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Evaluating GGBS and Clastic Sand as Eco-Friendly Substitutes for Sustainable Concrete

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ABSTRACT

Concrete, a widely used construction material, is under scrutiny due to its environmental impact, primarily stemming from cement production. Researchers are exploring alternative materials and mix designs to mitigate these effects. Supplementary cementitious materials (SCMs) like Ground Granulated Blast Furnace Slag (GGBS) show promise, reducing carbon emissions and enhancing concrete properties. Additionally, the extraction of natural aggregates poses environmental and health risks, necessitating the use of sustainable waste materials. Various wastes, including GGBS and clastic sand, are being investigated for their suitability in concrete production. This study aims to evaluate the performance of concrete incorporating GGBS and clastic sand (CLS) as substitutes. Understanding their impact on concrete properties will aid in developing more sustainable construction practices, contributing to reduced carbon emissions. Test results show mechanical property improvements with increasing GGBS and CLS content up to an optimal point, beyond which further enhancement ceases, likely due to unreacted materials acting as fillers. Using the response surface method, compressive strength values closely match experimental observations with a confidence level exceeding 95%. This research underscores the potential of GGBS and CLS in enhancing concrete sustainability and performance, crucial for environmentally responsible construction practices.

1. INTRODUCTION

Concrete is widely used in construction worldwide due to its durability, versatility, and cost-efficiency. However, the manufacturing process of traditional concrete results in substantial environmental consequences, primarily due to the extensive use of cement, a key ingredient that contributes to carbon emissions. Researchers and industry practitioners have been investigating alternate materials and mix designs to improve the sustainability of concrete production in response to environmental concerns. An effective method involves including supplemental cementitious materials (SCMs) [1-5] and alternative aggregates, which decrease the concrete's environmental impact and improve its mechanical characteristics. Ground Granulated Blast Furnace Slag (GGBS) is a Supplementary Cementitious Material (SCM) that has garnered interest because of its pozzolanic and hydraulic characteristics, which make it a suitable option for partially replacing cement in concrete mixes [6].

The advancement of any country is primarily dependent on construction operations, which have witnessed substantial expansion in recent decades, resulting in an increasing need for concrete. The extraction and mining of natural aggregates have increased significantly to fulfill the growing demand for concrete production, leading to the depletion of resources and the accumulation of stone and slurry wastes. These waste materials are frequently discarded in local landfill sites, releasing dust that presents occupational exposure hazards and negatively impacting the respiratory health of workers and nearby communities. The ongoing reduction of natural resources presents dangers related to waste disposal and health risks, emphasizing the urgent requirement to use sustainable waste materials as replacements for traditional fine and coarse aggregates in concrete [7]. The coarse and fine aggregates, which comprise 70% - 80% of the volume of concrete, are essential components. Several studies have concentrated on maximizing the use of sustainable waste materials in concrete based on researchers' discoveries. Various waste products, such as GGBS, fly ash, ceramic waste, and stone slurry, are currently used in concrete manufacturing. Crushed rock dust functions as a filler, decreasing the overall empty spaces in concrete. These waste elements have positively impacted concrete's qualities, enhancing its mechanical strength and durability. Additionally, they contribute to environmental sustainability in construction operations [8].

Furthermore, the exhaustion of natural sand reserves and the ecological consequences of its exploitation have led to inquiries into substitute fine aggregates. Clastic sand, produced through the mechanical fragmentation of rocks, offers a promising sustainable substitute for natural sand in concrete manufacturing. This research aims to investigate the behavior of concrete incorporating GGBS as a partial replacement for cement and clastic sand as a substitute for natural fine aggregate. The study will assess the fresh properties and mechanical properties of such concrete mixes. Understanding the performance of these alternative materials and their interactions in concrete will contribute to the development of more sustainable construction practices and the reduction of carbon emissions in the construction industry.

2. MATERIALS AND METHODS

2.1 Cement

53-grade Ordinary Portland Cement [OPC], conforming to IS 269-2015 [9], was utilized. Specific gravity, a fundamental physical test, was conducted according to IS 4031 Part 6 [1988] [10], yielding a specific gravity of 3.14 and normal consistency of 31% for the cement sample, which falls within the acceptable limit.

2.2 Fine aggregate

The selected fine aggregates adhere to the standards outlined in IS 383-2016 [11] and fall under the category of zone II grade (fineness modulus - 2.85, water absorption - 1.5%, free surface moisture - 1.4% and specific gravity - 2.65).

2.3 Coarse aggregate

The coarse aggregate is assessed according to the IS 383-2016 standard [11], with a maximum aggregate size of 20mm (fineness modulus 7.17 and specific Gravity - 2.66).

2.4 GGBS

The GGBS utilized adhered to the ASTM C 989 [12] standard and was procured from a reputable manufacturer. Chemical analysis of the GGBS was conducted using XRF technique, and the results are detailed in Table 1, showcasing its chemical properties. The physical properties of the GGBS are also presented in Table 1.

Table 1. Chemical and physical properties of GGBS

Composition	Proportion (%)
SiO_2	31.65
Fe_2O_3	0.37
Al_2O_3	12.40
CaO	43.17
MgO	5.80
MnO	0.58
SO_3	0.37
Na_2O	0.91
K_2O	0.18
TiO_2	0.40
LOI	2.01
Fineness (%)	3.00
Avg particle size (µm)	12.00
Specific gravity	2.60

2.5 Clastic sand

Tables 2 and 3 present the physical properties and chemical properties. In our research, the clastic sand was observed to fall within the sub-mature group and sub-arkose type. The grains exhibited moderate sorting, with a shape ranging from sub-angular to sub-rounded.

Table 2. Physical properties of clastic sand

Physical Properties	Test Value
Color	Red
Fineness modulus	2.80
Bulk density	1650 (kg/cum)
Water absorption	1.05
Specific gravity	2.56

Table 3. Chemical properties of clastic sand

Chemical Properties	Test Value
SiO_2	94.68
Fe_2O_3	4.90
Al_2O_3	0.24
CaO	NIL
LOI	0.17

2.6 Chemical admixture

A Polycarboxylate (PCE) based admixture was utilized. To ensure optimal workability and consistent slump values, a high-range water-reducing admixture (HRWRA) based on polycarboxylate was employed. Throughout the study, standard tap water was utilized. PCE was keeping constant throughout the research.

2.7 Mechanical properties

The fresh concrete mixtures were prepared with GGBS and clastic sand and tested to assess their fresh properties according to IS: 1199-1959 [13]. The sustainable concrete specimens at ages of 7d, 28d and 56d was tested on a UTM. The specimen was considered to have failed when the load value stopped increasing, and the loading was stopped according to IS 516-1959 [14] specifications. Additionally, cylindrical specimens measuring 150 mm × 300 mm (D × L) and prisms of 100 × 100 × 500 mm (B × D × L) were cast to determine the variation in splitting tensile strength (SPT) and flexural strength (FS), respectively. SPT was conducted at 28 and 56 days in accordance with IS 5816-1999 [15] specifications, while FS was evaluated as per IS 516-1959 specifications [14].

2.8 Durability test

To conduct the absorption resistance test on concrete cubes, first ensure that the cubes are properly cured under standard conditions. Weigh each dry cube accurately to obtain the initial dry weight (Wd). Submerge the cubes completely in water for a specified period, typically 24 hours, then promptly remove and wipe off excess water. Weigh the wet cubes immediately to determine the wet weight (Ww). Calculate the water absorption percentage using the formula [(Ww - Wd) / Wd] × 100%. Repeat the procedure for multiple cubes to ensure consistency and reliability of results. Analyze the obtained water absorption values to assess the porosity and absorption resistance of the concrete mix. Adhere to relevant standards and safety precautions throughout the testing process.

3. MIX PROPORTIONS

Nine concrete mixtures were created using GGBS and clastic sand. These mixtures were divided into two groups. In the first group, cement was partially substituted with GGBS at varying percentages of 15%, 25%, 35%, and 45%.

In the second group, after determining the optimal quantity of GGBS, sand was replaced with clastic sand at percentages of 10%, 20%, 30%, and 40%. Table 4 provides an overview of the quantities of cement, GGBS, fine aggregate, clastic sand, coarse aggregate, water, and chemical admixtures used in each mixture.

Table 4. Mix proportions

Mix ID	Nomenclature	Cement	GGBS	Fine Aggregate	Clastic Sand	Coarse Aggregate	Superplasticizer	Water
G0	NC	392	0	822	0	1077	0.75	156.8
G15	GGBS15+CS0	333.2	58.8	822	0	1077	0.75	156.8
G25	GGBS25+CS0	294	98	822	0	1077	0.75	156.8
G35	GGBS35+CS0	254.8	137.2	822	0	1077	0.75	156.8
G45	GGBS45+CS0	215.6	176.4	822	0	1077	0.75	156.8
G35CS10	GGBS35+CS10	254.8	137.2	739.8	82.2	1077	0.75	156.8
G35CS20	GGBS35+CS20	254.8	137.2	657.6	164.4	1077	0.75	156.8
G35CS30	GGBS35+CS30	254.8	137.2	575.4	246.6	1077	0.75	156.8
G35CS40	GGBS35+CS40	254.8	137.2	493.2	328.8	1077	0.75	156.8

4. RESULTS AND DISCUSSION

4.1 Slump cone test

Slump tests were conducted for each batch of concrete in accordance with IS: 1199-1959 (Reaffirmed 2004) [13]. Workability, a measure of the plasticity of fresh concrete, was assessed using the slump test method. The mix designations for M0 to M4 correspond to the M35 controlled concrete series, with GGBFS replacement percentages of 0%, 15%, 25%, 35%, and 45% with OPC, respectively. Similarly, M5 to M8 represent the same concrete mixes with optimum dosages of GGBFS and clastic sand replacement percentages of 10%, 20%, 30%, and 40% with fine aggregate.

It was observed that the workability decreases with the addition of GGBFS as a replacement for OPC. Higher percentages of GGBFS resulted in lower workability (i.e., G15 to G45). This decrease in workability can be attributed to the increased surface area of the cementitious material due to the inclusion of GGBFS. G0, G15 and G25 mixes showed high slump cone values but further increase GGBS content (G35 & G45) showed lower slump cone values. Additionally, the addition of clastic sand (i.e. G35CS10 to G35CS40) also led to a reduction in slump values as shown in Figure 1.

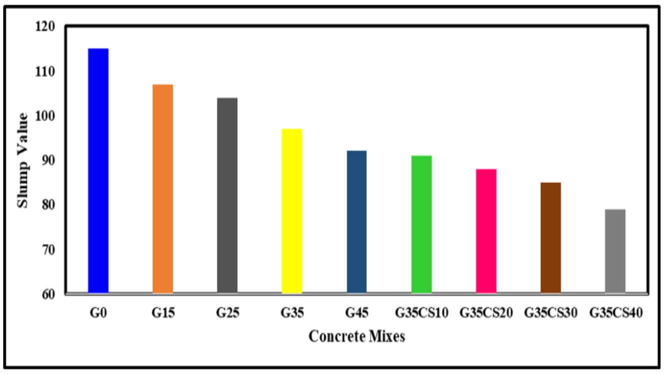

Figure 1. Slump flow values

4.2 Compressive strength

Figure 2 clearly illustrates that GGBS mixes incorporating CLS exhibit higher compressive strength compared to the G0 mix. At an early age (7 days), the compressive strength of mixes G15, G25, G35, and G45 improved by 3.67%, 8.76%, 13.45% and 5.63%, respectively, in comparison to the G0 mix. Concrete mixes of G35CS10, G35CS20, G35CS30 and G35CS40 showed enhancement of 18.15%, 21.28%, 15.02% and 10.32% for the curing period of 7 days. Additionally, it was observed that the compressive strength of GGBS mixes increased when cement content was replaced with up to 35% GGBS, albeit declining slightly with higher GGBS content. This enhancement in early age CST of GGBS mixes may be attributed to the accelerated hydration reaction facilitated by GGBS. Further increment in CS with addition of CLS and optimum content was 20%.

Similar trends were observed at 28 and 56 days of curing. Concrete Mixes with GGBS and CLS (G35CS10, G35CS20, G35CS30, and G35CS40) exhibited improvements in CST values of 21.6%, 23.73%, 17.86%, and 15.2% for 28 days, respectively, compared to NC. Furthermore, for 56 days, the enhancements were 16.66%, 20%, 15.71%, and 12.85% of the mixes G35CS10, G35CS20, G35CS30, and G35CS40, respectively. These results indicate a higher percentage strength gain at 7 and 28 days of curing compared to other age, suggesting rapid development of CST in the G35CS30 mix.

The strength of the concrete increases until about 35% of Ground Granulated Blast Furnace Slag (GGBFS) is used. This occurs due to the formation of calcium hydroxide ($Ca(OH)_2$) during the hydration process, which contributes to concrete reinforcement. However, the strength diminishes if the proportion of GGBFS exceeds 35%. This occurs due to a scarcity of oxides for the hydration process, resulting in a reduced production of Calcium Silicate Hydroxide (C-S-H) and $Ca(OH)_2$. These findings align with the results of Elchalakani et al.'s (2014) study. Insufficient amounts of $Ca(OH)_2$, SiO_2, and Al_2O_3, which are crucial for the pozzolanic process, result in incomplete utilization.

Incorporating GGBS and CLS serves a dual purpose in concrete. Firstly, it operates as a filler, enhancing the density of the micro and nanostructure. Secondly, it activates during hydration, resulting in accelerated strength gain. However, beyond 35% and 30% replacement of cement and sand with GGBS and CLS respectively, a decrease in strength was observed.

This decrease is attributed to the higher quantity of GGBS and CLS particles compared to the quantity of liberated lime in the hydration process, resulting in excess silica leaching out and weakening pore bonding strength. Consequently, at this stage, the combination of GGBS and CLS primarily fills the pores without actively participating in the hydration process.

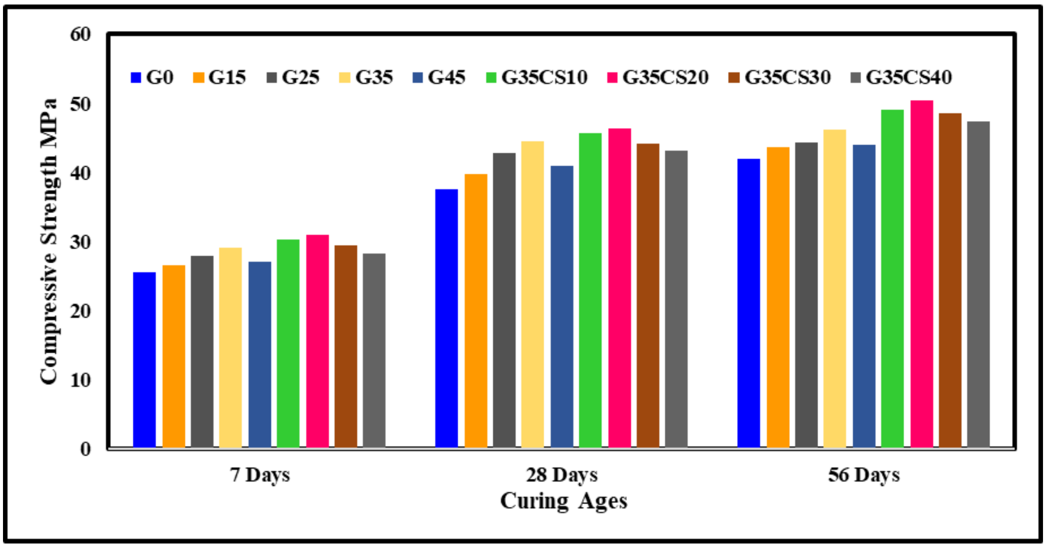

Figure 2. CS of sustainable concrete using GGBS and CLS

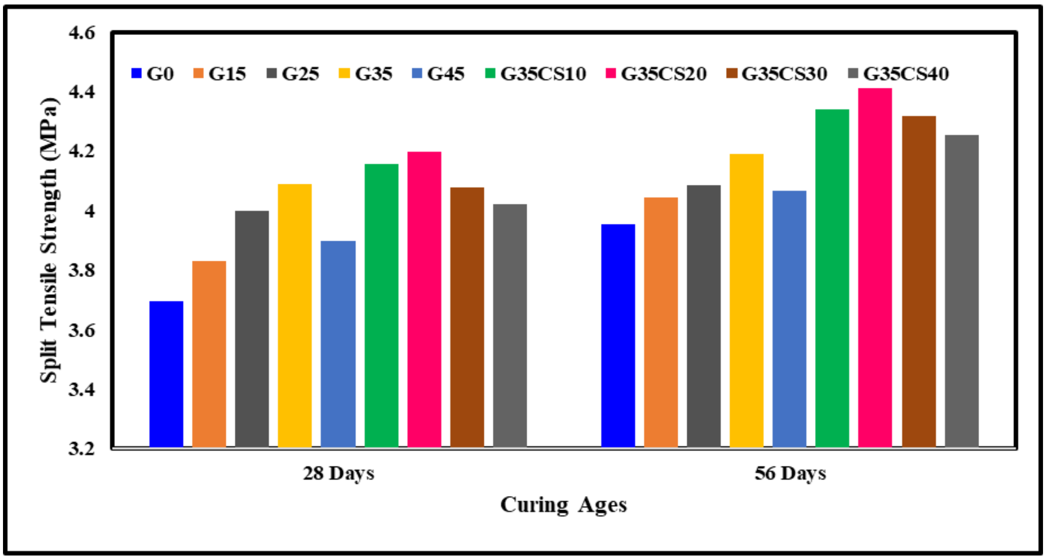

Figure 3. SPT of sustainable concrete using GGBS and CLS

4.3 Split tensile strength

Figure 3 illustrates the variation in Splitting Tensile Strength (SPT) for mixes of NC, GGBS with and without CLS. Notably, GGBS mixes incorporating clastic sand exhibited higher tensile strength values compared to NC. At an early age (28 days), mixes G15, G25, G35, and G45 displayed improvements of 3.63%, 8.25%, 10.66% and 5.49%, respectively, over the G0 mix. Among these, G35 with varying clastic sand demonstrated superior strength compared to G0, G15, G25, and G45 mixes. Particularly, G35CS20 exhibited the highest SPT values among all the mixes i.e. 13.63%.

Similar trends were observed at the 56-day of curing period. Concrete mixes contain optimum GGBS quantity and varying clastic sand (G35CS10, G35CS20, G35CS30, and G35CS40) showed enhancements in tensile strength of 9.69%, 11.56%, 9.15% and 7.52%, respectively, compared to G0 mix over the 56-day curing period. This improvement can be attributed to the enhanced properties of the concrete matrix and the robust interphase bonding between the binders (i.e., cement, GGBS, and CLS) and aggregates. Utilization of GGBS and CLS results in a denser Interfacial Transition Zone (ITZ), thereby augmenting tensile strength.

4.4 Flexural strength

The results clearly demonstrate that GGBS mixes incorporating CLS exhibit higher flexural strength compared to NC. At an early age (28 days), the flexural strength of mixes G15, G25, G35, and G45 improved by 8.59%, 11.68%, 17.18% and 8.93%, respectively, compared to NC. Additionally, optimum GGBS content and varying clastic sand (G35CS10, G35CS20, G35CS30, and G35CS40) showed enhancements in tensile strength of 23.71%, 25.42%, 18.21% and 14.94% respectively, compared to NC and GGBS mixes over a 28-day curing period.

Similar outcomes were observed with higher strength mixes containing GGBS and CLS compared to mixes with only GGBS at a curing age of 56 days as showing in Figure 4. This indicates that the rapid development of CST in the G35CS20 mix of 20.06% at a later age (56 days) suggests that GGBS and CLS not only act as fillers to increase the density of the micro and nanostructure of concrete but also serve as activators in the hydration process. Overall, the inclusion of GGBS and CLS enhanced the strength across all tested cases compared to NC.

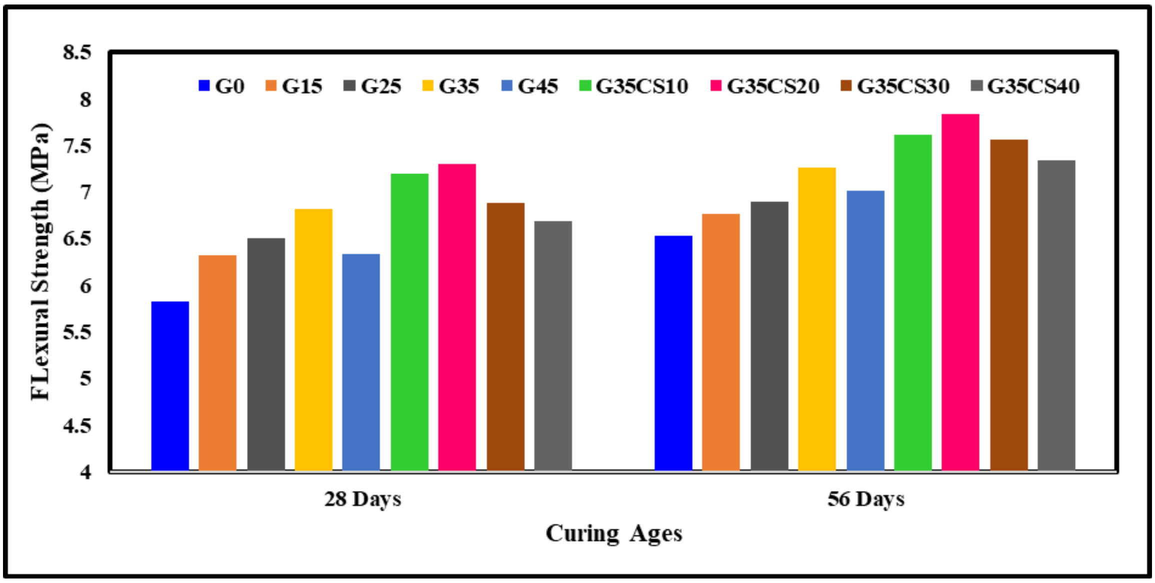

Figure 4. Flexural strength of sustainable concrete using GGBS and CLS

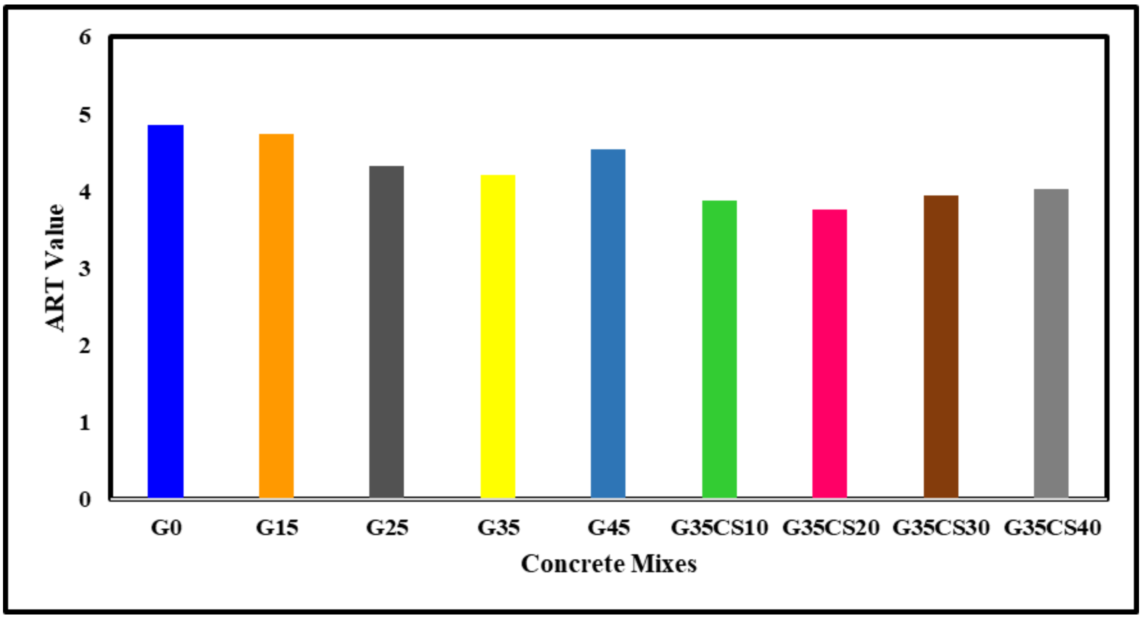

Figure 5. Absorption resistance test of sustainable concrete using GGBS and CLS

4.5 Abrasion resistance test

The inclusion of GGBS and CLS in concrete increase absorption resistance due to a denser matrix, decreased permeability, enhanced chemical resistance, reduced microcracking, and improved curing conditions. GGBS fills voids effectively, forms additional binding compounds, and creates a protective barrier against water ingress. Its pozzolanic activity and slower hydration rate lead to improved durability and decreased water absorption, making the concrete more resistant to moisture penetration. However, despite the presence of these factors, the average depth of wear remained below 2 mmm in all samples at all replacement levels and did not exceed 3.5 mm. Concrete mixes of G15, G25, G35 and G45 showed percentage of absorption resistance are 2.46%, 11.11%, 13.37% and 6.58%, respectively, compared to G0 mix. Similar pattern was observed for concrete mixes of GGBS and CLS. Concrete mixes contain optimum GGBS quantity and varying clastic sand (G35CS10, G35CS20, G35CS30, and G35CS40) showed better absorption resistance values (%) of 20.16%, 22.63%, 18.93% and 17.28%, respectively, compared to G0 mix, as shown in Figure 5.

5. RESPONSE SURFACE METHOD

The Design of Experiment is a statistical method used to explore how independent variables affect experimental outcomes. It offers several benefits, such as reducing the number of experimental runs needed, assessing the quadratic effects of responses, identifying potential interrelationships between variables, and determining optimal responses.

In this study, RSM was used to predict the mechanical properties of concrete. RSM is a statistical and mathematical tool utilized for refining, developing, and optimizing processes in both research and industry.

It can analyze the impacts of multiple factors and their interactions on various response variables. Below Equation illustrates this relationship, linking the variables β and £ within a given system [16-19].

Table 5. Empirical and expected values by regression analysis

GGBS	Clastic Sand	Curing Ages	Actual CS Values	Predicted CS Values	Residual
0.0	0.0	7	25.56	24.4351	1.12485
58.8	0.0	7	26.50	27.2104	-0.71042
98.0	0.0	7	27.80	28.0833	-0.28333
137.2	0.0	7	29.00	28.1744	0.82560
176.4	0.0	7	27.00	27.4837	-0.48365
137.2	82.2	7	30.20	30.4714	-0.27136
137.2	164.4	7	31.00	31.1289	-0.12890
137.2	246.6	7	29.40	30.1470	-0.74703
137.2	328.8	7	28.20	27.5258	0.67425
0.0	0.0	28	37.50	38.3972	-0.89720
58.8	0.0	28	39.80	41.2760	-1.47596
98.0	0.0	28	42.80	42.2179	0.58215
137.2	0.0	28	44.40	42.3779	2.02208
176.4	0.0	28	41.00	41.7562	-0.75617
137.2	82.2	28	45.60	44.9537	0.64634
137.2	164.4	28	46.40	45.8900	0.51002
137.2	246.6	28	44.20	45.1869	-0.98688
137.2	328.8	28	43.20	42.8444	0.35562
0.0	0.0	56	42.00	41.1184	0.88155
58.8	0.0	56	43.60	44.1352	-0.53519
98.0	0.0	56	44.30	45.1691	-0.86908
137.2	0.0	56	46.20	45.4211	0.77886
176.4	0.0	56	44.00	44.8914	-0.89137
137.2	82.2	56	49.00	48.3686	0.63143
137.2	164.4	56	50.40	49.6766	0.72341
137.2	246.6	56	48.60	49.3452	-0.74520
137.2	328.8	56	47.40	47.3744	0.02560

$$£ = X_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{j=k}^{k} \beta_{ii} X_{ii}^2 + \sum_{i=1}^{k} \sum_{j=1}^{k} \sum_{J\neq 1} \beta_i X_i X_j + \varepsilon$$

In the equation, β_o, β_i, β_j, and β_{ij} denote the regression coefficients. X_i and X_j represent the independent variables. X represents factors, β denotes coefficients, Ɛ signifies error, and £ stands for response. In the current research, four input or independent parameters were 'GGBS', 'Clastic Sand,' and 'Curing ages' while the response or dependent parameters comprised 'Compressive Strength (CS).

The current study employed a methodology that integrated regression analysis, response surface analysis, contour plots and residual plots to evaluate the variables, including their main effects. Table 5 shows the input and response parameters.

A polynomial mathematical model was employed to fit nine experimental datasets for Compressive Strength (CS) across the following materials: GGBS and Clastic Sand (CLS). The equations representing the response surface models that offer the most optimal fit for CS equation are derived as follows:

CS = 17.51 + 0.0616 GGBS + 0.03679 Clastic Sand + 1.0703 Curing Ages- 0.000254 GGBS*GGBS- 0.000121 Clastic Sand * Clastic Sand - 0.011585 Curing Ages * Curing Ages + 0.000084 GGBS * Curing Ages + 0.000161 Clastic Sand * Curing Ages (1)

The determination coefficients for the CS models was 0.98. Figure 6 compares the actual and predicted values of CS along with residual error. The response surface analysis yielded a regression model comprising the variables "CS" plotted against "Cement, GGBS, FA and CLS" as depicted in Figure 7. Table 5 presents expected and empirical measurements of CS accompanied by residual error. The anticipated response surface and contour plots displayed an error rate below 5%, demonstrating a confidence level of 95%.

The plot illustrating the relationship between the predicted and residual values provides valuable insights into the proximity of the expected Compressive Strength (CS) values to the actual data collected from experiments.

In Figure 8, data points that closely follow the reference line indicate minimal errors, whereas those situated farther away indicate higher levels of error. The observed deviations in Figure 8 were found to fall within an acceptable tolerance range, as indicated by two residual values closely aligned with the reference line. Residual values for CS of 11 and 1 were identified within the intervals of 0 - 1 and 1 - 2, respectively. Similarly, residual values within the ranges of 0 to -1 and -1 to -2 were observed under reference lines 13 and 1, respectively. Figure 9 shows the main effects plot for CS [20-22].

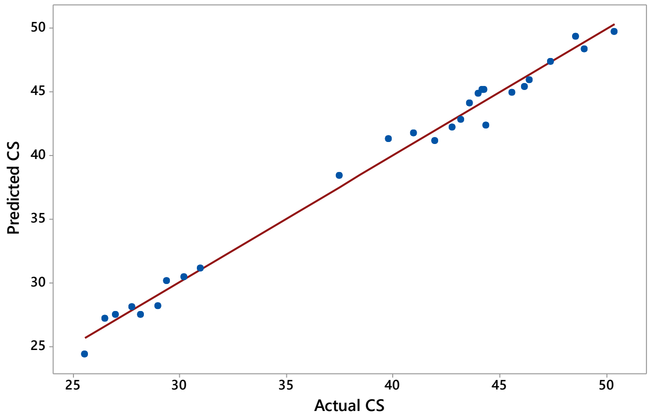

Figure 6. Scatter plot between actual and predicted values of CS

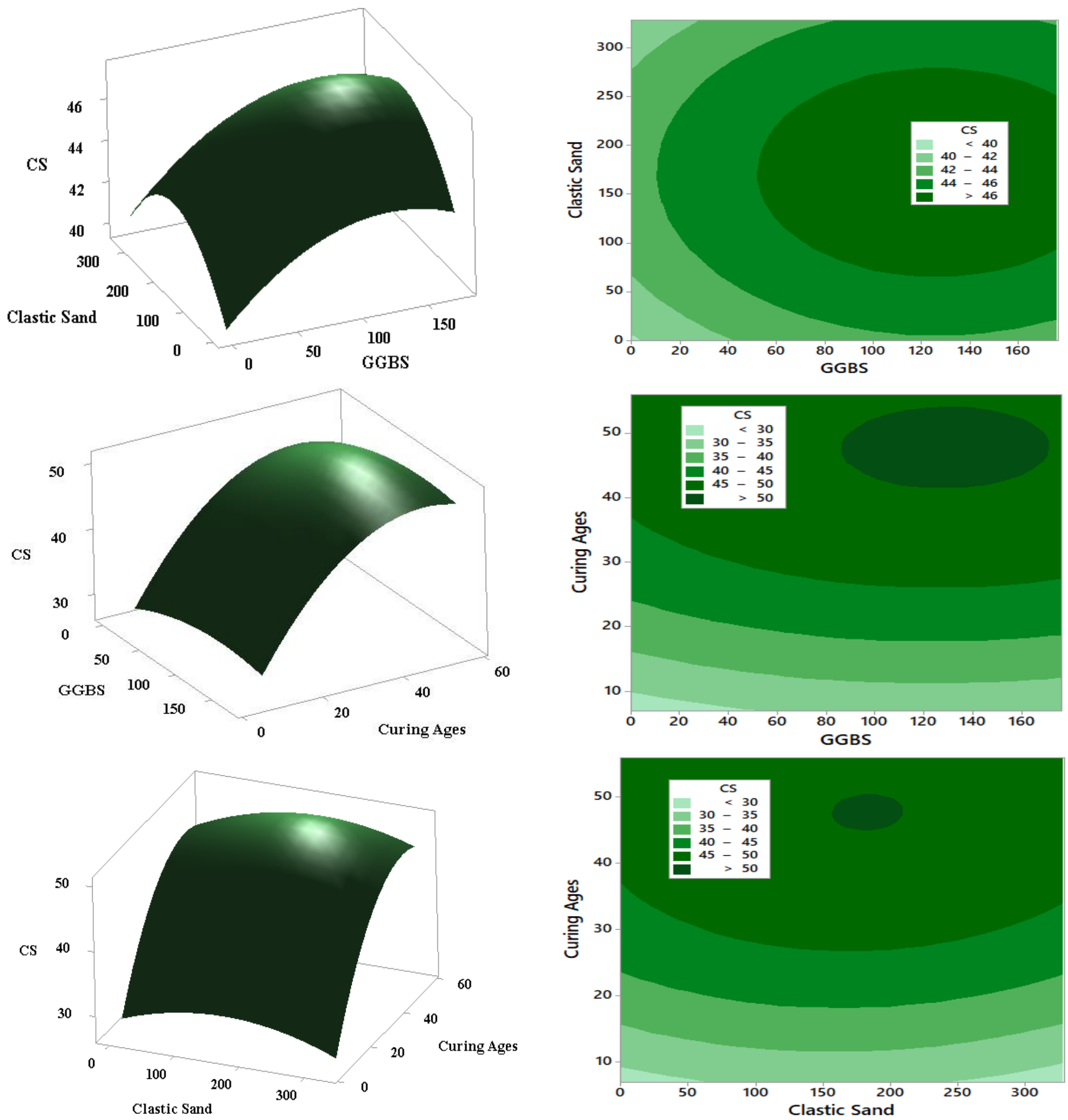

Figure 7. Response surface and contour plots for "GGBS", "CLS", "Curing Ages" Vs mean CS

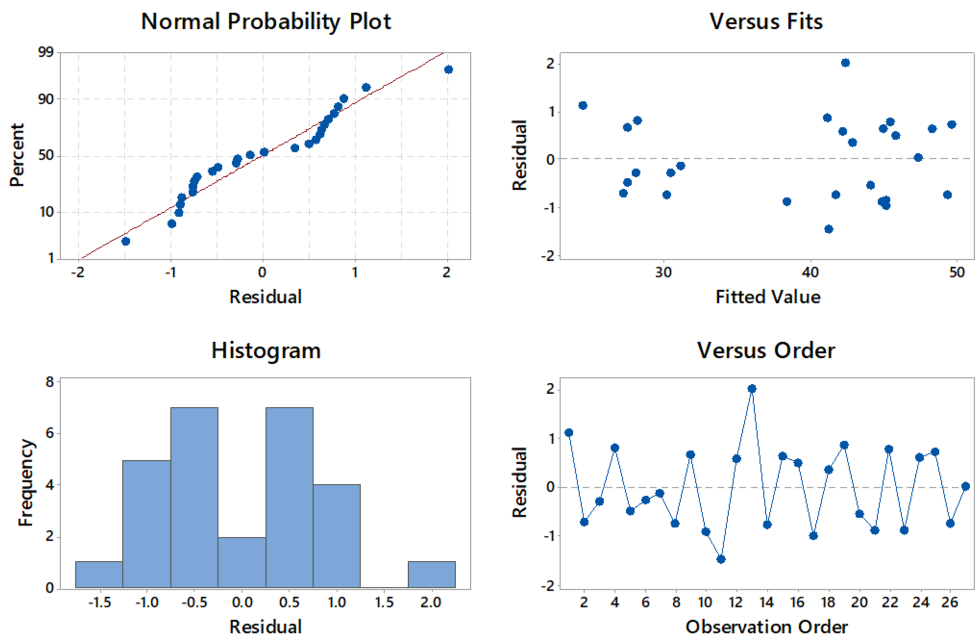

Figure 8. Residual plots of CS

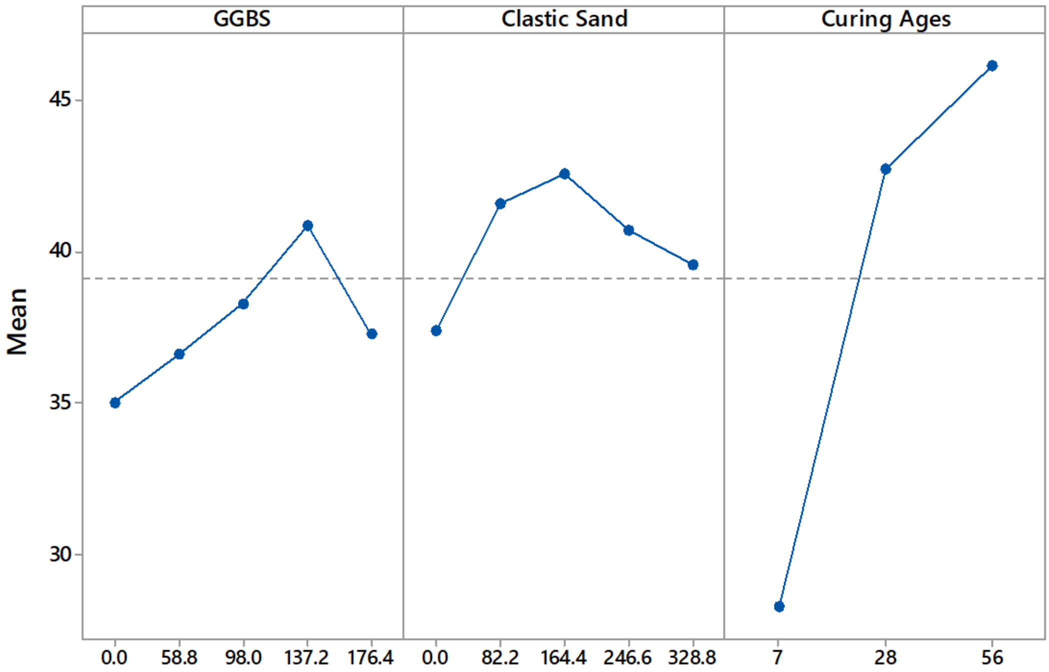

Figure 9. Main effects plots CS

6. CONCLUSIONS

The following study investigates the workability, mechanical properties, and absorption resistance of sustainable concrete, with varying levels of GGBS and CLS. The ensuing findings can be summarized as follows:

- The workability of sustainable concrete decreased with the increase in GGBS content, and when combined with CLS, it also showed medium workability.
- The mechanical properties of sustainable concrete improve with increasing GGBS content up to a peak level, beyond which they decline. There exists an optimal threshold for GGBS content that maximizes strength. This optimal level of GGBS content, combined with CLS, for optimal strength, is approximately 35% and 20% of the total binder content and fine aggregate, respectively.
- Absorption resistance test values showed better values with GGBS and CLS combination.
- The results obtained from the RSM models, constructed using actual data, demonstrate the potential and usefulness of these models for accurately simulating the investigated properties of concrete.

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