 2020. Therefore, many researchers began to study about the recycled aggregates. Many research in recycled aggregate is focused on shear behavior (B. Liu et al., 2019), impact properties (Wang et al., 2020), shrinkage properties (Yu et al., 2021), chloride permeability (Liang et al., 2019), grading method (X. Liu et al., 2021), shrinkage and creep (Chinzorigt et al., 2020).

Concretes containing 20 to 100% of mixed recycled aggregates (MRA) were assessed for their performance. Compressive and flexure strength did not vary considerably at replacement ratios of less than 50%. However, both parameters showed statistically significant differences at higher percentage. Furthermore, longer curing times greater than 90 days resulted in a smaller loss of strength when compared to traditional concrete. The morphological analysis shows that the recycled aggregate and natural aggregate interfacial transition zone are very similar (Cantero et al., 2018). Also, it is feasible to create recycled aggregate concrete with similar instinctive and long-lasting properties like natural aggregate mixtures up to 25% replacement. Thus, the RACs (97% concrete mixtures and 3% brick mixtures by weight) can be a viable structural alternative to ordinary concrete (Ozbakkaloglu et al., 2018).

The MRA incorporates recycled fine aggregates (RFA) and recycled coarse aggregate (RCA). The fusion of 35% RFA and 70% RCA mix and 70% RFA and 35% RCA mix proclaimed 25% and 28% more extensive strength, respectively. As a result of Taguchi-response surface optimization of MRA, the microstructure of MRA concrete improved, and the water absorption decreased with the significant incorporation of RFA and RCA in concrete. In structural applications, not subject to harsh environmental conditions, treated mixed recycled aggregates hold much promise (Zhang et al., 2019). Additionally, the untreated mixed recycled aggregate performs satisfactorily as a replacement for coarse natural aggregate by up to 30%. Therefore, the mixed recycled aggregate incorporation was favorable in strength and microstructural properties comparable to conventional concrete. The recycled aggregate inclusion can promote the consumption of all forms of building demolition wastes that are directly gathered in order to boost the economy in the construction industry (Joseph et al., 2022).

The permeability properties of concrete with recycled aggregates are being investigated to encourage the complete recycling of concrete without leaving any residue. Because of their highly porous nature, recycled coarse aggregates has a higher sorptivity value when used in concrete mixes. Numerous relationships have been established to predict the water permeability of recycled aggregate concrete mixtures made with varied cement contents based on the first and secondary absorption rates. The entirely replaced recycled aggregate concrete mixes showed acceptable sorptivity and strength characteristics, and they may be used to create environment-friendly masonry units (Hameed et al., 2022). However, several studies in different locations must be done to determine whether adding recycled aggregate to concrete affects its mechanical properties. Also, simultaneous replacement is necessary to obtain the correct model for predicting the properties of concrete with precision.

For modelling the relationship between input and response parameter, the type of approach, both the response surface methodology (RSM) and desirability functional approach, were used (Amiri et al., 2022). Compared to other models, RSM has higher accuracy and can reasonably anticipate the strength properties of concrete at various ages (Poorarbabi et al., 2020). The optimal combinations for novel construction concepts can be found using systematic optimization techniques, which are effective methods. By considering mechanical, economic, and environmental factors, the optimization enables the selection of the optimal response from the available options (Dabbaghi et al., 2022).

The strength parameters of the concrete specimens are always dependent on the particle's arrangements. While comparing the other predicted models using various approaches, the fuzzy technique is a good fit for predicting the responses of the experiment. The fact that all the rules are expressed verbally, much like how people think, is another benefit of fuzzy logic (Akkurt et al., 2004). The way our brains operate appears to be more like fuzzy logic. However, probability theory and fuzzy logic have few things in common. The Bayesian framework is used to create probabilistic approaches that cope with limited information, but fuzzy logic does not necessarily need to be justified in terms of probabilistic reasoning (Garza-Ulloa, 2018).

The production of cost-effective, environment-friendly concrete using waste resources have drawn considerable interest worldwide (Amran et al., 2021). Also, designing of experiments will reduce the materials and costs for examining various studies. Therefore, the optimization of the experiment can predict the responses with the error as low as possible (Uysal et al., 2019). This study attempts to develop empirical models using Minitab18.1 and MAT Lab in order to forecast the compressive, flexure, and split tensile strength of concrete from the various mixture composition considering the factors which affect the strength as replacement percentage of coarse and fine recycled aggregate.

2. Materials and methods

2.1. *Materials*

This experimental study uses coarse recycled aggregate (CRA) and fine recycled aggregate (FRA) from CDW instead of natural coarse and fine aggregate in concrete. The different compositions of concrete with recycled aggregate were selected at 0 to 100% for the simultaneous replacement in conventional concrete. First, the CRA was kept in a constant replacement level of 30% and FRA at varying replacement levels of 30, 60, and 100%. Similarly, this study included other compositions keeping CRA at constant levels 60 and 100%, and mixing with FRA at varying replacement levels of 30, 60, and 100%. For forecasting the strength behavior of concrete specimens with recycled aggregate, these nine different compositions were designed to have mixes with characteristics strength of 30 MPa with a water-to-cement ratio of 0.42 based on IS 10262-2019.

The Ordinary Portland Cement of 53 Grade with a specific gravity of 3.15 was used in this current study, which satisfied all the requirements of IS 12269: 2013. The coarse recycled aggregate is taken as a mixture of 60% of 20mm aggregate (specific gravity (SG) of 2.3 and rodded density (RD) of 1452 kg/m^3) and 40% of 12.5mm aggregate (SG of 2.41 and RD of 1381 kg/m^3) for achieving maximum packing density. The natural aggregate also taken as a mixture of 60% of 20mm aggregate (SG of 2.71, RD of 1668 kg/m^3) and 40% of 12.5mm aggregate (SG of 2.68, RD of 1642 kg/m^3). The fine recycled aggregate of maximum 4.75 mm size having a SG of 2.35 and RD of 1613 kg/m^3 were used. The manufactured sand (M-sand) of maximum 4.75 mm size having a SG of 2.6 and RD of 1861 kg/m^3 have been utilized to fulfill the requirements of IS 2386-2020 (Parts I–IV). The physical properties of aggregates are shown in Table 1. The cubes of 150 x 150 x 150 mm size, beams of 100 x100 x 500 mm, and cylinders of 150 x 300 mm were casted to determine the hardened properties of concrete as per IS 516 (Part1 /Sec 1)-2021.

Table 1. Physical properties of aggregates.

Physical Properties	M-sand	Fine recycled aggregate	Coarse natural aggregate		Coarse recycled aggregate	
			20mm	12mm	20mm	12mm
Fineness modulus	2.78	3.4	3.72	3.5	2.32	2.42
Water absorption (%)	2.67	3.92	0.5	0.67	2.3	1.95
Loose air-dried bulk density (kg/m^3)	1628	1459	1475	1453	1319	1186
Specific gravity	2.6	2.35	2.71	2.68	2.3	2.41
Flakiness index (%)	-	-	8.3	-	17.25	-
Elongation Index (%)	-	-	7.8	-	11.7	-

2.1.1. Methodology

The casted cubes, cylinders, and beams were tested for finding concrete's the compressive, flexure, and split tensile strength. After knowing the strength properties at various curing days, the data was used for designing the experiment, which is very important for predicting and optimizing the results. Response surface methodology and fuzzy logic are powerful methods for experimental design, data analysis, and optimization. In this study, the experiment was designed using Minitab18.1 software and fuzzy logic tool in MAT Lab. The correlations were built using investigations on the hardened characteristics of concrete made with recycled aggregate. The factors affecting the response parameters were selected as coarse and fine recycled aggregates and studied at 30, 60, and 100% levels. The compressive strength at different curing periods, spilt tensile, and flexural strength at 28 days of curing were decided as the output variables. The regression model taken from the response surface methodology was a full quadratic model with linear, quadratic, and two-way interactions. The forecasted values were compared with experimental values, and the responses were optimized using Minitab software and fuzzy logic tool in MAT Lab.

3. Experimental results and analysis

The hardened properties of concrete made using recycled aggregates were examined and the experimental results are shown in Tables 2 and 3. The hardened properties of recycled aggregate concrete showed almost comparable strength to that of ordinary concrete, except the mix having 100% fine recycled aggregate. The results were comparable with the study conducted on recycled aggregate concrete with different mixing approaches (Jagan et al., 2021). Using the Minitab18 program, the expected values of the responses were produced. A full quadratic model was used for each factor, and the regression equation provides the coefficients of the parameters. The final mathematical models arrived after the regression equation provided the expected values. The variance analyses of the predicted response surface models for each response variable are explained in separate sections of this article. The p value strategy was used in this study to evaluate hypotheses; specifically, a p value of 0.05 shows that model terms with a better accuracy in predicting the responses. Also, fuzzy logic model was developed with CRA and FRA replacement percentage as input variables with three linguistic terms (30, 60, and 100%) and six output responses, such as compressive strength at 7, 28, 56, and 90 days of curing, flexure, and split tensile strength at 28 days of curing in MAT Lab R2022a.

Table 2. Experimental design with process data and the response of compressive strength.

Mix ID	CRA (%)	FRA (%)	CS - 7 days (N/mm²) Trails	CS - 7 days (N/mm²) Average	CS - 28 days (N/mm²) Trails	CS - 28 days (N/mm²) Average	CS - 56 days (N/mm²) Trails	CS - 56 days (N/mm²) Average	CS - 90days (N/mm²) Trails	CS - 90days (N/mm²) Average
Mix 1	30	30	25.98	26.41	40.74	39.93	49.23	47.65	50.26	50.42
			27.40		40.10		46.07		51.14	
			25.85		38.96		47.65		49.86	
Mix 2	30	60	24.97	24.6	33.95	35.83	46.90	43.14	44.29	44.15
			23.90		36.49		40.40		43.91	
			24.94		37.04		42.12		44.25	
Mix 3	30	100	17.87	18.52	29.16	27.61	37.22	35.23	36.65	38.5
			18.00		26.13		35.52		38.93	
			19.68		27.54		32.95		39.92	
Mix 4	60	30	26.70	27.43	36.09	37.06	43.37	42.48	46.22	45.61
			25.28		38.20		42.50		44.46	
			30.33		36.88		41.57		46.16	
Mix 5	60	60	23.65	22.87	34.39	36.05	41.64	38.43	45.47	44.01
			22.60		37.57		39.80		45.26	
			22.36		36.20		33.83		41.29	
Mix 6	60	100	20.88	19.33	28.17	27.83	33.50	33.5	37.64	41.56
			16.46		29.01		34.35		41.77	
			20.64		26.30		32.65		45.26	
Mix 7	100	30	24.81	26.2	35.41	34.1	43.51	41.54	41.07	42.94
			26.92		34.47		40.90		41.96	
			26.86		32.43		40.22		45.79	
Mix 8	100	60	25.48	23.61	34.36	33.62	39.47	38.87	40.14	40.6
			22.18		32.89		38.02		41.2	
			23.17		33.61		39.12		40.45	
Mix 9	100	100	15.80	16.48	28.16	26.54	30.21	32.53	41.3	39.34
			17.12		26.61		31.65		39.80	
			16.52		24.85		35.73		36.92	

♠CS – Compressive strength

Table 3. Experimental process data and the response of flexure and split tensile strength.

Mix ID	CRA (%)	FRA (%)	FS - 28 days (N/mm²) Trails	FS - 28 days (N/mm²) Average	STS - 28 days (N/mm²) Trails	STS - 28 days (N/mm²) Average
Mix 1	30	30	4.95	4.73	1.63	1.9
			4.42		2.37	
			4.82		1.70	
Mix 2	30	60	4.58	4.01	2.10	1.84
			3.25		1.87	
			4.20		1.55	
Mix 3	30	100	3.9	3.62	1.85	1.99
			3.17		2.34	
			3.79		1.78	
Mix 4	60	30	5.2	5.14	3.21	2.72
			4.78		2.87	
			5.44		2.08	
Mix 5	60	60	3.78	3.48	1.83	2.09
			3.37		2.15	
			3.29		2.29	
Mix 6	60	100	3.88	3.33	1.97	1.64
			3.18		1.55	
			2.93		1.40	
Mix 7	100	30	4.32	4.73	2.65	2.26
			4.83		2.35	
			5.04		1.78	
Mix 8	100	60	3.35	3.20	1.85	1.96
			2.97		2.11	
			3.28		1.92	
Mix 9	100	100	2.93	3.00	1.86	1.50
			3.28		1.04	
			2.79		1.60	

♠♠FS – Flexural Strength, ♠♠♠STS – Split Tensile Strength

3.1. *Response surface methodology*

3.1.1. Modelling for compressive strength

The experimental data demonstrate that, with the increased addition of recycled aggregates, the response of compressive strength decreases. The results of the ANOVA for compressive strength variation at 7, 28, 56, and 90 days of curing period were obtained using the response surface model.

The variance table was examined to evaluate whether the effects are statistically significant in the model. At seven days of curing period, the compressive strength of recycled aggregate concrete depends on FRA due to its significant effect at linear as the p value is less than 0.05 (p = 0.002). The quadratic terms CRA^2 (p = 0.556), FRA^2 (p = 0.428), and two-way interaction (p = 0.431) were statistically insignificant at the required level of 5%. The term FRA (p = 0.001) at linear, FRA^2 (p = 0.049), and the two-way interaction (p = 0.010) are critical factors as the p value is less than 0.05 determines the compressive strength of recycled aggregate concrete at 28 days of curing. Both the terms, linear CRA (p = 0.095), and quadratic CRA^2 (P=0.891) were insignificant.

The compressive strength of recycled aggregate concrete depends on the term FRA (p = 0.001), CRA (p = 0.008) at linear, and quadratic CRA^2 (p = 0.044) at 56 days of curing. These terms are important because they have a p value under 0.05. The quadratic FRA^2 (p = 0.390) and two-way interaction (p = 0.155) were statistically insignificant. The compressive strength of recycled aggregate concrete at 90 days of curing relies on a factor, FRA (p = 0.013) at linear, which is significant as the p value is less than 0.05. The quadratic (p = 0.657) and two-way interaction (p = 0.073) were insignificant.

RSM provides much information based on small number of experiments. In order to describe a behavior of the application using traditional approaches, numerous experiments are required (Ba & Boyaci, 2007). Figure 1 depicts the contour plot and response for the impact of each variable on this parameter. The graphical presentation of results provided a simplified approach of optimization and identification of variable interactions. Each curve depicts an infinite number of possible combinations of variables (Boutra et al., 2022). Following hypothesis testing, the regression equation demonstrated a direct relation between each main effect and response (Boudjema et al., 2018). The Equations 1, 2, 3, and 4 give the final mathematical models of compressive strength at various curing periods.

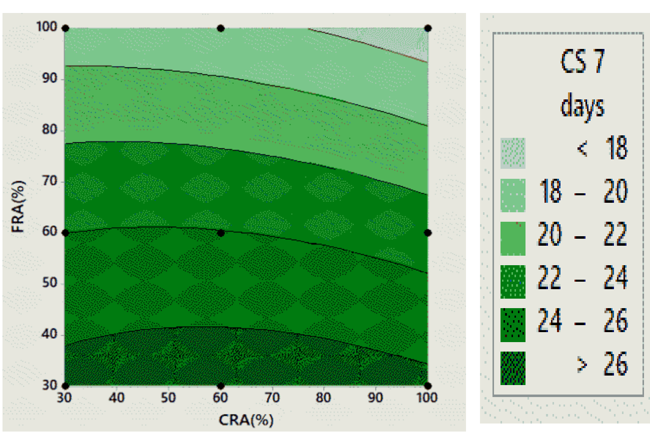
$$CS(7\ days) = 26.65 + (0.063 *\ CRA) - (0.0234 * FRA\ ) - (0.000413 * CRA^2) - (0.000572 * FRA^2) - (0.000389 * CRA * FRA) \quad (1)$$

$$CS(28\ days) = 45.32 - (0.1474 *\ CRA) - (0.0472 * FRA\ ) +\ (0.000067 * CRA^2) - (0.001437 * FRA^2) + (0.001807 * CRA * FRA) \quad (2)$$

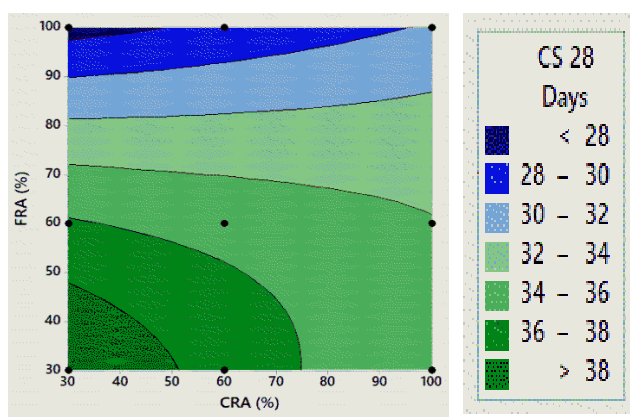
$$CS(56\ days) = 58.95 - (0.3202 *\ CRA) - (0.1208 * FRA\ ) + (0.001668 * CRA^2) - (0.000501 * FRA^2) + (0.000648 * CRA * FRA) \quad (3)$$

$$CS(90\ days) = 57.85 -\ (0.061 *\ CRA) - (0.261 * FRA\ ) - (0.000685 * CRA^2) + (0.000509 * FRA^2) + (0.001610 * CRA * FRA) \quad (4)$$

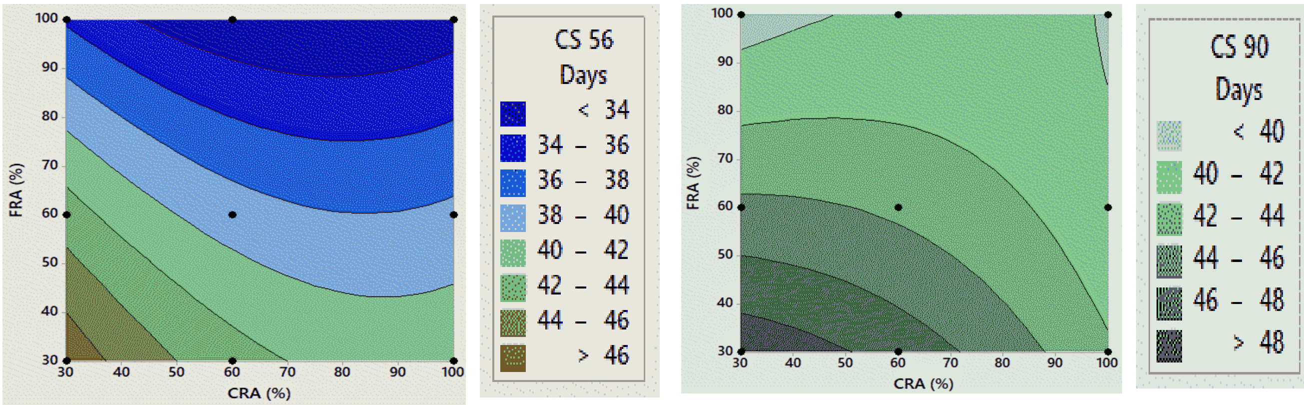
Where CS is compressive strength, CRA is replacement percentage of coarse recycled aggregate and FRA is replacement percentage of fine recycled aggregate.



Contour plot for CS at 7 days



Contour plot for CS at 28 days



Contour plot for CS at 56 days

Contour plot for CS at 90 days

Figure 1. Contour plot of strength properties.

The contour plot for the compressive strength of concrete by varying the curing period is shown in Figure 1. The improvement in compressive value was recorded in the range of 18 to 26 N/mm^2, 28 to 38 N/mm^2, 34 to 46 N/mm^2 and 40 to 48 N/mm^2, respectively, for the curing days of 7, 28, 56, and 90 days.

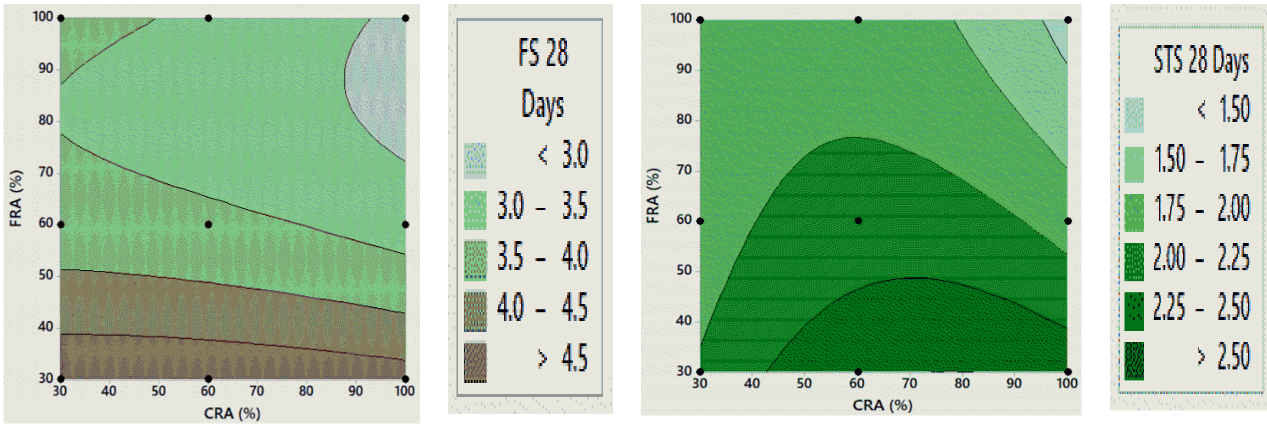
3.1.2. Response surface for flexural and split tensile strength

The flexural behavior of recycled aggregate concrete at 28 days depends on the term FRA (p = 0.005) at linear, and the quadratic FRA^2 (p = 0.042) was significant due to the p value being lower than 0.05. The linear CRA (p =0.109), the quadratic CRA^2 (p = 0.743), and the two-way interaction (p = 0.387) were insignificant. The split tensile strength of recycled aggregate concrete was influenced by the variable, the parameter FRA (p = 0.074) at linear which was significant because of having p value almost closer to 0.05, at 28 days of curing. The quadratic terms (p =0.505) and CRA (p = 0.927) were insignificant for the predicted model. The contour plot and response in Figure 2 depicts the impact of each variable on this attribute. The final mathematical models of flexure and split tensile strength at 28 days are provided by Equations 5 and 6.

$$FS(28\ days) = 6.934 + (0.0074 * CRA) - (0.0845 * FRA) - (0.000056 * CRA^2) + (0.000533 * FRA^2) - (0.000108 * CRA * FRA) \quad (5)$$

$$STS\ (28\ days) = 1.418 + (0.0363 * CRA) - (0.0068 * FRA) - (0.000201 * CRA^2) + (0.000067 * FRA^2) - (0.000161 * CRA * FRA) \quad (6)$$

where FS is flexure strength, STS is split tensile strength, CRA is replacement percentage of coarse recycled aggregate and FRA is replacement percentage of fine recycled aggregate.



Contour plot for FS at 28 days

Contour plot for STS at 28 days

Figure 2. Contour plot of strength properties

3.1.3. Model statistics

All models in this investigation meet the chosen statistical significance level of 5%. Table 4 displays each response's anticipated R-squared, F values, and modified R-squared values.

Table 4. Statistics of model for response variables.

Responses	*R*-squared (%)	Modified *R*-squared (%)	*F* value	Probs < F	Model accuracy
CS - 7 day	97.21	92.56	20.89	0.015	Significant
CS - 28 day	97.31	92.83	21.70	0.015	Significant
CS - 56 day	99.31	98.16	86.38	0.002	Significant
CS - 90 day	94.95	86.53	11.28	0.037	Significant
FS - 28 day	95.63	88.34	13.13	0.030	Significant
STS - 28 day	77.93	41.14	2.12	0.085	Significant

3.2. Optimization using Fuzzy logic

Fuzzification, rule base, inference engine, and defuzzification are often the four main parts of a fuzzy inference system (FIS). Fuzzification is the process of transforming input variables to fuzzy value using membership functions. The parameter utilized by the fuzzy inference system replicates how people would make decisions based on fuzzy rules. Finally, the fuzzy set, which results from inference process, is transformed into crisp output in the last phase using a specific defuzzification technique (Alaneme & Mbadike, 2021).

3.2.1. Fuzzy logic model design

Input variables of the fuzzy logic were coarse and fine recycled aggregate; the output variables were flexure, split tensile and compressive strength of recycled aggregate concrete. Mamdani's fuzzy inference approach handled system modifications in creating a fuzzy logic model. Membership functions having a value between 0 and 1 were used by Mamdani fuzzy logic for both input and output. Figure 3 shows a block diagram of fuzzy tool box. The membership function with Low, Medium, and High terms indicated as L, M, and H, respectively, for input and output variables.

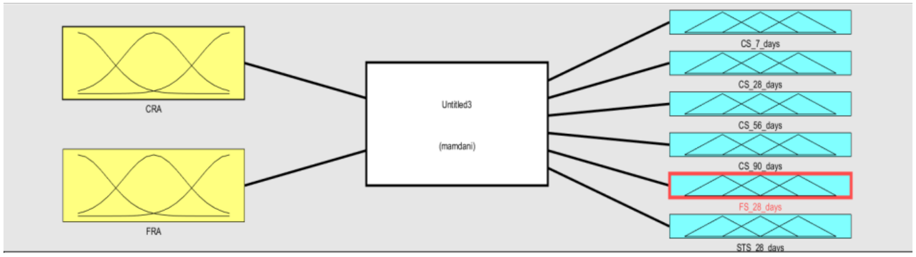


Figure 3. Block diagram

3.2.2. Fuzzy rule base

A set of linguistic statements known as fuzzy rules describe how the FIS should decide whether to classify an input or control output. No mathematical equations, conditions, and relationships that are not linear are needed in the fuzzy inference setup in the type of "IF-THEN" control statements. It consists of fuzzy rules encompassing all potential responses concerning the input and output generated by the experiments for fuzzy inference system (Alaneme & Mbadike, 2021). The assigned rules presented in Table 5, were used to evaluate the input and output response of model.

Table 5. Formation of rule base.

Mix ID	CRA (%)	FRA (%)	CS - 7 days	CS - 28 days	CS -56 days	CS - 90days	FS - 28 days	STS -28 days
Mix 1	L	L	H	H	H	H	H	M
Mix 2	L	M	H	H	H	H	H	L
Mix 3	L	H	L	L	L	L	M	M
Mix 4	M	L	H	H	H	H	H	H
Mix 5	M	M	H	H	M	H	M	H
Mix 6	M	H	L	L	L	M	L	L
Mix 7	H	L	H	M	H	M	M	H
Mix 8	H	M	H	M	M	M	L	M
Mix 9	H	H	L	L	L	L	L	L

3.3. Response optimization

The optimization plot was used to see the minimum and maximum responses for recycled aggregate concrete with all the input and output parameters. As shown in Figures 4 and 5, the optimum value of various strength properties of recycled aggregate concrete were obtained at a simultaneous replacement level up to 44% coarse and 65% fine recycled aggregate. Achieving favorable outcomes for all replies was indicated by composite desirability scores near to 1.

According to Figure 4 and 5, the compressive, flexure, and split tensile strength at simultaneous replacement of 44 % coarse and 65% of fine recycled aggregate showed similar strength results in response surface methodology and fuzzy logic.

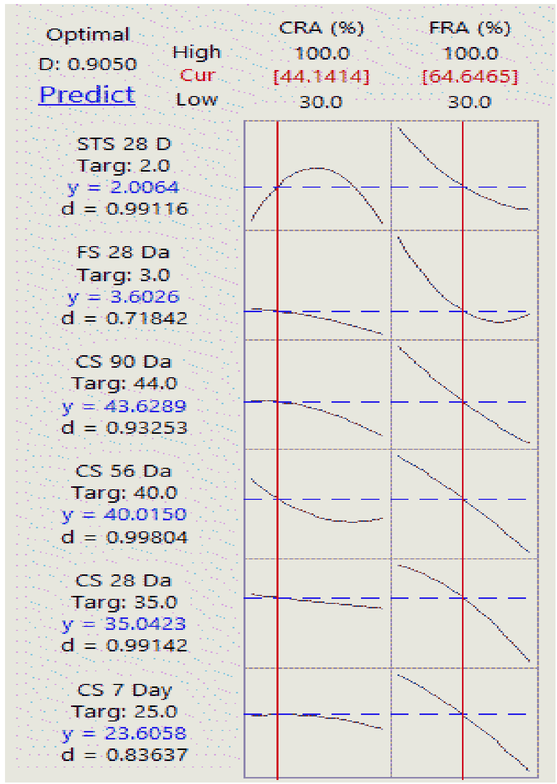


Figure 4. Optimization plot with RSM.

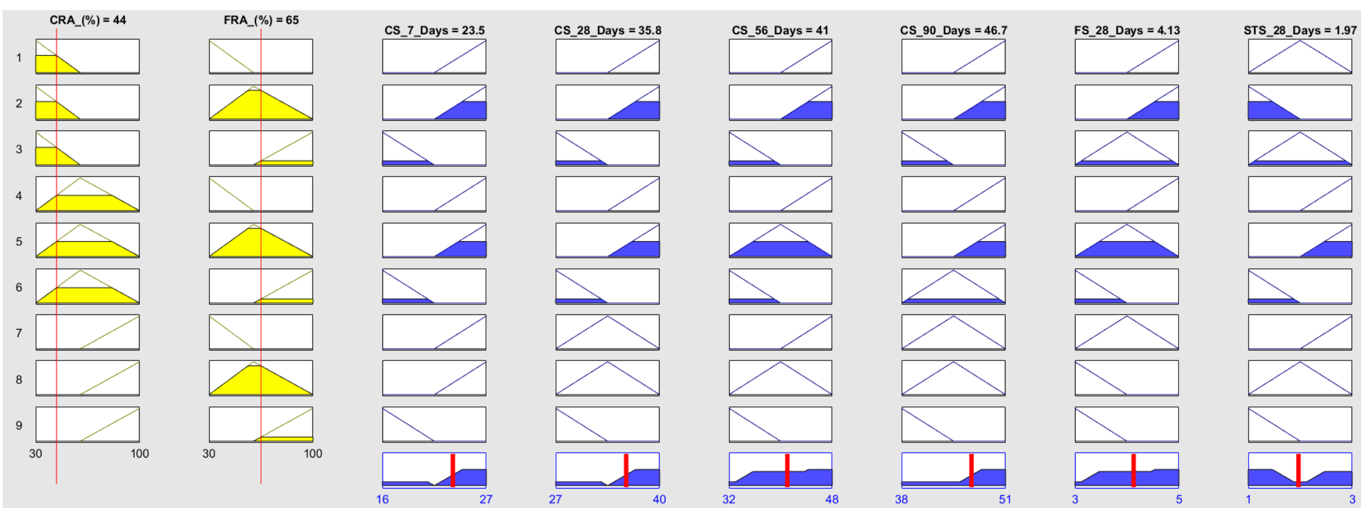


Figure 5. Optimized results using fuzzy logic.

The RSM and fuzzy logic model show optimized results which is closer to one, giving favorable results for all the responses as shown in Table 6.

Table 6. Optimized results.

SI. No	Method	CRA	FRA	CS - 7 days Fit	CS - 28 days Fit	CS - 56 days Fit	CS - 90 days Fit	FS - 28 days Fit	STS - 28 days Fit
		(%)		(N/mm²)					
1	RSM	40	55	24.6	36.5	42.03	44.94	3.85	2.02
2	Fuzzy Logic			25	37.7	41.8	48.7	4.23	1.83
3	RSM	44	65	23.61	35.04	40.02	43.63	3.6	2.0
4	Fuzzy Logic			23.5	35.8	41	46.7	4.13	1.97

Therefore, the simultaneous replacement of recycled aggregates can effectively be used in the production of concrete. Utilizing optimization approaches, the produced model's findings were satisfactory, and the optimized values offered promising solutions for waste management and sustainable construction. Furthermore, RSM was proven to generate a considerable quantity of information quickly with the fewer experiments (Sinkhonde et al., 2021).

4. Conclusions

This study replaced both coarse and fine aggregate portion of concrete with recycled aggregate produced from the construction and demolition wastes. The experiments were conducted to reveal the variation in properties of concrete with the addition of recycled aggregates. The properties of recycled aggregate concrete such as compressive strength at various curing times, 28 days split tensile strength, and 28 days flexural strength were discovered by experiment. The trial results were examined using fuzzy logic and RSM by Minitab18 and MAT Lab software. All models were determined to be significant using the full quadratic model.

- The model was generated in terms of equation which includes the terms like linear, quadratic and two-way interactions in RSM. The rule base was formed with human perspective using the experimental data in fuzzy logic. The final optimized result based on fuzzy logic was similar to that of the RSM techniques.
- The contour plots showed the interaction effects with two input variables and all the responses of the experiments conducted. In addition, the contour plot showed how the response parameter changes for the changes in the replacement proportion of recycled aggregates.
- While making concrete with effects similar to regular concrete, both in response surface approach and fuzzy logic, maximal strength was obtained up to 44% coarse and 65% fine recycled aggregate combination.

According to response surface approach and fuzzy logic, the experimental data closely matched the predicted model, indicating the predicted model's reliability. These models can be applied to frame specifications for concrete mix design. This study on the strength parameters of concrete with simultaneous replacement of recycled aggregate can be used as structural concrete with a characteristic strength of 30MPa. Still, further investigations are required for durability concerns to promote wider applicability of such sustainable concrete. The recycling of demolition debris into aggregate benefits the environment by reducing waste and protecting landfill space and natural resources.

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