Flexural optimization of slag-based geopolymer concrete beams modified with corn cob ash

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Abstract. The present study investigates the flexural strength of Geopolymer Concrete (GPC) beams produced by Ground Granulated Blast Furnace Slag (GGGBS) and Corn Cob Ash (CCA). In the Design Of Experiment (DOE), Box-Behnken Design (BBD) of Response Surface Methodology (RSM) was used to optimize the strength. GGBFS was replaced at 0, 20, and 40 wt.% of CCA. The mixes were activated with 14 molar concentration (14 M) of both sodium silicate (Na\textsubscript{2}SiO\textsubscript{3}) and sodium hydroxide (NaOH) solutions. The mix design properties such as alkaline liquid-to-binder ratio, binder-to-aggregate ratio, binder ratio, and curing time were statistically employed as continuous (independent) variables to optimize the response factor (flexural strength). Compared to the control sample (Portland cement concrete), GPC exhibited higher compressive and flexural strengths at up to 40 wt.% of CCA replacement. The models predicted the response of flexural strength with the variability of less than 5%. Moreover, the correlation between the experimental and optimized flexural strengths yielded high precision with 99.6% $R^2$. Therefore, the response models in this study would be advantageous in optimization of mix design proportions to obtain the target flexural strength of GPC beams produced by GGBFS and CCA.

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1. Introduction

In recent years, Geopolymer Concrete (GPC) has emerged as the eco-friendly and sustainable concrete. Geopolymer concrete utilizes Supplementary Cementitious Materials (SCMs) as the source materials for its production and it exhibits higher mechanical strength [1] and excellent durability properties [2] than Portland Cement Concrete (PCC). Supplementary cementitious materials have received extensive attention by researchers that have successfully applied them to the construction of civil engineering infrastructures to replace Portland Cement (PC) utilization [3]. Moreover, reduction of environmental pollution, global warming, and sustainability problems has received international attention. Many researchers have valorized agro-industrial products such as Ground Granulated Blast Furnace Slag (GGBFS) [4], Corn Cob Ash (CCA) [5,6], metakaolin [7], fly ash, and Rice Husk Ash (RHA) [8,9] as excellent PC alternatives to sustainable products, infrastructure, and development. Oyebisi et al. [6] investigated the mechanical properties, microstructural behavior, and mineralogical phases of GGBFS-based GPC incorporating CCA at 0–100 wt.% CCA under ambient curing conditions [6]. The results indicated that up to 40 wt.% of CCA replacement exhibited higher strength than PCC. The results also showed the possibility of blending CCA with GGBFS for GPC production in ambient conditions for structural application. Furthermore, an about 80–90%
reduction of CO₂ emissions per ton and 43–59% reduction of energy needs (MJ/t) were observed during geopolymer cement production compared with PC [10].

Different parameters such as chemical compositions of source materials, types and concentrations of alkaline solutions, water content, and curing temperatures can influence the properties of geopolymer mixes [10]. Following the traditional experimental design method, a large number of experiments are required to evaluate the influence of different parameters at various levels on the GPC properties which are expensive and time consuming. However, an appropriate Design Of Experiment (DOE) can be used to evaluate the effects of these factors with a small number of experiments [11]. Moreover, the proportion of concrete constituents is a vital aspect of concrete technology because it ensures quality, safety, and economy. The concrete mix proportion is accomplished by application of specific parameters and appropriate procedure to select the best composition of constituents and achieve the desired goals or properties. The ultimate objective is to minimize the required effort and maximize the expected benefit [11]. Therefore, the needed action or the desired use in any practical circumstance can be termed as optimization that evaluates a function’s conditions, thus minimizing or maximizing the values [11].

A beam element in the structural system is often subject to flexural bending. Therefore, high flexural strength is required for a structural beam to resist the bending failure. Apart from being a flexural member, a beam is designed to withstand ultimate bending moments, shear forces, and torsional members, if any. In most cases, the design of concrete beams is governed by deflection rather than strength [12], indicating that the deflection of a concrete beam depends on its flexural strength. The deflection of concrete beams is influenced by tension and compression reinforcements, stress level, concrete size and age, aggregate properties and mineralogy, water content, and curing conditions of concrete samples [12].

Response Surface Methodology (RSM) is a statistical and analytical method that examines the effect of a set of quantitative experimental variables of factors on response [13]. RSM is usually employed to identify a set of vital elements (operating conditions) generating the “best” response [13]. Further, RSM models a relationship between the quantitative factors and the response. On the contrary, Box-Behnken Design (BBD) is a response surface three-level design in which all the design points are either at the center of the design or centered on the edges of the cube, equidistant from the center [13]. Unlike the Central Composite Design (CCD) of RSM, BBD allows an efficient estimation of quadratic terms in a regression model and consists of fewer design points, hence less expensive to run [14]. Moreover, it ensures that all design points fall within the safe operating limits (within the nominal high and low levels) for the process [13].

Alsanusi and Bentaher [15] predicted the compressive strength of concrete from early age test result using BBD. The results indicated that the developed models could predict the required compressive strength of concrete from early ages. Dai et al. [16] optimized the mix proportion of cement paste backfill materials via BBD. The experimental findings were indicative of the feasibility of producing the industrial standard backfilling materials. Moreover, Liu et al. [17] evaluated the effect of mix proportion parameters on Basalt Fiber Reactive Powder Concrete (BFRPC) through the BBD model. The experimental results also showed that the silica fume-to-cement ratio was a significant factor for BFRPC and it also had remarkable interaction with basalt fiber content, sand-to-binder and water-to-binder ratios on the fluidity, compressive, and flexural strengths of BFRPC. Optimization of the alkali-activated mortar incorporating GGBFS and natural pozzolan was conducted through Taguchi method. The obtained results indicated that the flow and strength values for the materials could be optimized using the DOE, as mentioned earlier [11]. However, Ramkumar et al. [18] employed the CCD of the RSM to optimize the mechanical strengths of fly ash-based GPC. It was concluded that the RSM validated the influence factors with an average difference of less than 5%, hence acceptable. However, the optimization of GPC beams modified by GGBFS and CCA is a novel development as no study has been conducted on optimizing its flexural strength through RSM-BBD.

In this respect, the present study aims to optimize the flexural strength of GPC beams produced by both GGBFS and CCA. To this end, the BBD model of RSM was employed to arrive at an optimum combination of mix parameters of GPC. The selected mix parameters were CCA-to-GGBFS ratio, alkaline liquid-to-binder ratio, binder-to-aggregate ratio, 14 molar concentrations of NaOH and Na₂SiO₃ solutions, and curing times and mix design proportions. In addition, the flexural strengths of M 25–40 concrete grades were selected as the target strengths. The GPC samples were cured under ambient conditions (23 ± 5°C, 65% relative humidity), eliminating the heat curing conditions, which was not feasible for field application. Ultimately, the developed models can be applied to predict the flexural strength of geopolymer concrete incorporating natural pozzolans in a building sector, thus reducing cost, energy, and time while conducting laboratory works.

2. Materials and methods

2.1. Materials

GGBFS, corncob, and 42.5R Portland Limestone Cement (PLC) were locally sourced and used as precursor
Table 1. Physical properties of the precursor materials used.

| Properties                | GGBFS | CCA  | PLC  |
|--------------------------|--------|------|------|
| SG (g/cm³)               | 2.90   | 2.44 | 3.15 |
| Fineness (%)             | 7.6    | 7.8  | 7.50 |
| SSA (m²/kg)              | 420    | 505  | 375  |
| Mean particle size (µm)  | 20.68  | 19.14| 23.45|

Materials. Corn cob was valorized, and 25 wt.% of corncobs was obtained as CCA. Therefore, both GGBFS and CCA, as shown in Figure 1, were used as the source materials to produce GPC, while PLC was used as a binder to produce PCC (control concrete). The Specific Gravity (SG) of the precursor materials was obtained following the BS EN [19] procedure through kerosene and SG bottle, the results of which are presented in Table 1. Furthermore, the fineness and Specific Surface Area (SSA) of the materials were obtained based on BS EN [20] procedure, the results of which are given in Table 1. Moreover, the Particle Size Distribution (PSD) of the materials was analyzed over the range size of 0.5–900 µm using Laser diffraction, Model Beckman Coulter LS-100, as shown in Figure 2. The results of the mean particle size are presented in Table 1. According to this table, more volume of both CCA and GGBFS would be required when mixed with PLC due to their lower SG and higher fineness than PLC. In addition, both CCA and GGBFS would favorably react with the cement Portlandite and alkaline environment due to their higher SSA and lower particle size than that of PLC [7]. The chemical compositions of the precursor materials were analyzed using XRF spectrophotometer machine, Philips PW1800. The obtained results are shown in Table 2.

The characterization of the used source materials were analyzed using Scanning Electron Microscopy (SEM), JEOL 7000600. All images were observed at 4000× magnification in a high vacuum from the working distance ranging from 8.3 to 10.6 mm at a constant 15 kV accelerated voltage. The results are shown in Figure 3. The GGBFS particles, as depicted in Figure 3(a), are characterized by an amorphous shape with an uneven surface. On the contrary, the

Table 2. Chemical compositions of the precursor materials used.

| Oxide composition (%) | GGBFS requirements for GGBFS | CCA requirements for GGBFS | PLC requirements for PLC |
|-----------------------|------------------------------|---------------------------|-------------------------|
| CaO                   | 36.52                        | 32 - 38                   | 12.62                   |
| SiO₂                  | 35.77                        | 32 - 38                   | 60.5                    |
| Al₂O₃                 | 14.11                        | 14 - 19                   | 8.78                    |
| Fe₂O₃                 | 0.92                         | 0.72 - 2.0                | 9.13                    |
| MgO                   | 9.45                         | 6 - 10                    | 1.23                    |
| K₂O                   | 0.52                         | 0.1 - 0.7                 | 1.25                    |
| Na₂O                  | 0.3                          | 0.2 - 0.7                 | 0.65                    |
| SO₃                   | 1.08                         | 0.2 - 1.0                 | 1.25                    |
| L.OI²                 | 1.32                         | 0.5 - 3.0                 | 2.89                    |

²LOI is loss of ignition at 800°C.
internal structure of CCA particles, as shown in Figure 3(b), is irregular in shape with a wrinkled surface. Hence, these results are consistent with the findings of other similar studies such that GGBFS reveals an amorphous form with sharp needles, while pozzolan, CCA in this case, indicates irregular shape with hollow pores [12].

Aggregates, fine aggregates (sharp sand ≤ 4.5 mm), and coarse aggregates (granite ≤ 12.5 mm size) were locally sourced and used. As shown in Figure 4, PSD was conducted on the aggregates based on BS EN [24] procedure. Moreover, SG and Water Absorption (WA) were determined in line with BS EN [24] established method. According to the results, SG and WA for both fine and coarse aggregates were 2.60 and 2.64 g/cm³ and 0.7 and 0.8%, respectively. Besides, Moisture Content (MC) was determined based on BS EN [24] procedure, which was calculated as 0.3 and 0.2% for both fine and coarse aggregates, respectively.

The alkaline activators including NaOH pellets (99% purity) and Na₂SiO₃ gel were sourced in Lagos, Nigeria. Na₂SiO₃ gel (SS) consists of Na₂O, SiO₂, and H₂O with 9.4, 30.1, and 60.5% respectively, with the SiO₂/Na₂O weight ratio of 3.20 and SG of 1.40 g/cm³ at 20°C. Following the application of chemistry procedures of Rajamani and Jeyalakshmi [25], 400 g of NaOH pellets were measured and dissolved in 600 g of clean water to prepare 14 M activator using Na₂SiO₃ to NaOH solutions (SS/SH) with a ratio of 2.5:1. The activator and proportion were selected in compliance with those of other relevant studies [6,26] such that 14 M activator yielded the highest mechanical strength among 12 and 16 M as well as PCC. Moreover, the ratio of 2.5:1 for Na₂SiO₃-to-NaOH solutions exhibited higher mechanical performance than those of 1.5:1, 2:1, and 3:1 on days 7, 28, 59, and 90 of curing [6].

2.2. Mix design quantities
A 0–40 wt. % GGBFS content was selected and replaced by CCA in accordance with the findings of similar studies [6,26] to ensure the target strength of the structural applications. The mixes were designed in accordance with BS EN [27] procedure to achieve the concrete target strengths of 25, 30, and 40 MPa for grades of M25–40, respectively, due to their general applications in the construction sector. Consequently, GGBFS was replaced by CCA content at 0, 20, and 40% for all concrete grades. The results of mix design proportions are presented in Tables 3–5 for M 25, 30, and 40, respectively.

2.3. Mix preparation, casting, and curing
As shown in Figure 5, the mix was prepared in accordance with the BS [28] and BS EN [29] procedures using a standard cube 150 mm³ for compression and a standard beam of 150 mm deep and 750 mm long for flexure. The samples were cured under ambient conditions (23 ± 5°C and 65% RH) and tested on days 28, 59, and 90.

2.4. Compressive and flexural strength tests and analysis
The compressive and flexural strengths were tested in accordance with the BS EN [30] and BS EN [31] procedures using the digital compressive testing machine (Model: YES-2000) and fully automatic transverse
Table 3. Mix proportions for M 25 (kg/m³).

| Mix ID | PLC  | GGBFS | CCA | NaOH solution | Na₂SiO₃ gel |
|--------|------|-------|-----|---------------|------------|
| K0     | 340  | 0     | 0   | 0             | 0          |
| K1     | 0    | 340   | 0   | 60            | 150        |
| K2     | 0    | 272   | 68  | 60            | 150        |
| K3     | 0    | 204   | 136 | 60            | 150        |

Conditions: FA = 715 kg/m³; CA = 1035 kg/m³; alkaline liquid-binder (AL/B) ratio for GPC = 0.62; water-cement (w/c) ratio for PLC = 0.62; binder-aggregate (B/Agg) ratio = 0.19.

Table 4. Mix proportions for M 30 (kg/m³).

| Mix ID | PLC  | GGBFS | CCA | NaOH solution | Na₂SiO₃ gel |
|--------|------|-------|-----|---------------|------------|
| L0     | 390  | 0     | 0   | 0             | 0          |
| L1     | 0    | 390   | 0   | 60            | 150        |
| L2     | 0    | 312   | 78  | 60            | 150        |
| L3     | 0    | 232   | 156 | 60            | 150        |

Conditions: FA = 675 kg/m³; CA = 1031 kg/m³; alkaline liquid-binder (AL/B) ratio for GPC = 0.52; water-cement (w/c) ratio for PLC = 0.52; binder-aggregate (B/Agg) ratio = 0.23.

Table 5. Mix proportions for M 40 (kg/m³).

| Mix ID | PLC  | GGBFS | CCA | NaOH solution | Na₂SiO₃ gel |
|--------|------|-------|-----|---------------|------------|
| M0     | 500  | 0     | 0   | 0             | 0          |
| M1     | 0    | 500   | 0   | 60            | 150        |
| M2     | 0    | 400   | 100 | 60            | 150        |
| M3     | 0    | 300   | 200 | 60            | 150        |

Conditions: FA = 585 kg/m³; CA = 1031 kg/m³; alkaline liquid-binder (AL/B) ratio for GPC = 0.42; water-cement (w/c) ratio for PLC = 0.42; binder-aggregate (B/Agg) ratio = 0.31.

Figure 5. Mixing and casting the samples.

Figure 6. Strength tests: (a) Compression and (b) flexure.

2.5. Design of Experiment (DOE)

2.5.1. Box-Behnken Design (BBD)

The BBD of RSM were employed to evaluate the interaction between the selected continuous variables [alkaline liquid-to-binder ratio (AL/B), binder-to-aggregates ratio (B/Agg), CCA/(CCA + GGBFS) ratio (C), and curing time (T, day)], response variable, and flexural strength (fₑ, MPa). Minitab statistical software was engaged and the BBD was created using four different continuous variables, the results of which are shown in

\[
fₑ = \frac{1.5P}{kb²},
\]

where \(fₑ\) is flexural strength (MPa), \(P\) is applied load at failure (N), \(l\) is distance between the supports (mm), \(b\) is concrete sample width (mm), and \(d\) is concrete sample depth (mm).
Table 6. Continuous variables at a 3-different level for Box-Behnken Design (BBD).

| Variables | Symbol | Low  | Centre | High |
|-----------|--------|------|--------|------|
| $A/B^a$   | A      | 0.42 | 0.52   | 0.62 |
| $B/Agg^b$ | B      | 0.19 | 0.25   | 0.31 |
| CCA/(CCA + GGBFS)$^c$ | C | 0    | 0.20   | 0.40 |
| Curing time | T | 28   | 30     | 90   |

$^a$ alkaline liquid to binder ratio; $^b$ binder to aggregate ratio; $^c$ corn cob ash to slag ratio.

Table 6. Therefore, the experimental run number was estimated using the illustration presented in Eq. (2) [13]:

$$N = 2v(v - 1) + c_p,$$

(2)

where $N$ is number of experimental runs, $v$ is total continuous variables, and $c_p$ is total applied central point.

Following Eq. (2), 27 experimental runs were conducted based on four continuous variables and three applied central points, as shown in Table 6. In addition, full quadratic polynomial, as illustrated in Eq. (3), accurately optimizes the relationship between the continuous and response variables, thus yielding high precision [13,14].

$$Y = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n} a_{ii} x_i^2 + \sum_{i<j} a_{ij} x_i x_j,$$

(3)

where $Y$ is response variable ($f_r$), $a_0$ is model coefficient constant, $x_i, x_j$ is continuous variables ($A, B, C, \text{and} T$), $a_i$ is linear coefficient, $a_{ii}$ is quadratic coefficient, and $a_{ij}$ is interaction coefficient.

### 2.5.2. Optimization of variables

This study aimed to optimize the design variables by minimizing the continuous variables ($A, B, C, \text{and} T$) and maximizing the response variable ($f_r$) using the optimization concept. Following this concept, the response variable or value was converted into a composite desirability function ($D$) in the range of 0–1, as illustrated in Eq. (4) [13,32]. The closer the composite desirability to 1, the better the optimization [13].

$$0 \leq D \leq 1.$$

(4)

According to Eq. (4), $D = 1$ if the response value ($f_r$) is at its goal or target. In addition, $D = 0$ if the response value is outside an acceptable region. Moreover, the desirability is composite based on the expressions illustrated in Eqs. (5)–(7) to maximize, minimize, and make the response to be as close as possible to the target, respectively [32]. Therefore, Eqs. (5)–(7) were used to validate the results of the optimization study.

$$\begin{cases}
D = 0 & \text{if} \ r \leq L \\
D = (r - \frac{L}{T} - L)^w & \text{if} \ L \leq r \leq T \\
D = 1 & \text{if} \ r \geq T
\end{cases}$$

(5)

$$\begin{cases}
D = 1 & \text{if} \ r \leq T \\
D = (r - \frac{U}{T} - U)^w & \text{if} \ T \leq r \leq U \\
D = 0 & \text{if} \ r \geq U
\end{cases}$$

(6)

$$\begin{cases}
D = (r - \frac{L}{T} - L)_{w1} & \text{if} \ L \leq r \leq T \\
D = 1 & \text{if} \ r \geq T \\
D = (r - \frac{U}{T} - U)_{w2} & \text{if} \ T \leq r \leq U \ \ (7)
\end{cases}$$

where $D$ is composite desirability function (0–1), $r$ is response, $L$ is lower value/limit, $U$ is upper value/limit, $T$ is target value/limit, and $w$ is weight.

### 3. Results and discussion

#### 3.1. Mechanical strengths

Figure 7(a)–(c) present the results of compressive strength for concrete grades of 25, 30, and 40, respectively. Figure 8(a)–(c) show the results of flexural strength for concrete grades of 25, 30, and 40, respectively. The results revealed that both compressive and flexural strengths increased upon increasing the curing age for all concrete mixtures at all concrete grades levels. There was about 3–15%, 2–7%, and 2–8% increases in the flexural strength as the curing age increased from 28–90 days curing for M 25–40, respectively. Further, both compressive and flexural strengths increased upon increasing the GGBFS content in the mix. Unlike PCC, GPC exhibited higher compressive and flexural strength at all curing ages and concrete grades that could be attributed to the reaction between the glassy phase of GGBFS and
alkaline liquid, thus resulting in the X-Ray Amorphous Aluminosilicate Gel (X-RAG) which, according to Chen and Brouwers [33] and Khale and Chaudhary [34], contributed to the higher mechanical strength in the GPC. On the contrary, there was a gradual decrease in both compressive and flexural strength of GPC as the replacement level of CCA in the mix increased from 20–40 wt.%. The gradual reduction in strength may be attributed to the reduction in aluminosilicate glassy phase of GGBFS. Therefore, the reactive presence of Calcium-Silicate-Aluminate-Hydrate (C-S-A-H) in the geopolymer paste decreased and the pores of geopolymer matrix increased, thus reducing the strength [12]. However, the partial replacement of GGBFS by 20–40 wt.%(CCA) met the target strength of M 25–40 at the 28-day curing age and surpassed the strength of the control sample (PCC). Statistically, on day 90 of curing, there was about 13–22%, 9–15%, and 7–14% increase in the flexural strength as the percentage content of GGBFS in the mix increased from 60–100% for M 25–40, respectively, compared with PCC. The experimental results, as shown in Figure 8(a)–(c), confirmed that GPC exhibited higher resistance against bending than that of the conventional concrete (PCC). Therefore, both GGBFS and CCA can be used as natural pozzolans as an PLC alternative in the flexural strengthening of the concrete beam.

3.2. Analysis of response surface design
Following the creation of BBD and establishment of response surface design from data in a worksheet, as illustrated in Table 6, the fitted model analysis results for a response surface design are presented in Table 7. The model’s accuracy and the influence of continuous variables on the flexural strength were examined by analyzing variance (ANOVA).

The regression model in Table 7 indicates that the terms in the model have a significant effect on the
flexural strength because $P = 0.000$, which is less than $\alpha$-level (0.05) [35]. In addition, the $P$-values for the continuous variables, $A$, $B$, $C$, and $T$ are 0.000, 0.000, 0.000, and 0.000, respectively, indicating the significant linear effect. The resisting performance of the concrete against bending depends on the proportions of alkaline liquid, binder and aggregate contents, and curing time. The following terms, $(A)^2$, $(B)^2$, and $(A \times B)$, were regarded as non-significant terms and removed from the model according to the $P$-value. Moreover, according to Table 7, the $P$-values of 0.333, 0.164, and 0.645 for the squared effects, $(C)^2$, and $(T)^2$, respectively, were higher than 0.05, indicating that the relationship between $f_r$ and $C$ as well as $f_r$ and $T$ exhibited no significant quadratic effect. However, the $P$-values of 0.000, 0.018, 0.000, and 0.0015 for the $A \times C$, $A \times T$, $B \times C$, and $B \times T$, respectively, were less than 0.05, indicating a significant interaction effect. The effect of both $A$ and $B$ on the resisting performance of concrete against deflection depends on $C$ and $T$. There was still no significant interaction effect between $C \times T$ on the yield of $f_r$ because $P$-value = 0.173 was higher than 0.05. However, as shown in Table 7, the $F$-value for all significant terms was greater than 5, confirming that the model terms were substantial [36] to the yield of flexural strength. Finally, the model yielded no lack-of-fit or pure error because both linear and interaction terms were significant, hence included in the model.

The special effect was also evaluated using the coded coefficient analysis to examine the correlational level of the continuous variables, the results of which are presented in Table 8. According to the results, all model terms corroborated the ANOVA regression analysis, as shown in Table 7, thus yielding a significant effect. In addition, VIF values were higher than 10 and the $P$-values were less than 0.05. However, the squared terms of both $C \times T$ and the interaction term between $C \times T$ yielded VIF of 1.00, indicating that the variables were not correlated [14]. As a result of the ANOVA and coded coefficient of the model, the regression model equation between the response ($f_r$) and continuous variables ($A$, $B$, $C$, and $T$) can be illustrated, as shown in Eq. (8). The model summary yielded $S$, $R^2$, $R^2$ (adj), and $R^2$ (pred) as 0.0743028, 99.61%, 99.32%, and 98.66%, respectively, showing that the model equation could predict the relationship between the response variable and continuous variables at 100% confidence bound. Ultimately, this developed model equation can be used to predict the flexural optimization of the concrete strength incorporated with SCMs.

$$f_r = 24.59 - 23.00A - 27.10B + 151.90C - 0.221T$$

$$- 1.111C^2 + 0.00015T^2 - 169.40AC + 0.2421AT$$

$$- 262.70BC + 0.412BT - 0.00494CT.$$  

(8)
Table 8. Coded coefficient analysis of the regression model.

| Term | Effect | Coef. | SE coef | T-value | P-value | VIF |
|------|--------|-------|---------|---------|---------|-----|
| Constant | 5.8871 | 0.0338 | 174.41 | 0.000 | 177.61 |
| A | -8.518 | -1.299 | -18.37 | 0.232 | 0.000 |
| B | -6.637 | -3.139 | 0.229 | -14.48 | 0.000 |
| C | -1.0220 | -0.5110 | 0.0215 | -23.81 | 0.000 |
| T | 0.5103 | 0.2551 | 0.0214 | 11.90 | 0.000 |
| C² | -0.0889 | -0.0444 | 0.0303 | -1.47 | 0.164 |
| T² | 0.0288 | 0.0144 | 0.0307 | 0.47 | 0.615 |
| A × C | -6.775 | -3.388 | 0.284 | -11.94 | 0.000 |
| A × T | 1.501 | 0.751 | 0.283 | 2.65 | 0.018 |
| B × C | -6.305 | -3.133 | 0.280 | -11.24 | 0.000 |
| B × T | 1.533 | 0.767 | 0.280 | 2.74 | 0.015 |
| C × T | -0.0612 | -0.0306 | 0.0214 | -1.43 | 0.173 |

Figure 9. Normal probability plot for the $f_r$ (MPa).

In practice, a balanced or nearly balanced design with a large number of observations does not significantly affect the residuals (the difference between the observed and fitted response variables) if departed moderately from a straight line or normality [13]. Hence, the normally distributed residual from the analysis is required for a balanced design. As shown in Figure 9, the residuals generally follow a straight-line pattern, hence no evidence of non-normality or unknown variables in the model. Furthermore, in a designed experiment, the order of observations affects the response variable if the residuals fluctuate in a random pattern around the center line [13]. The result versus order for the response variable, as shown in Figure 10, exhibited a randomly scattered pattern about zero, hence no evidence of the correlation among the error terms.

3.3. Effects of continuous variables on the response value (flexural strength)

Following the fitted model generation based on the stored model, Figure 11 shows the main results of continuous variables on the response variable ($f_r$). According to Figure 7, the constant variables influenced the response variable because the plotted lines were not horizontal [13]. Furthermore, as observed, a decrease in the values of $A$, $B$, and $C$ resulted in increased resistance of the concrete beam against bending under the applied load. This measure accelerates the geopolymer paste setting time, boosts the geopolymerization process, compacts the microstructures, minimizes the geopolymer matrix pores, and consequently leads to higher flexural strength performance [8,37]. There was about 11–29% decrease in the water-to-geopolymer solid ratio as the alkaline liquid-to-binder ratios in the mixes decreased from 0.62–0.42 for M 25–M 40 concrete grades. Furthermore, a concrete mix with a low water-to-binder ratio and high cement content exhibited decreased strength in case of using higher aggregate particles [12]. Therefore, a more insufficient water-to-binder ratio would not result in higher strength in this mix at later ages, the reason for which could be associated with the shrinkage that induced stresses and restrained aggregate particles, hence cement-paste cracking and loss of the cement-aggregate bond [12] which are attributed to a lower binder to aggregates ratio with increasing flexural strength obtained in this study. In addition, Kaplan [38] reported that the mechanical interlocking and crack-arresting capacities of
coarse aggregates significantly contributed to increased compressive and tensile strength of concrete rather than flexural strength. Here, the binder-to-aggregate ratio is a secondary factor in the flexural strength of concrete [38]. However, longer curing times were attributed to the higher resistance of concrete beam against bending under the applied load rather than the shorter curing times. Upon comparing the effects of each continuous variable on the response variable, the results in Figure 11 indicate that both A and B exhibited a higher magnitude of the main effect than C and T. Alkaline liquid to binder (A) and binder to aggregate (B) rates yielded a more significant difference between the vertical positions of the plotted points.

3.4. Establishment of desirable response value and operating conditions

3.4.1. Operating conditions of B and A on the flexural strength

Figure 12 shows the flexural strength with the binder-to-aggregate and alkaline liquid-to-binder proportions following the model equation. In contrast, both CCA/GGBFS ratio and curing time were kept constant. Figure 12 illustrates the visualized effect of both B and A on both 2D contour lines of the binder.

According to Figure 12, a higher flexural strength was attributed to the lower binder-to-aggregate and alkaline liquid-to-binder ratios at a constant of 80% GGBFS on day 56 of curing. However, any change in the hold values alters the shape patterns of the continuous variables. As shown in Figure 12, the darkest green area indicates the contour, which yields the highest flexural strength (12 MPa). Therefore, the resistance of the concrete beam against bending under the applied load can be maximized to around 0.20, 0.45, 0.20, and 56 for B, A, C, and T, respectively.

3.4.2. Operating conditions of C and A on the flexural strength

The effect of the interaction between C and A on the flexural strength of the concrete beam is illustrated in Figure 13. It was also revealed that the lower the proportions of both C and A in the concrete mix, the higher the flexural strength, while keeping both B and T constant at 0.23 and 56, respectively. The most upper flexural strength (15 MPa) was obtained around 70% GGBFS and 0.42 of A for the concrete mix at the constant values of 0.23 and 56 for B and T, respectively. Since the 2D contour plot is indicative of the minimax response surface [13], these proportions

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**Figure 11.** The main effect of continuous variables on the flexural strength.

**Figure 12.** Interaction between B and A on the flexural strength ($f_c$, MPa).

**Figure 13.** Interaction between C and A on the flexural strength ($f_c$, MPa).
can be selected for a flexural strength of concrete incorporating natural pozzolans and targeting 15 MPa.

3.4.3. Operating conditions of T and A on the flexural strength

The operating conditions of both T and A on the flexural strength, as given in Figure 13, pointed to almost the same interaction with the results presented in Figure 12. Figure 14 shows that a long curing time (T) and a low alkaline liquid to binder ratio (A) increased the flexural strength of concrete. The strength was maximum (12 MPa) around days 30–56 of curing and 0.45 of A, holding both binder to aggregate ratio (B) and C at 0.23 and 0.20 constant.

3.4.4. Operating conditions of C and B on the flexural strength

Figure 15 shows the interaction between C and B concerning the flexural strength of the concrete beam. It was revealed that a low proportion of binder-to-aggregate (B) increased the resistance of the concrete beam against bending at the constant values of both T and A. As reported earlier in Figure 11, the ratio (C) of binders had no significant effect on the yield of flexural strength, thus confirming the results given in Figure 15. Therefore, the highest flexural strength (10 MPa), as shown in the left-upper region (darkest green area) in Figure 15, was yielded around 0.40 of C and 0.20 of B, holding both A and T at the constant values of 0.54 and 56, respectively. Therefore, the interactive effects of the continuous variables (A, B, C, and T) on the flexural strength of concrete beam incorporated with SCMs using both 2-D contour lines would be conductive to not only the optimization of the mix design proportions for obtaining target and maximum flexural strength of GPC but also the implementation of future studies.

3.5. Optimization

Figure 16 presents the optimization results of the flexural strength based on the combination of desirability functions into composite desirability (D) in the stored models. Minitab 17 statistical software displays a global solution by default, which is the best of all local solutions. The universal solution combines the variable settings to obtain the desired responses. The desirability of each variable predicts how close the expected response is to the target requirements, and it is measured on a scale of 0 to 1. The vertical brown and horizontal blue lines, as shown in Figure 16, signified a current setting and a current response value, respectively. The current setting showed alkaline liquid-to-binder ratio (A), binder-to-aggregate ratio (B), CCA/(CCA + GGBFS) ratio (C), and curing time (T, day) as 0.42, 0.23, 0.20, and 90, respectively. It is shown that a current response (an optimized flexural strength of 10.52 MPa) could be obtained only at the minimized values of A, B, and C and a maximized value of T. In this respect, this current response demonstrated that A, B, C, and T obtained their ideal settings which could significantly optimize the flexural strength at these absolute values. Therefore, the flexural optimization results for the concrete strength supported a relationship, as illustrated in Eq. (5), such that D = 1 because the response r (10.52 MPa) was higher than the target (7.40 MPa). As given in Eq. (8), this relationship was employed to affirm the validity of the optimization parameters. The result yielded a flexural strength of 10.52 MPa, thus ensuring the accuracy of the optimized equation.

3.6. Relationship between experimental and optimized flexural strengths

Through the fitted linear regression equation, the relationship between the optimized flexural strength (Ofr) and experimental flexural strength (Efr) is given in Figure 17. The results indicated that there was a strong correlation between the optimized flexural and experimental flexural strength. The coefficient of determination (R²) also demonstrated that the model was 99.6% fit to predicting the relationship between Ofr and Efr at both 95% confidence and predictive intervals. Furthermore, the standard distance (S) of
Figure 16. Optimization results for the flexural strength ($f_r$, MPa).

Figure 17. Relationship between $O_f$ and $E_f$.

the response demonstrated that the data values were concentrated on the regression line; hence, the data values fitted the regression line and the model equation could significantly predict the response [39].

4. Conclusions

The present study evaluated the flexural strength of the concrete modified by both Corn Cob Ash (CCA) and Ground Granulated Blast Furnace Slag (GGBFS). The obtained results were compared with those of the control samples Portland Cement Concrete (PCC). In this study, while the flexural strength was maximized, the mix proportion properties were minimized. Finally, the following conclusions were made:

i. There was about 2–15%, 8–20%, and 5–16% increase in the compressive strength on day 28 of curing when GGBFS was replaced with 0–40 wt% CCA for concrete grades 25, 30, and 40, respectively, compared with the control (conventional) concrete;

ii. On day 28 of curing, there was about 1–26%, 10–14%, and 2–10% increase in the flexural strength ($f_r$) of Geopolymer Concrete (GPC) as the percentage substitution of CCA in the mix increased from 0–40% compared with PCC for concrete grades 25, 30, and 40, respectively;

iii. There was about 30% increase in the flexural strength when the strength was optimized at 0.42, 0.23, 0.20, and 0.90 for $A$, $B$, $C$, and $T$, respectively;

iv. There was a strong correlation between the experimental flexural and optimized flexural strength.

Given the limitations, this study suggests the benefits of focusing on three prospective solutions for further research. First, the model equation can be beneficial to the optimum design proportions of concrete beams, thus reducing the cost and time of carrying out laboratory experiments. Second, CCA and GGBFS utilization offers higher flexural strength than Portland Limestone Cement (PLC). Third, CCA and GGBFS can be used as natural pozzolans for further application.

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