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TECHNICAL PAPER

# Investigating the optimal combination for gravel and granite in blended palm oil fuel ash concrete

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**Abstract**

Global production of palm oil in 2022 was estimated at 73 million metric tonnes. The processing of palm oil generates a huge quantity of waste which is often left unprocessed leading to environmental pollution. Gravels are obtained from weathered rocks and are readily available and cheaper than granite as coarse aggregate in concrete. An innovative way of transforming waste into wealth is by incorporating these materials into concrete for construction purposes. Thus, this study was done to obtain an ideal combination of gravel and granite in palm oil fuel ash (POFA)-blended concrete. A water/cement (w/c) ratio of 0.5 in a nominal concrete mix ratio of 1:2:4 was adopted to achieve a strength of 20 N/mm$^2$. The central composite method of optimization was utilized in designing the experiments. The best combination was determined to be 67% gravel, 33% granite and 32% POFA. This combination produced concrete with compressive strength of 23.80 N/mm$^2$ which is 19% higher than the 20 N/mm$^2$ target strength.

**Keywords** Gravel · Granite · Palm oil fuel ash · Concrete · Compressive strength

## Introduction

Globally, concrete has been accepted and used widely in construction. Cement is a prime material used for bonding the other components of concrete [2, 6, 9, 17, 36, 37, 46]. Unfortunately, the production of cement in commercial quantities contributes significantly to the discharge of carbon dioxide ($CO_2$) into the air during the manufacturing process and through the large burning of fossil fuels. It is on record that the annual production of cement in the world makes up more than 8% of the universal expulsion of $CO_2$ in the air [5, 29, 43]. To resolve this global challenge, several attempts have been made to incorporate agricultural wastes into concrete since the application of these by-products will not only remove the additional cost of production but also lead to the conservation of the environment. Hence, the innovative method of using blended cement in construction is growing rapidly due to its benefits in saving energy, protecting the environment, saving cost and resource conservation.

As of 2022, the global production of palm oil was estimated to be 73 million metric tonnes [21]. About 70% of the raw materials from which palm oil is produced result in waste [22]. POFA is generated from the calcination of some components of palm trees such as palm oil fibre, palm kernel shells, and palm oil husk, which are considered wastes and often dumped in open spaces generating environmental pollution leading to health hazards [35]. However, several research findings such as that of Thomas et al. [50], Sanawung et al. [42] and Pone et al. [40] have revealed that

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POFA possesses high pozzolanic properties just like silica fume and thus can be used as a replacement for cement for construction purposes. They recommended the use of up to 5% in concrete for precast and prestressed girders. Sata et al. [44] reported cube strengths of 81.3, 85.9 and 79.8 MPa at 28 days when they used POFA of 10 microns particle size as 10%, 20% and 30% partial replacement of cement, respectively, in concrete. Khankhaje et al. [25] in their findings reported that the concrete containing 10% cement replaced with POFA has the same drying shrinkage as that of normal concrete. However, this result became slightly increased at 28 days of curing due to the surge in unground POFA in cement. They concluded that concrete containing POFA will require more volume of water compared with normal concrete and that the concrete's compressive strength declines with the rise in the percentage replacement of POFA. Abdul Awal and Shehu [1] and Ranjbar et al. [41] also opined that the workability and density of concrete decline as the proportion of POFA in it rises.

Altwair et al. [4], Aprianti et al. [7] and Noorvand et al. [33] reported that POFA has a greyish colour but after some time, this colour turns darker due to the increase in the volume of unburnt carbon. A good number of researches have been conducted on POFA as agro-waste ash with the intent of determining its usefulness as a probable replacement for cement in concrete production.

The chemical constituents contained in POFA are to a great extent affected by the volume of unburnt carbon in it. Table 1 shows the oxide composition in POFA as reported by some authors.

Aggregates are granular materials used in construction and are important components of concrete as they occupy about 80% of its total volume [13]. Therefore, the quality of aggregates has a huge effect on the properties of concrete [18]. As global concrete consumption increases so also will the depletion of abiotic resources, such as aggregates [12]. Aggregate may be manufactured, natural, or recycled. Researchers have suggested the use of earth materials for concrete production to reduce the cost of construction and environmental pollution [20, 27]. Granite and Gravels are natural aggregates used in concrete production. Babagana [10] reported that granite and gravel have a specific gravity of 2.76 and 2.59, Aggregate Crushing Value (ACV) of 25.54 and 35, and Aggregate Impact Value (AIV) of 14.5 and 16.2, respectively. Both conform to the requirements for aggregate as stipulated in BS EN 12620 [13]. The particle size distributions for granite and gravel as presented by Babagana [10] are shown in Figs. 1 and 2.

Gravels which are typically rounded in shape are weathered rocks usually having diameters greater than 2 mm. Big sizes are of gravel known as cobble, pebbles, or boulders. This predisposes them to use less quantity of cement paste. This results in saving about up to 5% cement paste [11]. Gravel is a cheaper aggregate when compared with granite [38]. Thus, obtaining the optimum mix ratio for the component materials that will give the maximum strength in concrete will be of great benefit to the construction industry.

Optimization is a means of determining the action that best achieves a desired objective or goal. It implies obtaining an action that minimizes or maximizes the value of an objective function [26]. Response surface method (RSM), a method of optimization, is a group of statistical and mathematical methods used for process optimization. The RSM is appropriate for formulating, designing, optimizing, and improving experimental processes, especially where test results are affected by several variable factors [15, 34]. The basic concept of RSM is to find the connection between independent and dependent variables, study their interactions and obtain their optimal responses [51]. By cautious design of experiments, the goal is to optimize an output variable which is influenced by numerous input variables [28]. RSM is often deployed in finding factors that produce the desired minimum, maximum, or optimum response, and to model the connection between the response and the quantitative factors [53]. Many researchers have deployed RSM

**Table 1** Composition of oxides in POFA

| Oxide composition (%) | Chindaprasirt and Rukzon [16] | Sata et al. [45] | Jaturapitakkul et al. [24] | Altwair et al. [3] | Hassan et al. [19] | Usman et al. [52] |
|---|---|---|---|---|---|---|
| $SiO_2$ | 63.60 | 65.30 | 65.30 | 66.91 | 55.50 | 63.70 |
| $Al_2O_3$ | 1.60 | 2.60 | 2.56 | 6.44 | 8.96 | 3.70 |
| $Fe_2O_3$ | 1.40 | 2.00 | 1.98 | 5.72 | 3.25 | 6.30 |
| CaO | 7.60 | 6.40 | 6.42 | 5.56 | 8.81 | 6.00 |
| MgO | 3.90 | 3.10 | 3.08 | 3.13 | 2.45 | 4.10 |
| $Na_2O$ | 0.10 | 0.30 | 0.36 | 0.19 | 1.10 | – |
| $K_2O$ | 6.90 | 5.70 | 5.72 | 5.20 | 7.81 | 9.15 |
| $SO_3$ | 0.20 | 0.50 | 0.47 | 0.33 | 2.11 | 1.60 |
| LOI | 9.60 | 10.1 | 10.05 | 2.30 | 4.20 | 8.00 |

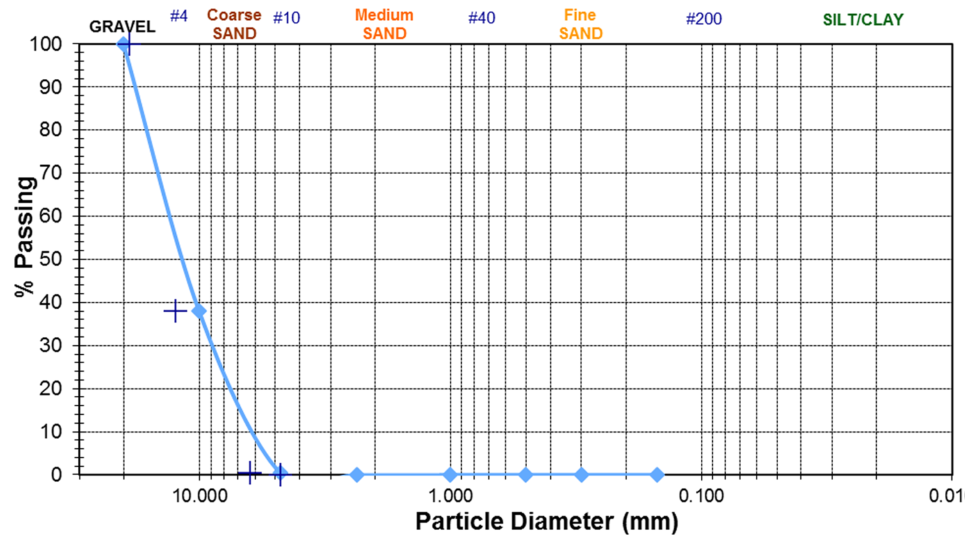


**Fig. 1** Particle size distribution for granite [10]

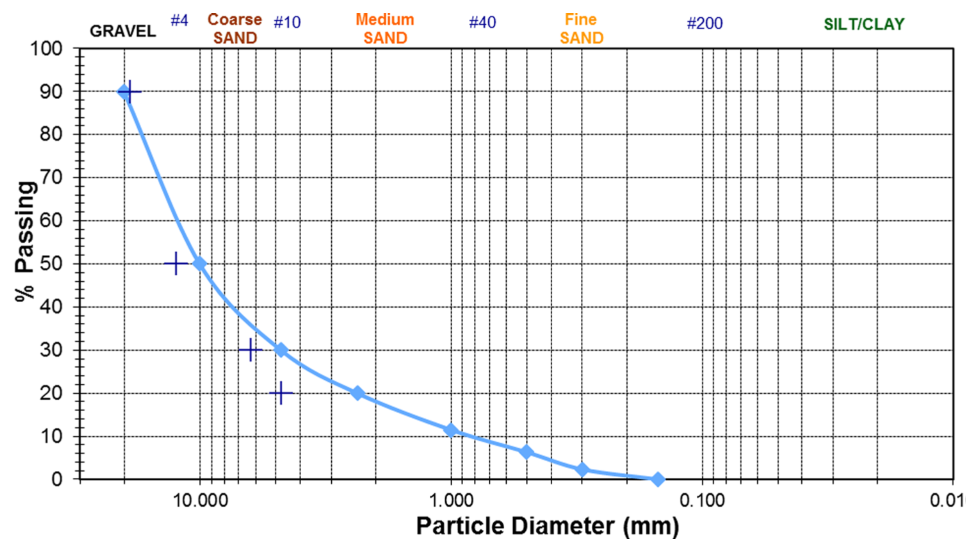


**Fig. 2** Particle size distribution for gravel [10]

in the modelling and optimization of concrete constituents [48].

## Methods and materials

Dangote brand of Ordinary Portland cement with 42.5R specification, meeting up to the requirements in NIS 444-1:2003 Standard [31] was adopted in this study. The fine aggregate utilized was river sand passing 5 mm sieve and retained on 2.36 mm sieve while the coarse aggregates are gravel and granite of 19 mm sieve size. All aggregates used conform to the requirements in BS EN 12620:2002+A1:2008 [13]. Water with a pH of 7 as recommended by Neville [30] and conforming to the requirements in NIS 554 [32] was utilized in mixing the concrete materials. The palm oil fibre incorporated into the mix was processed by washing and air drying before calcinating at 700 °C. This was done at the Mechanical Engineering Department, Foundry and Forging Workshop, Ramat Polytechnic Maiduguri. The ash gotten from the oven was allowed to cool before sieving it through BS sieve No 75 µm as recommended by Neville [30]. The specimen was subsequently inserted and sealed in a waterproof bag for preservation. It was analysed for its chemical composition at the Centre of Excellence, Nanotechnology and Advanced Material, National Agency for Science and Engineering Infrastructure (NASENI), Akure, Nigeria, using X-ray fluorescence (XRF) techniques.

Design Expert (Version 10) was used in designing the experimental matrix. RSM in central composite design (CCD) was utilized in optimizing the quantity of POFA, gravel, and granite for the concrete. Five levels of experiments were designed ($-\alpha$, $-1$, 0, $+1$, $+\alpha$) with POFA and Granite as the two independent variables. This resulted in

**Table 2** Designed experiment

| Variables | Parameters | Units | Codes | Levels | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | $-\alpha$ | $-1$ | 0 | $+1$ | $+\alpha$ |
| A | POFA | % | $X_1$ | 25 | 27.5 | 30 | 32.5 | 35 |
| B | Granite | % | $X_2$ | 0 | 25 | 50 | 75 | 100 |

**Table 3** Composition of oxides in POFA

| S/N | Chemical nomenclature | Chemical symbol | % POFA |
|---|---|---|---|
| 1 | Aluminium oxide | $Al_2O_3$ | 4.52 |
| 2 | Calcium oxide | $Ca_2O$ | 13.45 |
| 3 | Iron oxide | $Fe_2O_3$ | 4.86 |
| 4 | Magnesium oxide | MgO | 0.38 |
| 5 | Manganese oxide | MnO | 0.13 |
| 6 | Potassium oxide | $K_2O$ | 3.69 |
| 7 | Silicon oxide | $SiO_2$ | 65.02 |
| 8 | Sulphur trioxide | $SO_3$ | 11.07 |

thirteen (13) experimental investigations for slump height and compressive cube strengths of the concrete mix. A nominal mix ratio of 1:2:4 was adopted for a target compressive cube strength of 20 N/mm$^2$ for a fixed w/c of 0.5. Afterwards, the hardened concrete samples were subjected to compression testing at 7, 28, 56 and 90 days of curing to monitor the progression of their strength development. To optimize the variable quantities, the objective was to increase the percentage of POFA in the concrete and the resultant compressive cube strength while minimizing the percentage volume of granite, thus increasing the volume of the gravel to be used in the concrete mix. Table 2 presents a summary of the experimental design used for the study.

## Results and discussion

Table 3 presents the composition of the oxides in the tested POFA. The addition of the oxides of Silicon, Aluminium and Iron is 74.40%. The highest percentage of oxide in the ash was Silicon oxide ($SiO_2$). This satisfies the condition in ASTM C-618 [8] and BS EN 197-1 [14] for supplementary cementitious material. The oxide composition of the POFA is similar to that reported by Jamo et al. [23] and Syaizul et al. [49] but higher than the one reported by Panchal et al. [39].

The slump heights for the fresh concrete and compressive cube strengths for the hardened concrete for the different runs of experiments tested at 7, 28, 56 and 90 days are presented in Table 4. The slump height, which ranges from 76 to 92 mm, shows that the concrete produced was workable. This agrees with the findings of Sidek et al. [47] for similar percentage incorporation of POFA. It was noticed that the compressive strength increased progressively from the seventh day until the ninetieth day. The ninetieth-day

**Table 4** Slump heights and compressive strength of tested samples

| Std | Run | Factor 1 | Factor 1a | Factor 2 | Factor 2a | Response 1 | Response 2 (7 days) | Response 2 (28 days) | Response 2 (56 days) | Response 2 (90 days) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | A:POFA (%) | Cement (%) | Gravel (%) | B:Granite (%) | Slump height (mm) | Compressive strength (N/mm$^2$) | Compressive strength (N/mm$^2$) | Compressive strength (N/mm$^2$) | Compressive strength (N/mm$^2$) |
| 1 | 13 | 25 | 75 | 100 | 0 | 76 | 15.60 | 20.44 | 20.21 | 22.13 |
| 2 | 12 | 35 | 65 | 100 | 0 | 93 | 13.60 | 19.24 | 19.78 | 20.89 |
| 3 | 5 | 25 | 75 | 0 | 100 | 82 | 20.44 | 25.56 | 24.27 | 26.18 |
| 4 | 9 | 35 | 65 | 0 | 100 | 95 | 20.09 | 24.84 | 24.17 | 26.13 |
| 5 | 3 | 27.5 | 77.5 | 50 | 50 | 86 | 20.22 | 25.33 | 23.34 | 25.82 |
| 6 | 4 | 32.5 | 67.5 | 50 | 50 | 84 | 17.24 | 22.31 | 20.17 | 21.02 |
| 7 | 1 | 30 | 70 | 75 | 25 | 83 | 18.22 | 23.56 | 22.34 | 24.27 |
| 8 | 11 | 30 | 70 | 25 | 75 | 84 | 17.82 | 23.11 | 21.14 | 23.11 |
| 9 | 8 | 30 | 70 | 50 | 50 | 92 | 19.78 | 24.63 | 23.56 | 26.07 |
| 10 | 7 | 30 | 70 | 50 | 50 | 92 | 19.78 | 24.63 | 23.56 | 26.07 |
| 11 | 2 | 30 | 70 | 50 | 50 | 92 | 19.78 | 24.63 | 23.56 | 26.07 |
| 12 | 6 | 30 | 70 | 50 | 50 | 92 | 19.78 | 24.63 | 23.56 | 26.07 |
| 13 | 10 | 30 | 70 | 50 | 50 | 92 | 19.78 | 24.63 | 23.56 | 26.07 |

compressive strength is higher than the 28th-day strength reported by Panchal et al. [39]. This is expected as concrete comprising pozzolans are known to attain full strength at higher curing age [35].

## Model equations for slump height for fresh concrete and compressive cube strength for hardened concrete

Regression models were developed for slump height (fresh concrete) and compressive strength (hardened concrete) at 90 days of curing the samples. The equations revealed that the interactive factors are directly proportional to the responses considered in the experimental study. Models developed for slump height for the fresh concrete are shown in Eq. 1 while the model for the compressive strength at 90 days is presented in Eq. 2.

$$\text{Slumpheight} = +88.77 + 8.44A + 0.89B \quad (1)$$

$$\text{Compressivestrength} = +25.11 - 0.82A + 1.94B + 0.30AB - 1.26A^2 - 0.18B^2 \quad (2)$$

where $A$ = percentage of POFA (%); $B$ = percentage of granite (%).

## Impact of incorporating POFA and gravel–granite on the slump height of fresh concrete and compressive strength of hardened concrete

The three-dimensional relationships of POFA, gravel and granite on the height of slump for fresh concrete and compressive cube strength of hardened concrete are presented in Figs. 3 and 4. Figure 3 reveals that as the percentage of gravel in the concrete mix increased the slump height declined and reached the lowest height of 76 mm at 100% replacement of granite with gravel. This indicates that the concrete became less workable with the increase in the quantity of gravel. In the same manner, the slump height of the fresh concrete increased as the quantity of POFA in the concrete mix increased. The slump reached its peak at 35% incorporation of POFA, 0% of Gravel and 100% Granite. This result infers that the inclusion of POFA and Gravel in concrete reduced its workability and hence will require more water to make it workable.

From Fig. 4, it was discovered that the compressive strength of the hardened concrete increased as the percentage quantity of granite in the mix increased. Consequently, when the quantity of granite reduced (and the quantity of gravel increased), the concrete experienced a reduction in its compressive strength. Likewise, the increase in the percentage inclusion of POFA led to a decline in the compressive

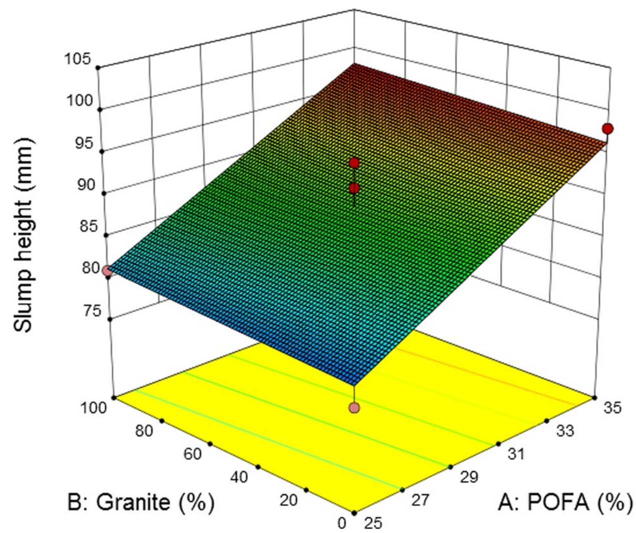


**Fig. 3** Slump height of fresh concrete incorporated with POFA, gravel and granite

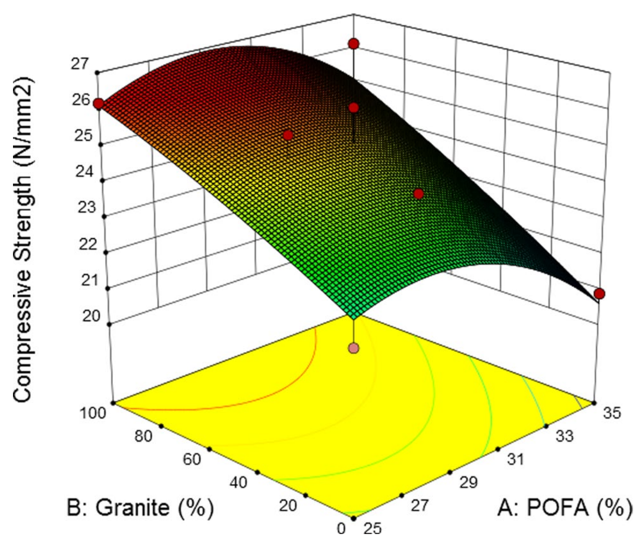


**Fig. 4** Compressive strength of hardened concrete incorporated with POFA, gravel and granite

strength of the concrete. However, for every combination of POFA, Gravel and Granite, the target compressive strength of 20 N/mm$^2$ was exceeded.

In getting the ideal combination for the materials in the concrete mix, the design function was to maximize the percentages of POFA and gravel and the compressive strength of the hardened concrete while the percentage of granite was minimized. The height of the slump for the fresh concrete was designed to range from 77 to 98 mm. These are the upper and lower limits of the slump heights gotten from the laboratory tests. Figure 5 presents the optimized results which reveal that at 32% POFA (68% cement) and 67% Gravel (33% Granite), a slump height of 92 mm for the

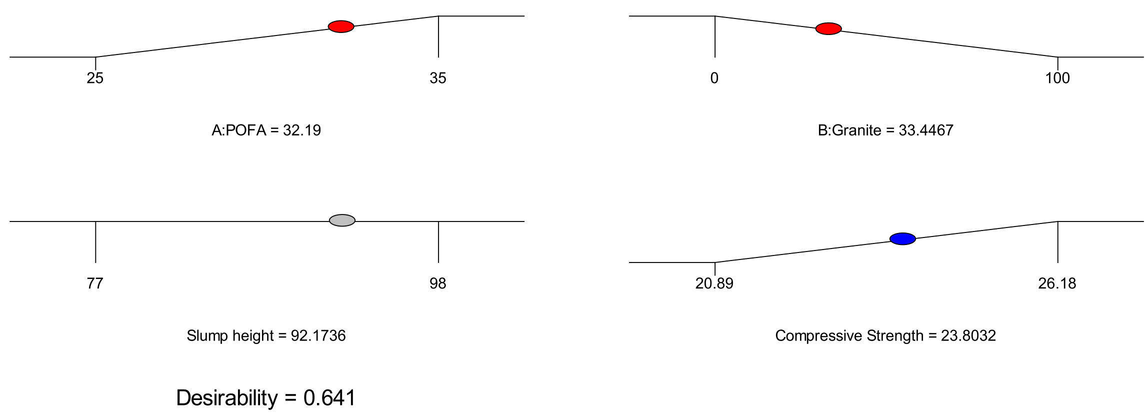


**Fig. 5** Optimized combination of POFA, gravel and granite blended concrete

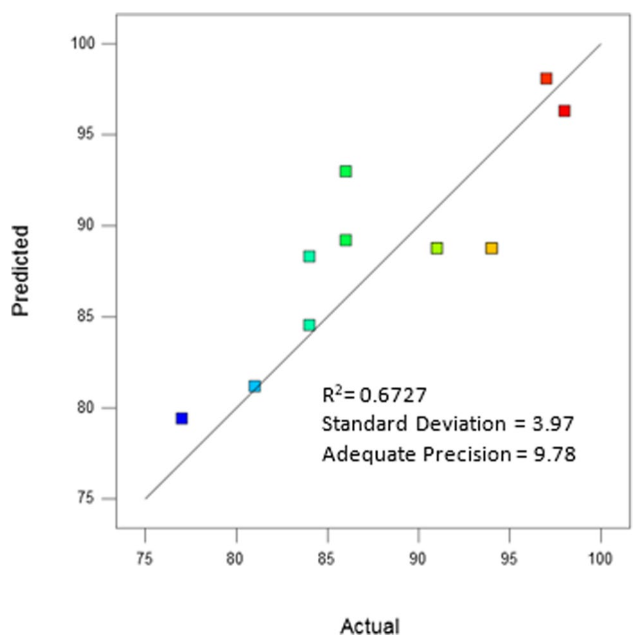


**Fig. 6** Relationship between predicted and experimental results of slump for the POFA, gravel and granite blended concrete

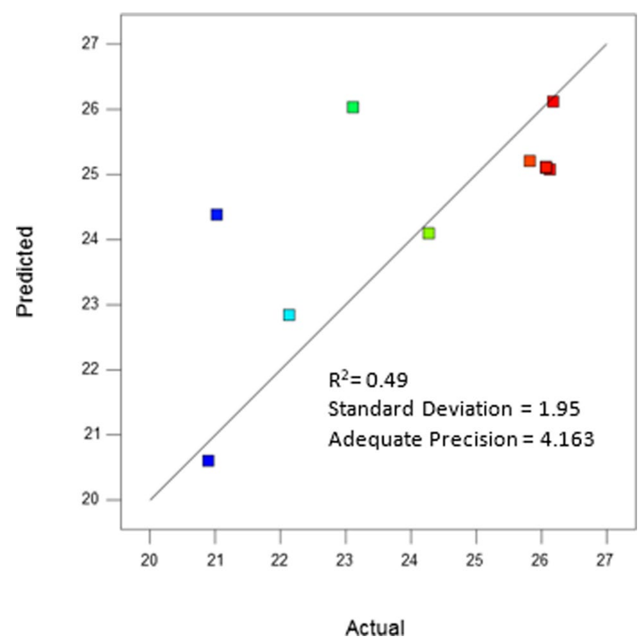


**Fig. 7** Relationship between predicted and experimental results of compressive strength for the POFA, gravel and granite blended concrete

fresh concrete and a compressive cube strength of 23.80 N/mm$^2$ will be obtained. This optimized strength is 19% higher than the target compressive cube strength of 20.0 N/mm$^2$ and 12% higher than the strength reported by Panchal et al. [39]. The slump height of 92 mm also indicates that the concrete is workable.

## Model validation

Figures 6 and 7 present the relationship that exists between the predicted and experimental values for the slump height of fresh concrete and the compressive strength for hardened concrete. The adequate precision value of 9.78 and 4.163 for the height of slump and compressive cube strength, respectively, is higher than 4.0 for both experiments. This is an indication that an acceptable signal-to-noise level exists, connoting that the model can be relied upon to pilot the design space, consequently, affirming the reliability of the model equations.

The $R^2$ value is an indication of the percentage of the variance in the dependent variable that the independent variables explain collectively. The low $R^2$ value is an indication that the materials used have an inherently greater amount of variation in their properties. However, each independent variable is statistically significant.

## Conclusion

This research considered the optimum combination of cement, POFA, gravel and granite in concrete to achieve a target compressive cube strength of Grade 20. The conclusions made from the study are:

1. POFA meets the requirement of being considered a pozzolan and is appropriate as supplementary cementitious material for use in concrete.
2. Inclusion of 32% POFA in place of cement, and 67% gravel in place of granite in concrete of 1:2:4 mix ratio at 0.5 water–cement ratio will result in concrete with a slump height of 92 mm and compressive cube strength of 23.80 N/mm$^2$. This optimized strength is 19% higher than the target compressive cube strength of 20.0 N/mm$^2$ and can be used for reinforced concrete production.

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**Data availability** Data sharing does not apply to this manuscript as no dataset was created during the study.

### Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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