International Journal of Scientific Engineering and Research (IJSER)
ISSN (Online): 2347-3878
SJIF (2025): 8.036

Experimental Modelling and Multi-Response Optimization of Fly Ash Carbon Black Bricks for Sustainable Construction Applications

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Abstract: ***Conventional clay brick manufacturing contributes significantly to environmental degradation due to excessive soil consumption and high energy demand. The use of industrial by-products such as fly ash and carbonaceous residues offers a promising alternative for sustainable masonry production. In this study, Fly Ash Carbon Black (FCB) bricks were developed using a Taguchi L27 experimental design to systematically evaluate the influence of material composition on compressive strength, water absorption, and green density. Statistical analysis through signal-to-noise ratios and ANOVA was employed to identify dominant factors affecting performance. A hybrid CRITIC-CODAS multi-criteria framework was further adopted to determine the optimal mix considering mechanical strength, durability, and density simultaneously. The optimized composition demonstrated improved structural behaviour with controlled moisture absorption while maintaining lightweight characteristics. The findings highlight the potential of carbon black as a functional additive in fly ash bricks and provide a structured methodology for developing environmentally responsible construction materials.***

Keywords: Fly Ash (FA), Carbon Black (CB), Taguchi L27, ANOVA, CRITIC-CODAS, Sustainable Bricks

1. Introduction

Brick masonry remains a widely adopted construction system because of its durability, availability, and cost effectiveness. However, traditional clay brick production is associated with high carbon emissions, depletion of natural soil resources, and significant energy consumption during firing. These environmental concerns have encouraged researchers to explore alternative masonry units incorporating industrial by-products.

Fly ash-based bricks have gained attention due to their ability to convert waste into valuable construction materials while maintaining acceptable mechanical performance. Previous studies have shown that carbonaceous additives such as coal char or biochar can influence pore structure and densification behaviour. Despite these developments, limited research has examined carbon black as a controlled additive within fly ash bricks under a structured multi-response optimization framework.

Most existing investigations focus on single-response Taguchi optimization or grey relational analysis. Such approaches often overlook the interdependence among performance characteristics such as strength, density, and durability. Therefore, the present work aims to develop an integrated experimental and decision-making framework combining Taguchi design, ANOVA, and CRITIC–CODAS analysis. The study seeks to enhance compressive strength, regulate water absorption, and achieve balanced density while promoting sustainable material utilization.

From a compliance perspective (especially in Indian contexts), fly ash-lime bricks are governed by **IS 12894:2002** (reaffirmed), while compressive strength and water absorption testing commonly references the **IS 3495 series**.

Sylajakumari et al. (2018) demonstrated the effectiveness of Taguchi–GRA for multi-response optimization in materials processing, highlighting improved decision consistency compared to single-response Taguchi analysis. Morozov et al. (2020) proposed methodology of integrated Taguchi experimental design with grey relational grading to evaluate multiple responses including **setting time, workability, and compressive strength** of fly ash–slag geopolymer.

Even without deliberate carbon addition, fly ash can contain unburned carbon that alters densification and brick properties; Dacuba et al. (2022) study explicitly discusses how unburned carbon can lead to less dense bricks and measurable differences in properties. A strong recent direction is the repurposing of **coal char** to produce high-strength, durable bricks. Yu et al. (2023) reported coal char-based bricks with markedly improved durability (e.g., very low boiling water absorption values in treated specimens) and improved freeze–thaw resistance, demonstrating the feasibility of carbonaceous residues as a functional brick ingredient.

Osman et al. (2024) provide a comprehensive review focusing on **biochar-based bricks and insulation materials** as sustainable alternatives for reducing the carbon footprint of buildings. The study highlights the increasing need for environmentally friendly construction materials due to rising greenhouse gas emissions associated with urbanization and industrialization. The review synthesizes preparation methods, material properties, emission reduction potential, and economic feasibility of biocharmodified building products. Singh et al. (2024) investigated the development of sustainable fly ash bricks incorporating **agro-forestry waste, construction and demolition (C&D) waste, and GGBFS** as alternative raw materials. The primary objective was to evaluate environmental impact and thermal performance while ensuring adequate mechanical properties for building applications. The study addressed the significant greenhouse gas emissions associated with traditional burnt clay bricks and emphasized the need for eco-friendly masonry solutions.

Kiran et al. (2025) investigated the incorporation of biochar, derived from biomass pyrolysis, as a partial cement replacement in cementitious composites to enhance sustainability while maintaining mechanical performance. The study addressed growing environmental concerns in construction by exploring carbon-negative additives capable of improving structural and durability characteristics. Maaze (2025) proposed a comprehensive framework integrating **technical optimization, life cycle assessment (LCA), and life cycle cost analysis (LCCA)** for fly ash cement brick production. The study employed a Taguchi orthogonal array with key factors including fly ash percentage, cement content, and water-to-binder ratio to achieve multi-response optimization targeting compressive strength, water absorption, shrinkage, efflorescence, and environmental impact.

Maaze (2025) used a Taguchi orthogonal array approach to optimize compressive strength while minimizing water absorption and sustainability indicators, combined with LCA/LCCA, demonstrating how experimental modelling can directly support sustainable manufacturing decisions. Mumtaz et al. (2026) 2026 studied on fly ash cement bricks applied ML models and reported multi-objective optimization including carbon emission reduction, illustrating the trend of data-driven modelling as a complement to classical DoE.

Although extensive studies have optimized fly ash bricks using Taguchi, GRA, and recent ML-based approaches, limited research explicitly integrates **carbon black as a functional carbonaceous additive** in fly ash bricks while simultaneously addressing **multi-response optimization (CS- WA- GD)** through a robust **CRITIC–CODAS decision framework**.

2. Experimental Modelling of Fly Ash Carbon Black Brick

The experimental modelling strategy adopted in this study replaces traditional trial-and-error mix development with a structured design of experiments framework. A Taguchi L27 orthogonal array was employed to evaluate the combined influence of fly ash, carbon black, cement, gypsum, quarry dust, and superplasticizer on brick performance.

Key responses considered were compressive strength (CS), water absorption (WA), and green density (GD), representing structural capacity, durability, and manufacturing quality respectively. Signal-to-Noise analysis and ANOVA were used to quantify factor significance, while CRITIC-CODAS provided a rational basis for multi-response ranking by considering both response variability and inter-criteria relationships. This integrated modelling approach enabled identification of an optimal mix that balances strength, durability, and lightweight characteristics.

3. Methodology

The present investigation adopts an integrated experimental–analytical framework to develop and optimize Fly Ash Carbon (FAC) bricks for sustainable construction applications. The overall methodology consists of five major stages: (i) material selection and mix design, (ii) experimental design using the Taguchi method, (iii) performance testing of bricks, (iv) statistical modelling through Signal-to-Noise (S/N) ratio and ANOVA, and (v) multi-response optimization using the CRITIC-CODAS decision-making approach. The workflow ensures systematic identification of influential factors and selection of an optimal brick composition considering mechanical and durability criteria simultaneously.

3.1 Material Selection and Mix Design

Fly ash obtained from thermal power plant residues was used as the primary binder material. Carbon black derived from pyrolysis processes was introduced as a lightweight carbonaceous additive. Ordinary Portland Cement provided matrix formation, while gypsum acted as a hydration regulator. Quarry dust was incorporated to improve particle packing, and a polycarboxylate-based superplasticizer was used to enhance workability. Rather than adopting a trial-and-error approach, mix proportions were treated as controllable factors within a structured experimental framework. The samples of raw material phots is shown in Fig. 1.0.

Figure 1: Carbon Black and Fly Ash

3.2 Taguchi Experimental design

A Taguchi L27 orthogonal array was selected to evaluate six parameters at three levels while minimizing the number of experiments. Brick specimens measuring 228.6 mm × 101.6 mm × 75 mm were fabricated using a hydraulic press with a compaction load of approximately 60 tons. This high compaction pressure improved inter-particle bonding and dimensional stability during moulding. After fabrication, specimens were cured under controlled environmental conditions to ensure adequate hydration prior to testing. Taguchi L27 orthogonal array considered by the same author (Giri babu and Krishnaiah, 2025). The processes of weighing and mixing raw materials are illustrated in Fig. 2.0.

Figure 2: Weighing and mixing of raw materials

The FCB brick mixes were compacted into standard-size specimens (228.6 mm × 101.6 mm × 75 mm) using a hydraulic press. A compaction load of 60 tons was applied to each brick individually, corresponding to an effective compaction pressure of approximately 25.34 MPa. This high compaction pressure facilitated improved densification, enhanced inter-particle bonding, and better dimensional uniformity of the molded specimens. The molding process is illustrated in Fig. 3.0.

Figure 3: Molding bricks and stacking

After molding, the specimens were cured and dried under controlled temperature and humidity conditions to ensure proper hydration and strength development. The curing process of the bricks is illustrated in Fig. 4.0.

Figure 4: Curing/Drying of Bricks

3.3 Testing of developed bricks

The fabricated bricks were evaluated for green density (GD), compressive strength (CS), and water absorption (WA) in accordance with **IS 3495** standards. The testing procedure and experimental setup are illustrated in Fig. 5.0.

Figure 5: Testing

3.4 Statistical Analysis

Signal-to-Noise ratio analysis was applied to identify robust parameter levels. Larger-the-better criteria were adopted for compressive strength and density, whereas smaller-the-better was used for water absorption. ANOVA was performed to quantify the influence of individual factors and to validate the experimental model.

3.5 Multi- response optimization using the CRITIC-CODAS

To achieve simultaneous optimization of multiple responses, objective weights were determined using the CRITIC method based on variability and correlation among responses. The CODAS technique was then applied to rank all experimental alternatives by evaluating their distance from the negative ideal solution. This integrated framework allowed balanced decision-making across competing performance criteria (Giri Babu et al. 2025) [15], [16].

4. Results and Discussion

The experimental results are presented in table 1.0. Eexperimental results revealed significant variation in compressive strength, ranging from low values near 3 MPa to values exceeding 10 MPa for certain mixes. Specimens FCB10–FCB12 exhibited superior performance, which can be attributed to improved matrix densification and reduced internal porosity.

Water absorption values varied between approximately 6% and 16%, showing an inverse relationship with both density and strength. During testing, mixes with higher density demonstrated reduced moisture ingress, suggesting improved particle packing and reduced capillary pore formation.

Table 1: Experimental Results

Specimen ID	Trail	Compressive Strength (MPa)	Water Absorption (%)	Green Green density (g/cc)
FCB1	1	3.86	10.93	1.87
FCB1	2	4.36	9.78	1.94
FCB1	3	4.12	10.14	1.90
FCB2	1	4.56	11.91	1.83
FCB2	2	4.84	10.57	1.86
FCB2	3	4.23	13.09	1.76
FCB3	1	4.09	10.30	1.87
FCB3	2	3.91	11.25	1.82
FCB3	3	3.82	11.76	1.79
FCB4	1	4.89	13.73	1.71
FCB4	2	5.41	14.91	1.64
FCB4	3	5.13	14.63	1.72
FCB5	1	5.54	14.15	1.67
FCB5	2	5.83	14.73	1.65
FCB5	3	5.98	13.54	1.73
FCB6	1	5.96	13.13	1.73
FCB6	2	6.12	11.79	1.81
FCB6	3	5.85	13.78	1.71
FCB7	1	6.7	13.37	1.73
FCB7	2	6.19	13.49	1.72
FCB7	3	7.04	13.95	1.64
FCB8	1	5.63	14.15	1.66
FCB8	2	6.18	11.30	1.83
FCB8	3	5.95	14.05	1.67
FCB9	1	5.32	14.90	1.62
FCB9	2	5.67	13.26	1.72
FCB9	3	5.92	12.23	1.78
FCB10	1	9.04	7.77	2.06
FCB10	2	9.27	8.05	2.08
FCB10	3	8.86	8.28	2.00
FCB11	1	8.84	7.89	2.02
FCB11	2	8.91	6.35	2.14
FCB11	3	8.82	7.70	1.99
FCB12	1	9.2	6.97	2.03
FCB12	2	9.5	7.38	2.00
FCB12	3	10.14	6.85	2.10
FCB13	1	4.97	11.31	1.83
FCB13	2	4.56	12.60	1.72
FCB13	3	4.76	12.38	1.78
FCB14	1	4.44	13.75	1.73
FCB14	2	4.56	12.38	1.81
FCB14	3	4.34	13.80	1.72
FCB15	1	3.81	15.41	1.63
FCB15	2	4.37	13.57	1.71
FCB15	3	4.05	15.65	1.62
FCB16	1	6.99	14.45	1.71
FCB16	2	6.28	15.61	1.62
FCB16	3	6.71	14.32	1.66
FCB17	1	6.7	15.22	1.76
FCB17	2	5.95	14.44	1.66
FCB17	3	6.07	14.24	1.67
FCB18	1	6.5	16.47	1.61
FCB18	2	6.8	16.71	1.66
FCB18	3	7.15	15.91	1.69
FCB19	1	6.44	9.06	2.04
FCB19	2	7.18	10.00	2.07
FCB19	3	6.7	10.17	2.03
FCB20	1	5.54	9.84	2.10
FCB20	2	5.08	10.53	1.96
FCB20	3	5.19	10.63	2.01
FCB21	1	6.25	10.07	2.04
FCB21	2	6.11	11.24	1.97
FCB21	3	6.02	10.22	1.92
FCB22	1	6.06	10.52	1.83
FCB22	2	5.92	10.91	1.89
FCB22	3	6.31	11.06	1.78
FCB23	1	6.31	11.90	1.83
FCB23	2	6.42	10.91	1.89
FCB23	3	6.03	12.12	1.79
FCB24	1	5.98	10.65	1.91
FCB24	2	6.19	10.99	1.91
FCB24	3	6.38	10.30	1.94
FCB25	1	3.24	11.36	1.78
FCB25	2	3.47	11.45	1.80
FCB25	3	3.8	12.00	1.81
FCB26	1	3.67	14.10	1.66
FCB26	2	4.1	13.70	1.70
FCB26	3	3.34	14.39	1.67
FCB27	1	3.89	10.24	1.85
FCB27	2	4.15	10.16	1.91
FCB27	3	3.68	11.26	1.79

The compressive strength of the fabricated Fly Ash Carbon Black bricks showed considerable variation, ranging from **3.24 MPa (FCB25)** to values exceeding **10 MPa for FCB12**, highlighting the strong sensitivity of structural performance to material composition. The superior behaviour observed in **FCB10–FCB12** can be associated with improved matrix densification and enhanced inter-particle bonding, which contributed to higher strength and simultaneously reduced water absorption. In contrast, lower strength levels recorded in **FCB1–FCB3** and **FCB25–FCB27** indicate less favourable packing characteristics, likely resulting in increased internal porosity and weaker structural continuity.

Water absorption values were distributed within the range of approximately **6–16%**, revealing a consistent inverse relationship with both density and compressive strength. Mixes achieving higher green density demonstrated reduced moisture ingress, suggesting that effective compaction and optimized binder interaction limit capillary pore formation. The observed green density values, spanning **1.61 to 2.14 g/cc**, confirm that the developed compositions maintain a lightweight profile while preserving sufficient mechanical integrity. These trends collectively emphasize the importance of balancing carbon black content and binder proportion to achieve an optimal compromise between strength, durability, and sustainable material utilization.

The L27 experimental results show that optimized proportions of fly ash, carbon black, and processing parameters can enhance compressive strength while maintaining water absorption within acceptable limits. These findings indicate that Fly Ash Carbon Black bricks can serve as a sustainable alternative to conventional clay bricks, achieving a balanced combination of structural performance and environmental benefits.

4.1 Influence of raw material composition Compressive strength

The experimental response data presented in Table 1.0 were transformed into Signal-to-Noise (S/N) ratios using Minitab 17 software. For compressive strength, the larger-the-better criterion of the Taguchi method was applied. Main effects plots and ANOVA were subsequently generated to evaluate factor significance, and the dominant process parameters were identified from the S/N response table, as summarized in Table 2.0.

Table 2: Response table for S/N ratios of Compressive strength

Level	FA	CB	Cement	Gypsum	Stone Dust	PCE
1	14.34	15.75	12.2	15.01	14.85	14.77
2	16.15	14.56	15.63	14.79	15.18	15.14
3	14.23	14.41	16.89	14.91	14.69	14.81
Delta	1.92	1.33	4.68	0.22	0.48	0.37
Rank	2	3	1	6	4	5

The S/N response table indicates that cement content is the most influential parameter governing compressive strength, followed by fly ash and carbon black. The higher delta value for cement (4.68) confirms its dominant role in matrix densification, while fly ash shows an optimum intermediate effect. Quarry dust, PCE, and gypsum exhibit relatively minor influence, indicating secondary contributions to strength development. The main effects plot derived from the S/N ratios (Fig. 6.0) further illustrates the dominance order of the factors and highlights the relationship between process parameters and compressive strength behaviour.

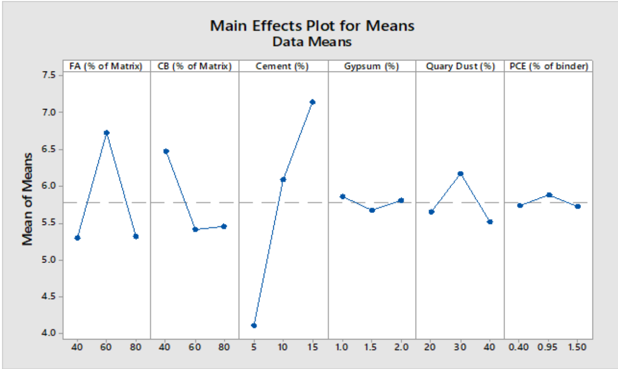

Figure 6: Main effects plot for S/N ratios of Compressive strength

The main effects plot shows that **cement content** has the strongest positive influence on compressive strength, increasing consistently from Level-1 to Level-3. Fly ash exhibits optimum performance at Level-2, while higher carbon black levels tend to reduce strength due to increased porosity. Quarry dust provides moderate improvement through enhanced particle packing, whereas gypsum and PCE show minimal influence. These trends support the statistical findings and indicate an optimal factor combination for improved strength with sustainable material use. Subsequently, **ANOVA** was performed to determine the percentage contribution of each parameter and to validate the adequacy of the developed model, as summarized in Table 4.3.

Table 4.3: ANOVA for S/N ratios of Compressive strength

Source	DF	Seq SS	Adj SS	Adj MS	F	P
FA (% of Matrix)	2	20.891	20.891	10.4454	23.32	0
CB (% of Matrix)	2	9.631	9.631	4.8157	10.75	0.001
Cement (%)	2	105.67	105.67	52.8349	117.94	0
Gypsum (%)	2	0.213	0.213	0.1067	0.24	0.791
Stone Dust (%)	2	1.095	1.095	0.5474	1.22	0.324
PCE (% of binder)	2	0.733	0.733	0.3666	0.82	0.461
Residual Error	14	6.272	6.272	0.448		
Total	26	144.505	S=0.6693; R-Sq=95.7%; R-Sq(adj)=91.9%			

The ANOVA results confirm that **cement content** is the most influential factor governing compressive strength, as reflected by its highest F-value and significant P-value (< 0.05). **Fly ash** and **carbon black** also show statistical significance, indicating their contribution to matrix modification. In contrast, gypsum, quarry dust, and PCE exhibit higher P-values (> 0.05), suggesting limited direct influence on strength and primarily supportive roles related to setting control, particle packing, and workability. The low residual error and standard error (S = 0.6693) indicate good experimental consistency, while the high **R^2 (95.7%)** and **R^2(adj) (91.9%)** confirm that the Taguchi–ANOVA model reliably captures compressive strength behaviour without overfitting.

4.2 Influence on Water absorption

The dominant raw materials on water absorption were identified from the data values in the response table for S/N ratios as shown in the table 4.4.

Table 4.4: Response table for S/N ratios of Water absorption

Level	FA	CB	Cement	Gypsum	Stone Dust	PCE
1	-22.09	-19.51	-21.67	-21.23	-21.81	-21.71
2	-21.23	-22.07	-22.22	-21.63	-20.62	-21.29
3	-20.87	-22.61	-20.3	-21.33	-21.76	-21.18
Delta	1.22	3.09	1.92	0.4	1.19	0.53
Rank	3	1	2	6	4	5

The S/N response analysis (Table 4.4) identifies **carbon black** as the dominant factor affecting water absorption, followed by cement and fly ash. Lower carbon black levels and higher cement content improved S/N values, indicating reduced pore connectivity and enhanced matrix densification. The main effects plot (Fig. 7.0) supports these trends, showing a strong influence of carbon black, moderate contribution of fly ash and quarry dust, and minimal variation for gypsum and PCE.

ANOVA results (Table 4.5) further confirm that carbon black is statistically significant (F = 59.46, $P < 0.05$), with cement and quarry dust also contributing to durability improvement, while gypsum and PCE remain insignificant within the tested range. The high model fit (**R^2 = 93.6%, R^2(adj) = 88.1%**) and low residual error demonstrate that the Taguchi L27 model reliably captures the water absorption behaviour of Fly Ash Carbon Black bricks.main effects plots are shown in figure 7.0

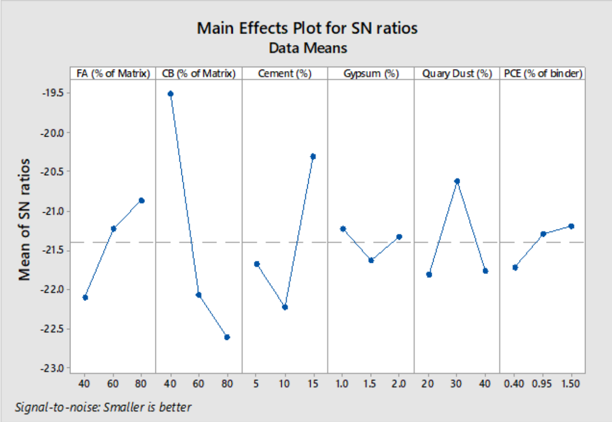

Figure 7: Main effects plot for S/N ratios of Water Absorption

Table 4.5: ANOVA for S/N ratios of Water Absorption

Source	DF	Seq SS	Adj SS	Adj MS	F	P
FA (% of Matrix)	2	7.1266	7.1266	3.5633	8.62	0.004
CB (% of Matrix)	2	49.1814	49.1814	24.5907	59.46	0
Cement (%)	2	17.5462	17.5462	8.7731	21.21	0
Gypsum (%)	2	0.7833	0.7833	0.3916	0.95	0.411
Stone Dust (%)	2	8.1484	8.1484	4.0742	9.85	0.002
PCE (% of binder)	2	1.4194	1.4194	0.7097	1.72	0.216
Residual Error	14	5.79	5.79	0.4136		
Total	26	144.505	S=0.6431;R-Sq=93.6%; R-Sq(adj)=88.1%			

4.3 Influence on Green density

The S/N response table (Table 4.6) indicates that **carbon black** is the primary factor influencing green density, exhibiting the highest delta value (1.191). Increasing CB content reduces density, reflecting its lightweight and pore-forming characteristics. **Fly ash** shows the second strongest influence, with density improving toward higher levels due to enhanced particle packing, while **cement** contributes moderately through matrix densification. Gypsum, quarry dust, and PCE display minimal variation, suggesting limited direct control over density within the tested range.

The main effects plot (Fig. 8.0) confirms these trends, showing a steep decline in S/N values with increasing CB and a gradual increase with higher FA levels. ANOVA results (Table 4.7) further identify CB as the dominant parameter (**F = 67.54, P < 0.05**), followed by FA (**F = 16.57**) and cement (**F = 8.35**). The high model fit (**R^2 = 93.2%, R^2(adj) = 87.4%**) and low residual error indicate reliable prediction of green density behaviour. Overall, green density optimization is mainly governed by the balance between CB and FA content, enabling lightweight yet structurally stable Fly Ash Carbon Black bricks.

Table 4.6: Response table for S/N ratios of Green density

Level	FA	CB	Cement	Gypsum	Stone Dust	PCE
1	4.867	5.876	5.014	5.213	5.058	5.058
2	5.132	4.926	5.057	5.106	5.278	5.214
3	5.489	4.686	5.417	5.17	5.152	5.219
Delta	0.621	1.191	0.404	0.107	0.221	0.164
Rank	2	1	3	6	4	4

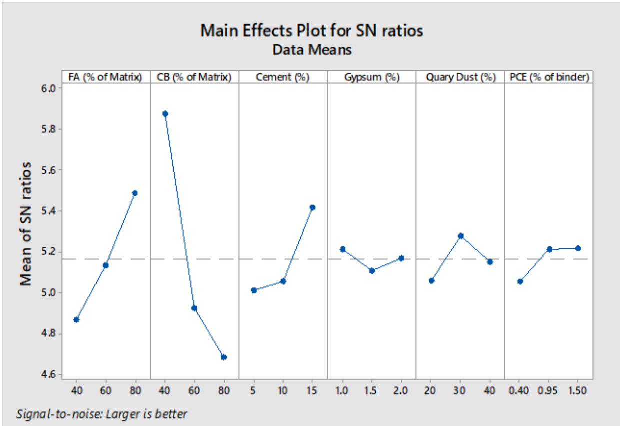

Figure 8: Main effects plot for S/N ratios of green density

Table 4.7 ANOVA for S/N ratios of green density

Source	DF	Seq SS	Adj SS	Adj MS	F	P
FA (% of Matrix)	2	1.7507	1.75075	0.87537	16.57	0
CB (% of Matrix)	2	7.137	7.13701	3.56851	67.54	0
Cement (%)	2	0.8827	0.88268	0.44134	8.35	0.004
Gypsum (%)	2	0.0523	0.05231	0.02615	0.5	0.62
Stone Dust (%)	2	0.2205	0.22051	0.11025	2.09	0.161
PCE (% of binder)	2	0.1564	0.1564	0.0782	1.48	0.261
Residual Error	14	0.7397	0.73969	0.05283		
Total	26	144.505	S=0.2299; R-Sq=93.2% ;R-Sq(adj)=87.4%			

4.4 Contribution of Raw material Composition

The contribution of each parameter was calculated from the ratio of sequential sum of squares to the total sum of squares obtained from ANOVA (Table 4.8). For **compressive strength**, cement shows the highest contribution (~73%), confirming its dominant role in matrix densification, while fly ash provides moderate influence and carbon black contributes marginally. In **water absorption**, carbon black dominates (~55%), indicating strong control over pore structure, followed by cement and quarry dust. For **green density**, carbon black again exhibits the largest contribution (~65%), with fly ash and cement showing secondary effects. The agreement between contribution percentages, S/N rankings, and ANOVA results demonstrates the reliability of the Taguchi L27 design, where cement governs strength, carbon black controls durability and density, and fly ash supports balanced performance with sustainability benefits.

Table 4.8: Contribution (%) of raw materials

Parameter	Compressive Strength (%)	Water Absorption (%)	Green density (%)
FA (% of Matrix)	14.46	7.92	16
CB (% of Matrix)	6.66	54.65	65.25
Cement (%)	73.14	19.49	8.07
Gypsum (%)	0.15	0.87	0.48
Quarry Dust (%)	0.76	9.05	2.02
PCE (% of Binder)	0.51	1.58	1.43
Error	4.34	6.43	6.76
Total	100	100	100

4.5 Optimum raw material composition

The Taguchi approach primarily identifies optimum levels for individual responses. Accordingly, the significant raw material factors and their corresponding optimum levels for compressive strength, water absorption, and green density are summarized in Table 4.9. The results indicate that cement at Level-3 is consistently required to achieve higher strength and lower absorption, highlighting its key role in matrix densification. Carbon black at Level-1 provides the most favourable performance across all responses by limiting porosity and maintaining stable density. Fly ash shows an optimum range between Level-2 and Level-3, balancing sustainability with performance, while quarry dust (Level-2) and higher PCE levels enhance particle packing and compaction. Gypsum exhibits only minor influence, functioning mainly as a setting regulator

Table 4.9: Effect of raw material composition on the responses and their optimum levels

Parameter	Compressive Strength	Water Absorption	Green density
FA (% of Matrix)	Level-2	Level-3	Level-3
CB (% of Matrix)	Level-1	Level-1	Level-1
Cement (%)	Level-3	Level-3	Level-3
Gypsum (%)	Level-1	Level-1	Level-2
Quarry Dust (%)	Level-2	Level-2	Level-2
PCE (% of Binder)	Level-2	Level-3	Level-3

The integrated optimum level table shows that cement Level-3 is consistently required to achieve higher compressive strength and reduced water absorption, confirming its dominant role in matrix densification. Carbon black Level-1 emerges as the best choice across all responses, indicating that lower CB content minimizes porosity and maintains stable green density. Fly ash demonstrates a balanced optimum between Level-2 and Level-3, supporting both sustainability and durability. Quarry dust Level-2 and higher PCE levels contribute to improved particle packing and uniform compaction, while gypsum exhibits minimal influence, acting mainly as a setting control additive.

4.6 Multi- Response Optimization

The relative importance of compressive strength (CS), water absorption (WA), and green density (DE) was evaluated using the CRITIC method, and the results are summarized in Table 4.10. The correlation matrix shows a strong association between WA and DE ($r = 0.9440$), indicating partial redundancy, whereas CS exhibits comparatively lower correlation with the other responses, suggesting higher independence. Although DE presents the largest variability (SD = 0.3442), CS achieves the highest contrast (0.2839) and conflict value (1.0852), leading to the maximum relative weight (0.4424). Consequently, the importance ranking follows the order CS > DE > WA, highlighting the dominant role of compressive strength in the multi-response framework.

Table 4.10: Correlation Matrix, Standard deviation, Contrast, Conflict and Relative weighs:

Responses	CS	WA	DE	Standard Deviation	Contrast	Conflict	Relative Weight
CS	1.0000	0.4442	0.4706	0.2617	0.2839	1.0852	0.4424
WA	0.4442	1.0000	0.9440	0.2556	0.1564	0.6118	0.2437
DE	0.4706	0.9440	1.0000	0.3442	0.2015	0.5854	0.3140

4.7 Overall Assessment scores of the alternatives

The CODAS method was applied to evaluate overall performance of all Taguchi combinations, and the resulting assessment scores are listed in Table 4.11. Among the alternatives, **FCB12** achieved the highest Euclidean (0.5906) and Taxicab (0.9922) distances, resulting in the top assessment score (**H_i = 0.6104**) and Rank-1 position. FCB10 and FCB11 also performed strongly, whereas most other mixes fall within a lower score range ($H_i \approx 0.18$–0.33). This clear separation between the top-ranked group and the remaining alternatives indicates that brick performance is highly sensitive to material composition, and only specific parameter combinations provide balanced improvements in strength, durability, and density.

Table 4.11: Assessment Score and ranking of alternate FCBs with varied compositions

Alt_FCBs	Euclidean	Taxicab	H_i	Rank
FCB1	0.2567	0.3999	0.2647	10
FCB2	0.1934	0.3268	0.1999	19
FCB3	0.2	0.3111	0.2063	18
FCB4	0.1329	0.201	0.137	24
FCB5	0.1766	0.2468	0.1816	22

FCB6	0.216	0.3488	0.2229	15
FCB7	0.2418	0.339	0.2486	11
FCB8	0.2018	0.3138	0.2081	17
FCB9	0.1789	0.2781	0.1845	20
FCB10	0.5553	0.935	0.574	2
FCB11	0.5527	0.9394	0.5715	3
FCB12	0.5906	0.9922	0.6104	1
FCB13	0.1767	0.305	0.1828	21
FCB14	0.1315	0.2273	0.136	25
FCB15	0.0572	0.0808	0.0588	27
FCB16	0.2326	0.2778	0.2381	13
FCB17	0.2059	0.2751	0.2114	16
FCB18	0.2404	0.2404	0.2452	12
FCB19	0.4299	0.7244	0.4443	4
FCB20	0.3547	0.5767	0.3662	6
FCB21	0.3562	0.6029	0.3683	5
FCB22	0.2765	0.4746	0.286	9
FCB23	0.2779	0.472	0.2873	8
FCB24	0.324	0.5557	0.3351	7
FCB25	0.1716	0.2426	0.1765	23
FCB26	0.0664	0.0984	0.0683	26
FCB27	0.2208	0.3391	0.2276	14

4.8 Validation Experiment

The optimum mix (FCB12) was validated using five replicate test specimens to quantify prediction error and assess statistical reliability with respect to the Taguchi–CODAC-based optimization

The optimal mix (FCB12) was verified through five replicate experiments to evaluate prediction accuracy and statistical reliability based on the Taguchi–CRITIC–CODAS optimization results (Table 4.12). The validation outcomes show close agreement between predicted and measured responses, confirming the robustness of the proposed framework. The average green density obtained from the trials was 2.03 g/cc, compared with a predicted value of 2.04 g/cc, with low variability (SD = 0.051, CV = 2.51%). Compressive strength exhibited high consistency, recording a mean value of 9.64 MPa against the predicted 9.61 MPa (SD = 0.147, CV = 1.52%). Water absorption averaged 7.03%, which is very close to the predicted 7.07%, with moderate variation (CV = 8.49%) typical of porosity-related properties. The narrow 95% confidence intervals further indicate stable performance, demonstrating that the optimized FCB12 composition provides reliable mechanical and durability characteristics.

Table 4.12: Results of Validation experiments

Response	Experimental Mean Value (FCB12)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	SD	CV (%)	% Error	95% CI Mean
GD (g/cc)	2.04	2.07	2.06	1.95	2.06	1.99	2.03	0.051	2.51%	−0.49%	1.97 – 2.09
CS (MPa)	9.61	9.42	9.58	9.74	9.63	9.81	9.64	0.147	1.52%	0.31%	9.46 – 9.82
WA (%)	7.07	7.3	7.82	6.9	6.15	6.98	7.03	0.597	8.49%	−0.57%	6.29 – 7.77

4.9 Discussion of Results

The experimental findings indicate that the performance of Fly Ash Carbon Black bricks is largely controlled by the interaction between material composition and processing conditions. The Taguchi L27 design enabled systematic evaluation of compressive strength, water absorption, and green density, revealing consistent trends across factor levels. Cement content was identified as the primary driver of compressive strength, reflecting its role in matrix formation and load transfer. Carbon black showed a pronounced influence on water absorption and density, suggesting its involvement in pore structure development and lightweight characteristics, while fly ash provided a balanced contribution that supports both performance improvement and sustainable material utilization.

Multi-response evaluation using the CRITIC–CODAS framework allowed simultaneous consideration of strength, durability, and density requirements. The optimized parameter combination achieved improved mechanical performance with controlled moisture uptake and stable density, highlighting the need for a compromise-based optimization strategy when multiple criteria are involved. Validation experiments confirmed close agreement between predicted and measured responses, demonstrating the reliability of the developed modelling approach.

From a practical standpoint, the results provide guidance for manufacturers aiming to improve quality and sustainability in brick production. Cement and carbon black emerge as key parameters for performance control, whereas fly ash offers environmental benefits through waste utilization. The comparatively low influence of gypsum, quarry dust, and PCE suggests that these additives can be adjusted primarily for workability and cost considerations without significantly affecting core properties. The top-ranked mix FCB12 (Fly ash: 40.71%, Carbon Black: 27.14%, Cement: 10.18%, Gypsum: 1.36%, Stone dust: 20.35%, PCE: 0.27%) represents the overall optimum composition, while the proximity of FCB10 and FCB11 indicates the presence of multiple near-optimal solutions. In contrast, alternatives with very low assessment scores ($H_i < 0.10$) may be avoided during mix design.

Overall, the proposed methodology offers a structured decision-support framework that enables rapid evaluation of alternative compositions with limited experimentation. Adoption of the optimized mix can support consistent product quality, reduced material wastage, and improved durability performance, thereby contributing to efficient and sustainable brick manufacturing practices.

5. Conclusions

An integrated experimental and multi-response optimization framework was developed in this study to design sustainable Fly Ash Carbon Black (FAC) bricks using Taguchi design, ANOVA, and CRITIC–CODAS techniques. The key findings can be summarized as follows:

- The Taguchi L27 design provided an efficient platform to examine the effect of raw material proportions on compressive strength, water absorption, and green density, allowing reliable optimization with a limited number of experiments.
- S/N ratio analysis and ANOVA helped identify the dominant parameters governing brick behaviour., highlighting the strong influence of material composition on both mechanical performance and durability.
- The combined use of CRITIC weighting and CODAS ranking enabled balanced multi-response evaluation, leading to the selection of the FCB12 composition as the overall optimal mix.
- Validation tests showed close agreement between predicted and measured values, with very small errors (−0.49% for GD, 0.31% for CS, and −0.57% for WA) and low coefficients of variation (1.52–8.49%), confirming the reliability of the developed framework.
- The optimized FAC bricks achieved improved strength and controlled water absorption while incorporating industrial by-products, supporting environmentally responsible and resource-efficient construction practices.

In summary, the Taguchi–ANOVA–CRITIC–CODAS approach offers a practical and scalable methodology for developing eco-friendly masonry materials with balanced structural performance and sustainability benefits.

6. Limitations and Future Scope

Despite the encouraging results obtained, several limitations of the present work should be noted. The investigation considered a limited range of material proportions within a Taguchi L27 design, which may not fully represent all possible interactions among constituents. Validation was performed using a small number of confirmatory trials, and long-term durability aspects such as freeze–thaw resistance, abrasion, and chemical exposure were outside the scope of this study. In addition, the optimization focused mainly on compressive strength, water absorption, and green density, without detailed microstructural analysis or a comprehensive life-cycle evaluation.

Future studies may expand this framework by incorporating additional performance parameters such as thermal conductivity, efflorescence behaviour, and durability under aggressive service conditions. Inclusion of microstructural characterization together with life-cycle assessment (LCA) and cost analysis would further strengthen the practical relevance of Fly Ash Carbon bricks for sustainable construction applications.

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