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Research Article

Optimal water-cement ratio and volume of superplasticizers for blended cement-bamboo leaf ash high-performance concrete

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Abstract

Attention on the use of High-Performance Concrete (HPC) for construction works has soared considerably due to the need for large volume of concrete with high level of strength for such works. The mechanical properties of HPC with Bamboo Leaf Ash (BLA) as partial replacement of cement with varying proportions of superplasticizer and water-cement ratio was investigated in this paper. The percentage of BLA was fixed at 5%, while the proportion of superplasticizer ranged from 0 to 1.5% by weight of cement. The concrete mix was designed to attain a characteristic strength of 41 N/mm^2 after 28 days of curing. X-ray Fluorescence (XRF) and X-ray Diffraction (XRD) were employed in determining the chemical constituents and crystallinity of the BLA respectively. The slump of the fresh HPC was also established. Concrete cubes (for water absorption and compressive strength) were cast and immersed fully in water for 56 days. Water absorption and compressive strength were established on the fully cured HPC. The optimal combination of materials at the end of the curing period is 0.360 water-cement ratio at 0.128 % superplasticizer. This resulted in a slump height of 49 mm, compressive strength of 53.61 N/mm^2 and 4.77% water absorption capacity.

1. Introduction

Büyüköztürk and Lau [1] and Odeyemi *et al.* [2] defined HPC as concrete that has high workability, strength and durability. It is made from appropriate materials combined based on a designed mix, properly and thoroughly mixed, conveyed, delivered, consolidated, and cured such that the concrete produced will provide exceptional behaviour in the structural element wherein it is used, the environment where it is placed and the loads that it is subjected to throughout its service life. Several factors affect the mix proportions for HPC. These include locally available materials, specified performance properties, personal preferences, local experience, and cost. Technology has helped to advance the use of many products in enhancing the properties of HPC. HPC has been primarily applied in structures needing prolonged service lives such as long-span bridges, oil drilling platforms, and parking structures. Büyüköztürk & Lau [1] reported that High Strength Concrete (HSC) and HPC may be regarded as synonymous. Reducing the water-cement ratio in HPC, a requirement in attaining high strength, largely enhances the properties of the concrete.

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In Nigeria, adequate shelter remains a basic need of people which has remained unsatisfied [3]. With research findings on the suitability of bamboo as a building material for use in low-cost domestic houses, the probability of average Nigerians hoping to have their houses has increased. Akeju & Falade [4] submitted that bamboo is cheaper, locally sourced, and a better substitute to steel reinforcement in columns and beams in residential houses because it has relative advantages over steel reinforcement. It does not suffer corrosion; it contains high fibre content and high water absorption capacity.

BLA is obtained from the calcination of bamboo leaves. The resulting ash components from the calcination of the bamboo leaves contain inorganic elements, mainly, potassium, silica, manganese, calcium and magnesium [5]. At early age, it is highly reactive, and its pozzolanic properties are like silica fume [6].

Asha et al. [7] examined the effect of incorporating BLA in concrete and their findings showed that due to the amorphous nature and the high silica content in BLA, it can be considered as a pozzolanic agricultural waste. However, their work did not report the water-binder ratio adopted nor the dosage of superplasticizer used. Onikeku et al. [8] examined the mechanical, physical, and durability properties of HPC by partially substituting cement with BLA calcined at 650°C at 0, 5, 10, 15, and 20% sequentially. Their work adopted a water-cement ratio (w/c) of 0.5 while the volume of superplasticizer used was varied. Their findings were that BLA enhanced the flexural, split tensile, and compressive strengths of the concrete at a benchmark of 10% as the optimal replacement level of cement with BLA. Further increase in BLA content reduced the slump, compacting factor, consistency, setting time, water absorption, compressive, split tensile and flexural strengths of the concrete.

Olutoge and Oladunmoye [9] also used BLA as supplementary cementitious material in concrete. They adopted a w/c of 0.5 without using superplasticizers. The authors concluded that the inclusion of BLA in concrete up to 20% can aid the compressive strength and workability of concrete. Dhinakaran and Chandana [5] also used BLA in concrete. They adopted a w/c of 0.5 without superplasticizers to produce concrete with a target strength of 25.8 MPa. They opined that 15% replacement of cement with BLA is the optimum.

Hunchate et al. [10] considered HPC containing superplasticizer and silica fume. They used a w/c of 0.29 and 5.11 kg of superplasticizer per meter cube (m3) of concrete for a target strength of 69 Mpa. They observed an increase in the compressive strength of the resulting HPC as the content of the silica fume increases to 15%. Dembovska et al., [11] studied the influence of pozzolanic additives on the growth in strength of HPC. A varying water-cement ratio ranging from 0.21 – 0.38 was adopted while a superplasticizer dosage of 0.5 kg per cubic metre of concrete was used. Their findings reveal that the inclusion of 10% silica fume by weight of cement resulted in the increase of the compressive strengths and bending of the HPC at 56 days of testing.

Latha et al. [12] conducted an investigation on HPC using waste materials such as slag sand and Bagasse ash obtained from some industries at varying percentages. Bagasse ash was partially used to replace cement while sharp sand was replaced with slag in varying proportions. A water-cement ratio of 0.34 and 1% of superplasticizer by weight of cement was adopted in the research. Their findings reveal that the use of 15% slag sand and 8% bagasse ash in concrete as a fractional replacement of cement increases its compressive strength. Increasing the quantity of the additives beyond these percentages resulted in a decline in the total strength of the concrete produced.

Odeyemi et al. [2] examined the compressive, splitting tensile, and flexural strengths of HPC containing Guinea Corn Husk Ash (GCHA) as an additive. A w/c of 0.31 and a superplasticizer dose of 1% by weight of cement was adopted in their research. They recommended up to 10% GCHA as a partial substitute for cement in the production of HPC.

Zhutovsky and Kovler [13] studied the effect that w/c has on the effectiveness of internal curing of HPC. They used differing w/c of 0.21, 0.25 and 0.33. They concluded that w/c has a substantial consequence on the cracking potential of concrete cured internally.

Some researchers such as Richard and Cheyrezy [14], Larrard and Sedran [15], Droll [16], Wen-yu et al. [17], Gao et al. [18], Wille et al. [19], and Shi et al. [20] suggested water-cement ratios ranging from 0.08 - 0.25 for use in the production of HPC. Also, a dosage of superplasticizers ranging from 1 to 8 % by weight of cement has been recommended by Schmidt et al. [21] and Wille et al. [19].

In view of the benefits of using HPC, several studies have considered the development of a rational or standardized method of concrete mix design for HPC using varying water-binder ratios and dosages of superplasticizers. However, no optimal quantity of both is currently available. Hence, there is a need to investigate the water-cement ratio and dosage of superplasticizer for blended Cement-Bamboo leaf ash HPC. Therefore, this study determined the optimal water-cement ratio and dosage of superplasticizers for cement-BLA blended HPC.

2. Research Methodology

2.1 Experimental Design

Design Expert (Version 12) was used to design the experimental setup where an RSM in a Central Composite Design (CCD) was utilized in optimizing the BLA, Superplasticizer percentage and w/c. The CCD entails that before carrying out the benchwork in the laboratory the mix combinations should be designed. Two independent variables, Superplasticizer (0-1.5%) and water Cement ratio (0.36 - 0.4) with 13 experimental runs, with 5 repeated runs for slump height, compressive strength, and water absorption were conducted in this study. The adopted mix proportion for cement, fine and coarse aggregates was 1:0.5:1. Batching was done by weight. Fig. 1 displays the design interface of the Design Expert.

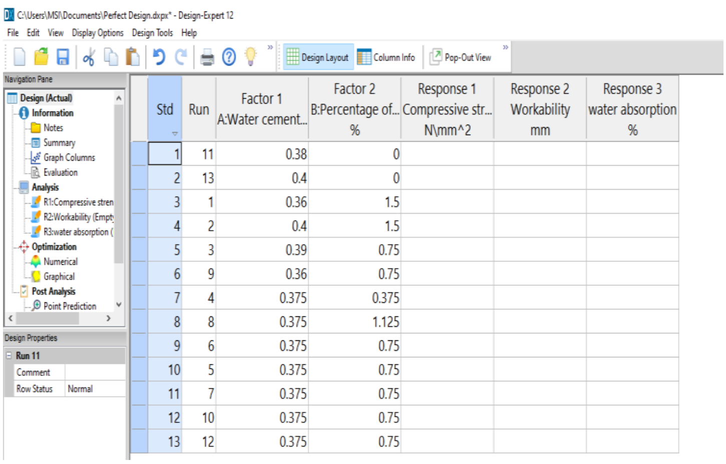

Fig. 1 Design Expert Interface

There were nine different concrete mixes from which eighty-one concrete cubes were cast for compressive strength test; eighteen cubes were cast for water absorption capacity test.

The samples were immersed fully in water for a total period of 56 days respectively with testing done at 7, 28 and 56 days.

2.2 Materials

The materials used in this study include Portland limestone cement of Dangote brand, fine aggregate (natural river sand), coarse aggregate (granite), COSTAMIX 200R Superplasticizer, water, and Bamboo Leaf Ash (BLA). The Bamboo Leaves (BA) calcinated to produce the BLA and the BLA used in the study are presented in Fig. 2 and 3.

Fig. 2 Bamboo leaves before calcination

Fig. 3 Bamboo leaf ash

2.3. Experimental Investigations

2.3.1 Properties of Materials Used

The natural river sand passed through a sieve of aperture size of 4.75 mm and had a fineness modulus of 3.76. The coarse aggregate had a maximum diameter of 10 mm and specific gravity of 2.63. Both properties conform to the standard stated in BS 12390 [22]. The Portland limestone cement was of Grade 42.5R with a specific gravity of 2.84. The potable water used in mixing the concrete had a pH of 7. The COSTAMIX 200R Superplasticizer conformed to ASTM [23] and the Bamboo leaf ash (BLA) had a specific gravity of 2.80. A summary of the materials used is presented in Table 1.

Table 1. Properties of materials used

Tests	OPC	Fine aggregates	Coarse aggregates
Fineness (%)	8.3		
Specific Gravity	3.10	2.66	2.63
Fineness Modulus		2.99	7.16
Water absorption (%)		0.4	0.3
Loose Bulk density (kg/m^3)		1446	1484

The Bamboo leaves (BL) were calcined to ashes at a temperature of 650 ˚C as recommended by Onikeku et al. [8], in a blast furnace at the Fabrication Workshop, Department of Mechanical Engineering, Institute of Technology, Ilorin, Kwara State. A milling machine was used to further ground the ashes into finer particles before passing them through a sieve of 90 μm aperture size.

2.3.2 Standard Consistency and Fineness of Cement

A standard consistency test was done to find the volume of water needed to yield a paste of standard consistency. This test conformed to BS EN 196-3 [24]. The fineness test of cement was carried out using British standard sieves. The weight of cement with particle size greater than 90 microns was determined after which the percentage of cement particles retained was calculated. The cement particles were placed in a sieve and unceasingly sieved by vertical and circular motion for 15 minutes. The residue retained on the sieve after the operation was weighed and recorded. The fineness of the cement was obtained from Equation 1.

$$\text{Fineness of cement (\%)} = \frac{Weight\ of\ retained\ cement}{initial\ weight\ of\ cement}\ X\ 100 \quad (1)$$

2.3.3 Specific Gravity of Aggregates

The test to determine the specific gravity of the aggregates was performed as stipulated in BS EN 1097-2:2010. The samples were screened thoroughly on a 20 mm sieve to remove all deleterious and unwanted particles. An empty bottle was weighed and recorded as W_1. The sample was transferred into the empty bottle, weighed, and designated as W_2. The bottle was gradually filled with distilled water to a marked gauge. Thereafter, the bottle was shaken to remove bubbles on the surface of the sample and entrapped air and the weight was recorded as W_3. Afterwards, the bottle was emptied, and oven-dried. It was then filled with distilled water to the marked gauge, weighed and designated as W_4. Equation 2 was used to determine the specific gravity.

$$\text{Specific Gravity} = \frac{W_2 - W_1}{(W_4 - W_2) - (W_3 - W_2)} \quad (2)$$

2.3.4 Chemical Composition, Crystallinity, and Micrograph of Samples

The oxide composition and crystallinity of the BLA were determined at the Umaru Musa Yar'adua University Katsina, Nigeria, using an Energy Dispersive X-ray Fluorescence (XRF) Spectrometer with model number Skyray EDX 3600B, and EMPYREAN Diffractometer system EMPYREAN for X-ray Diffraction (XRD) respectively. Scanning Electron Microscopy (SEM) for pozzolanic properties was carried out at Kwara State University, Malete with the aid of a Scanning Electron Microscope with model number ASPEX 3020 at an accelerating voltage of 16.0 kV. A Blazer's sputtering device was used to coat the samples with gold before they were observed under a microscope.

2.3.5 Slump Determination (Workability)

The slump test was carried out on the fresh HPC in conformity to BS EN 12350-2 [25]. The mould was placed on a clean, smooth, horizontal, and non-porous base plate. Concrete was filled into the test mould in three layers with the base held firmly in place using the handles. Each of the layers was compacted uniformly with a rounded end 15 mm steel rod 25 times. Excess concrete at the top of the mould was removed, and the surface levelled. Afterwards, the mould was gradually lifted in the vertical direction while the unsupported concrete slumped. The slump in height at the mid-point of the concrete was measured to the nearest 5 mm.

2.3.6 Compressive Strength Determination

The compressive strength was done in line with BS EN 12390-3 [26]. After 24 hours, the concrete samples were demoulded and fully immersed in water for curing. Only in cases of concrete having a high percentage of superplasticizer were the test specimens left to harden for 48 hours before curing. The specimens were tested for their compressive strength at 7-, 28- and 56-days of curing. The load was applied gradually at the rate of 140 kg/cm^2 per minute till the specimens failed. The compressive strength was determined using Equation 3.

$$\text{Compressive strength } (\text{N}/\text{mm}^2) = \frac{\text{Maximum load (kN)} \times 1000}{\text{Cross} - \text{ sectional Area (mm}^2\text{)}} \quad (3)$$

2.3.7 Water Absorption Capacity

The water absorption capacity test was carried out as stipulated in ASTM C642-06 [27]. The specimen was dried in an oven at 100 ^{0}C for a period of 48 hours and weighed. The weight was designated as W_1. Subsequently, the sample was immersed in water for another 48 hours. The samples were weighed at intervals until a constant mass was obtained which was designated as W_2. Equation 4 was adopted in determining the water absorption capacity of the sample.

$$\text{Water absorption capacity } \% = \frac{W_2 - W_1}{W_1} \text{X } 100 \quad (4)$$

2.3.8 Material Optimization

In optimizing the w/c and percentage of superplasticizer, the goal was to maximize the compressive strength of the concrete while keeping the variables in range. The 56th-day compressive strength results were used.

3. Results and Discussions

3.1 Material Properties

The values obtained for each of the investigations fall within the recommended values by the Standards used for this study: fineness of cement was less than 10%; specific gravity of less than 3.15 and 3.0 for cement and aggregates respectively; fineness modulus of 2.3 - 3.1 and 5.5 – 8.0 for fine and coarse aggregates respectively; and water absorption less than 3% and 0.8% for fine and coarse aggregates respectively.

3.2 Chemical Composition, Crystallinity, and Micrograph of samples

Fig. 4 shows the XRD pattern of the BLA where main Crystalline components sylvite (K_4C_{14}) peaks at 28.440 and 40.53 2θ, Quartz (Si_3O_6) peaks at 26.729 and 40.531 2θ and Calcite ($Ca_6C_6O_{18}$) peaks at 29.37 2θ. This result is similar to the one obtained by Ikumapayi [28]. Fig. 5 shows the SEM images of BLA. The BLA is closely packed, robust-like and honey-combed shaped at a magnification of 750. This is similar to the findings of Ikumapayi [28]. Table 2 shows that the addition of the oxides, Al_2O_3, Fe_2O_3, and SiO_2 of BLA utilized in this research, is 70.23 % with SiO_2 having the highest percentage of the oxide composition. This percentage requirement satisfies the requirement of a minimum of 70% for a supplementary cementitious material specified in ASTM C-618 [29] and BS EN 197-1 [30]. Likewise, the percentage composition of SO_3 of 0.43% and Loss of Ignition (LOI) of 6.7% are lesser than the highest limit of 4% and 10% respectively stipulated for pozzolanic additives in ASTM C-618 [29]. These corroborate that BLA is appropriate as pozzolan in concrete. These findings are also in agreement with the submissions of Olutoge and Oladunmoye [9], Adewuyi and Umoh [31], Dhinakaran and Chandana [5] and Asha et al. [7].

3.3 Workability

The 3D image of the connection between the slump height of HPC with varying w/c and varying percentage of superplasticizer is presented in Fig. 6. The slump height was highest at 1.5% dosage of superplasticizer and declined as the percentage of superplasticizer decreased. Likewise, the slump height increased as the water–cement ratio increased. The graph further reveals that the dosage of superplasticizer has the greatest impact on slump height than the water-cement ratio, thus, improving the workability of the concrete.

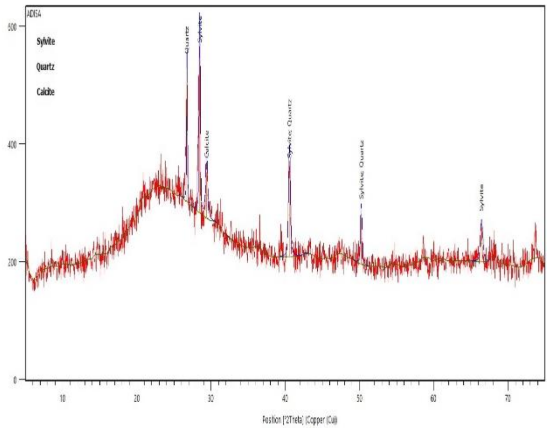

Fig. 4 XRD pattern of BLA

Table 2. Oxide composition of BLA

S/No	OXIDE	PERCENTAGE (%)
1	SiO_2	49.438
2	Al_2O_3	20.2033
3	K_2O	7.321
4	Cl	6.9117
5	CaO	2.598
6	MgO	1.90
7	P_2O_5	1.886
8	CeO_2	1.694
9	Fe_2O_3	0.5914
10	SO_3	0.4261
11	MnO	0.2656
12	L.O.I	6.7

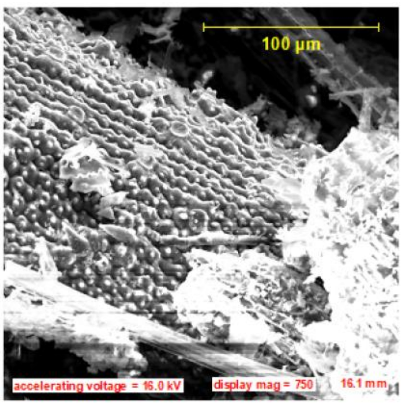

Fig. 5 SEM images of BLA

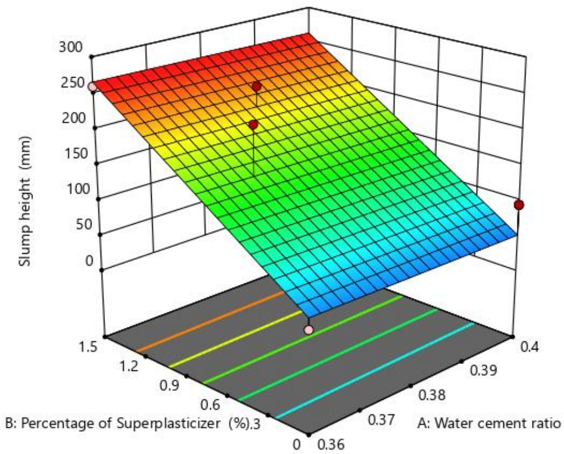

Fig. 6 3D relationship of slump height with varied percentage of superplasticizer and water-cement ratio

3.4 Compressive Strength

Fig. 7 reveals that the compressive strength of HPC after curing for 7 days declined as the measure of superplasticizer increases. Likewise, the compressive strength declined as the w/c increased from 0.36 to 0.38. A high dosage of superplasticizer and w/c had an adverse impact on the compressive strength of the BLA-HPC.

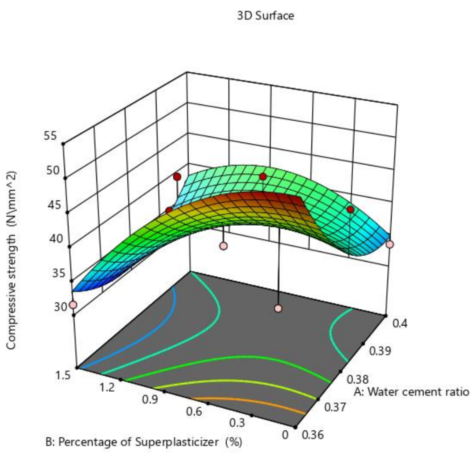

Fig. 7 Compressive strength of BLA-HPC after curing for 7 days

Fig. 8 shows the impact of w/c and percentage quantity of superplasticizer on the compressive strength of HPC after curing for 28 days. The result follows the same trend as was observed in the result obtained on the 7th day of curing.

Fig. 9 displays the 3D connection between compressive strength of HPC at 56 days with w/c and the percentage of superplasticizer. The result follows the same pattern as that of the results obtained on the 7th and 28th days of curing. Therefore, the higher the w/c and dosage of superplasticizer, the lower the strength of the BLA-HPC.

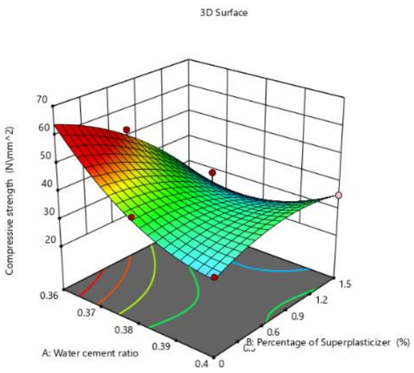

Fig. 8 Compressive strength of BLA-HPC after curing for 28 days

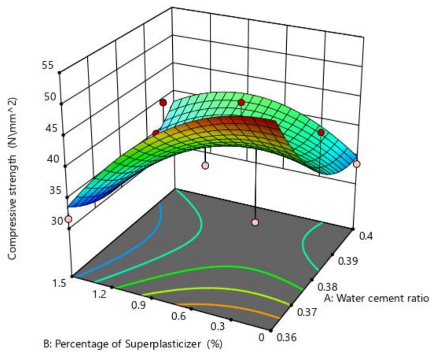

Fig. 9 Compressive strength of BLA-HPC after curing for 56 days

3.5 Water Absorption

Fig. 10 displays the relationship between the water absorption of 56 days cured HPC with the water-cement ratio and percentage of superplasticizer. The water absorption was highest at 1.5% percentage of superplasticizer, the water absorption was lowest at a water-cement ratio of 0.36 and highest at 0.4. Thus, a high dosage of superplasticizer increases the water absorption of HPC. However, the w/c has minimal influence on the water absorption of high-performance concrete.

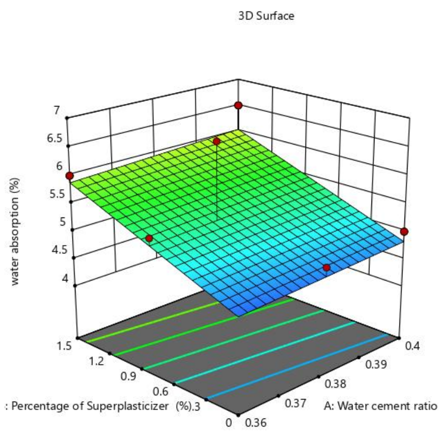

Fig. 10 Water absorption of BLA-HPC

3.6 Material Optimization

Using the test results obtained at 56 days of curing, the materials used for the HPC were optimized as shown in Fig. 11. It was discovered that to maximize the compressive strength of the concrete the optimal combination for the HPC is 0.360 w/c at 0.128 % superplasticizer. This resulted in 49 mm slump height, compressive strength of 53.61 N/mm2 and 4.77% water absorption capacity. The compressive strength attained in this study is higher compared to that obtained by Onikeku et al. [8]. However, the study of Onikeku et al. (2019) did not go beyond that of normal concrete having a maximum compressive strength of 38.5 N/mm^2 (gained at 10% BLA) and curing age of 28 days.

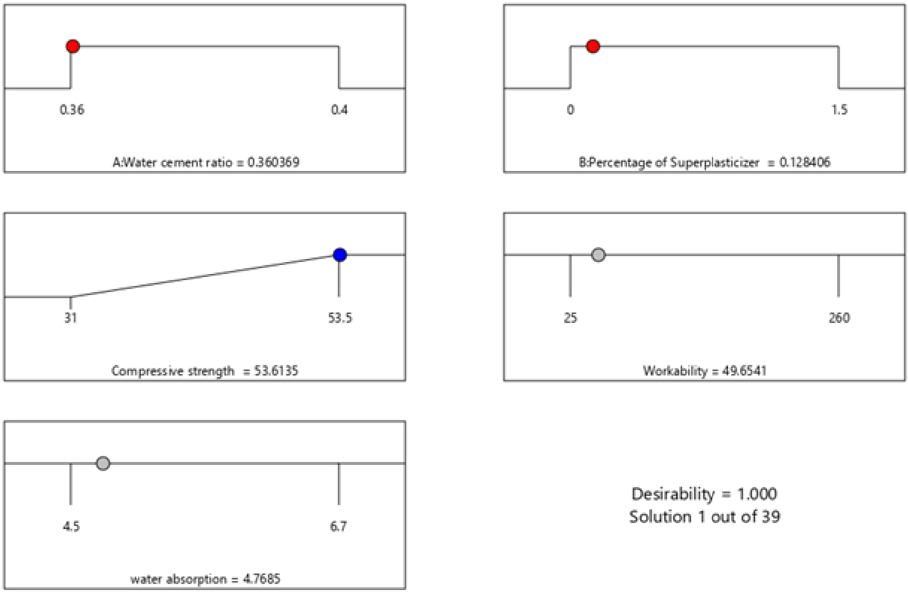

Fig. 11 Optimization of materials

3.7 Normal Probability Plot

The normal probability plot for compressive strength and workability was carried out to determine the normality of the residuals. The plots presented in Fig. 12 and 13 respectively show that normality has been satisfied since most of the plotted points are very close to the fitted line of the distribution. This implies that the normal distribution plot was able to analyze interested responses and explain the variation of the dependent variables and the effectiveness of the model [32,33].

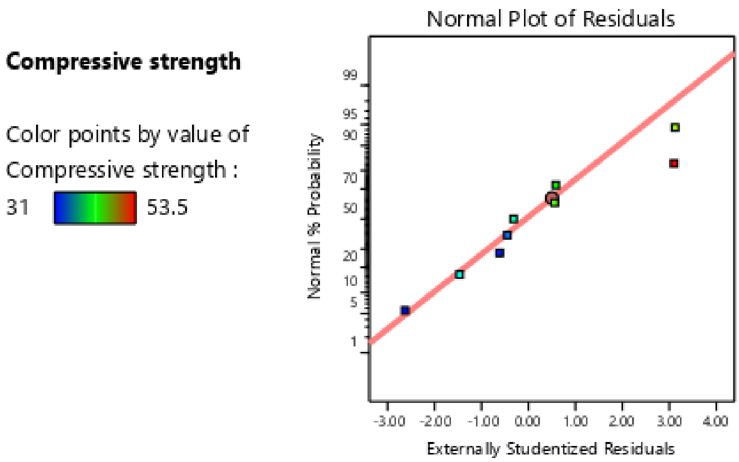

Fig. 12 Normal plot for compressive strength

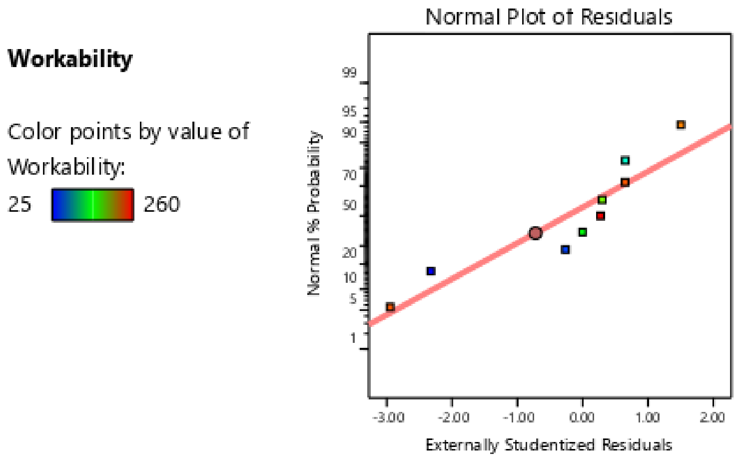

Fig. 13 Normal plot for workability

4. Conclusions

The need for High-Performance Concrete in construction works has increased in recent years. This is mainly due to the demand for large quantity of concrete with a high level of strength for such works. Lots of research have delved into the development of standardized methods of concrete mix design for HPC by adopting different water-binder ratios and dosages of superplasticizers. Nevertheless, none of these studies has reported an optimal quantity for both. Therefore, it is expedient to investigate the water-cement ratio and dosage of superplasticizers for blended Cement-Bamboo leaf ash HPC. For this reason, this study determined the optimal water-cement ratio and dosage of superplasticizers for cement-BLA blended HPC. The percentage of BLA was fixed at 5%, while the percentage of superplasticizer ranged from 0 to 1.5% by weight of cement. The mix of the concrete was designed to attain a strength of 41 N/mm^2 at 28 days of curing in water. XRD and XRF were employed in obtaining the crystallinity and the chemical constituents of the BLA respectively. The slump of the fresh HPC was also obtained. Concrete cubes were cast and immersed fully in water for 56 days. Water absorption and compressive strengths were established on the fully cured HPC. The inferences drawn from the study are:

- BLA is suitable as a pozzolan in HPC because the addition of the percentages of the oxides of aluminium, ferric and silicon oxides is higher than the minimum 70% stated in BS EN 197-1 [34] and ASTM C618 [29] for supplementary cementitious materials.
- A high dosage of superplasticizers improves the workability while low w/c reduces the workability of the HPC.
- Extreme dosages of superplasticizer decrease the compressive strength of the BLA-HPC while the low water-cement ratio increases its compressive strength.
- High dosages of superplasticizer increase the water absorption capacity of BLA-HPC. However, the w/c has minimal influence on the water absorption of high-performance concrete.
- An optimal combination of the constituent materials of the HPC after curing for 56 days gives 0.360 w/c at 0.128% superplasticizer. This resulted in 49 mm slump height, compressive strength of 53.61 N/mm^2 and 4.77% water absorption capacity.

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