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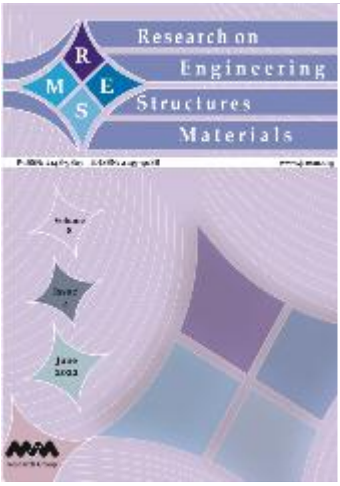

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Research Article

Performance of high strength concrete containing locust bean pod ash as cement replacement

Felix Nkapheeyan Isa[*1,a], Megat Azmi Megat Johari[1,b], Iorwuese Anum [2,c], Julius Lananzakan Agabus [2,d] , Solomon Maxwell Soji[2,e], Changlia Hassan Salihu[1,2,f]

[1]*School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal 14300, Malaysia*
[2] *Department of Building, Modibbo Adama University, Yola, Nigeria*

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Abstract

High-strength concrete (HSC) is becoming popular as a result of its great strength and superior durability. Despite the fact that several supplementary cementitious materials (SCMs) have been explored in HSC, the use of locust bean pod ash (LBPA) as an SCM has not been considered. This study evaluated the use of LBPA as an SCM in HSC. The locust bean pod (LBP) underwent a two-hour calcination process in a furnace at a temperature of 600 °C. At 5%, 10%, 15%, and 20% by weight of cement, LBPA was used in place of cement. The slump, strength (compressive: 100 × 100 × 100 mm cubes; flexural: 100 × 100 × 400 mm beam, and splitting tensile: 100 × 200 mm cylinder at 28 days), water absorption, resistance to sulfate and the effects of elevated temperatures were assessed. Mechanical properties of the concrete were statistically analyzed and optimized using linear Regression. The results showed that 5% LPBA replacement improved compressive, flexural and tensile strengths by 13.14%, 6.42% and 7.08% respectively over the control samples. Additionally, LBPA improved the performance of concrete against water absorption, sulphate attack, and elevated temperatures. The optimized model of 15% LBPA had the highest accuracy with percentage errors of 5.89% and 2.78% for compressive and flexural strengths respectively, while 5% had the highest accuracy for tensile strength with percentage error of 3.08%. The study concludes that LBPA can be successfully used as an SCM in HSC, with a 10% recommended optimum replacement amount.

1. Introduction

Due to urbanization, population expansion, and infrastructure development, concrete production has steadily increased over the past few decades; thus, concrete remains the most extensively utilized building material on the planet [1], [2]. Hence, the manufacturing of cement, which is the most crucial component of concrete which has increased to 3,500 million tons in 2020 and is anticipated to hit 3,700–4,400 million tons by 2050 [3]. This increase in cement production has a corresponding negative effect on the environment. The production of cement alone produces 1,350 million tons of greenhouse emissions annually according to estimates [4]. Also, around 110kWh of energy and 1,500 kg of primary ingredients are needed to produce one ton of cement [5]. Moreso, the construction industry alone contributes to 50% global CO_2 emission [6]. This environmental concern coupled with high cost of cement has led to the development of alternative construction materials. The shift from conventional to alternative materials is aimed principally at conservation of the environment, energy and natural resources associated with cement

*Corresponding author: nkapheeyan@student.usm.my
[a] orcid.org/0000-0002-2641-3714; [b] orcid.org/0000-0001-6490-4074; [c] orcid.org/0009-0002-4287-8164; [d] orcid.org/0009-0008-7261-4016; [e] orcid.org/0000-0002-7349-9573; [f] orcid.org/0009-0006-3942-1496
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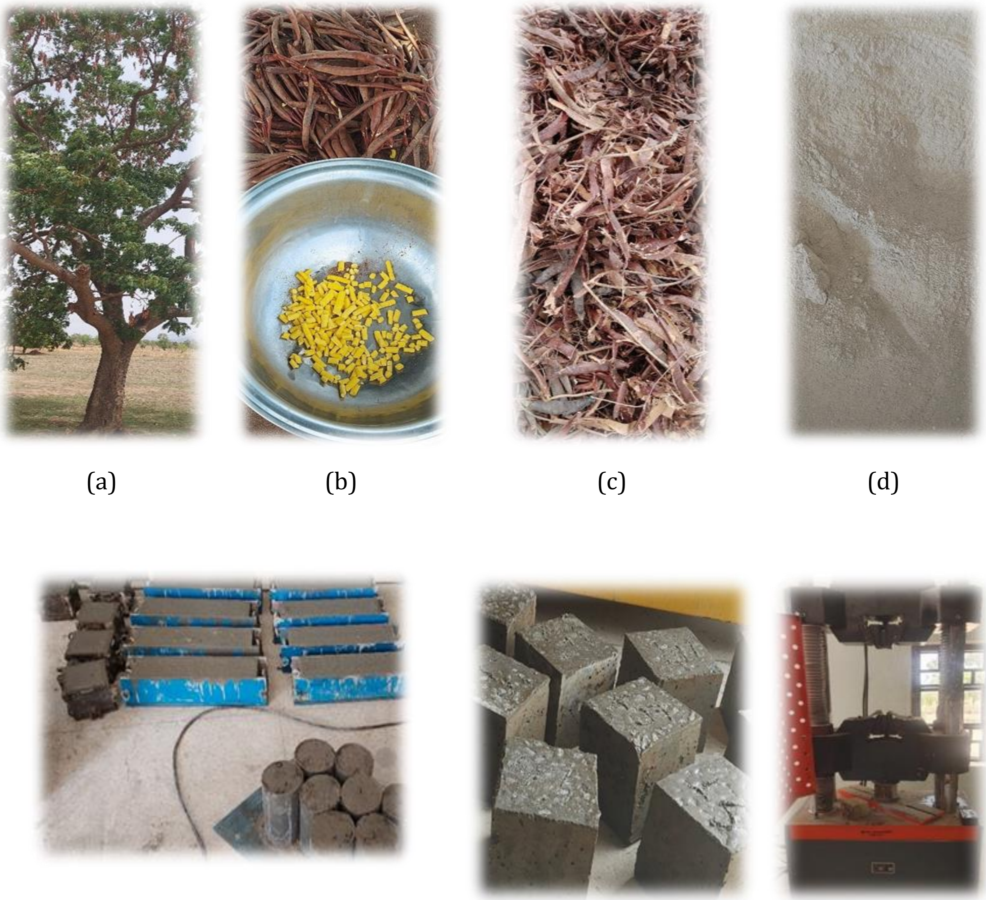
production as well as cost reduction [7]–[10]. To achieve the above objectives, SCMs have been consistently used to reduce cement consumption in concrete production [11], [12]. Agricultural wastes and industrial byproducts have been utilized as SCMs in concrete production with resultant positive effects [12]–[17].

Concrete that has a defined compressive strength of 55 MPa or more is termed high strength concrete (HSC) [18]. It is characteristically used in applications where high strength and/or durability are required, such as high-rise buildings and bridges. It is advantageous over normal concrete due to better workability, greater strength and improved durability [19]. Pozzolans, such as fly ash and silica fume, are commonly employed as SCMs in HSC. These compounds enhance the strength of concrete by interacting with the hydration products of Portland cement, resulting in the production of more C-S-H gel, which is the constituent responsible for providing concrete with its strength [20]. For instance, in their study, [19] included rice husk ash (RHA) as a replacement for cement in HSC.



(a) (b) (c) (d)

(e) (f) (g)

Fig. 1. Locust bean tree with ripe fruits (a), harvested locust bean fruit (b), locust bean pod (c), locust bean pod ash (d), cast concrete cubes, beams and cylinders (e), 'demoulded' concrete cubes (f), and a cube on a universal testing machine (g)

The varying percentages of rice husk ash used were 0%, 5%, 10%, 15%, and 20%. They obtained a cylindrical compressive strength of 56.2 MPa at 28 days of curing and concluded that 10% RHA was the optimum replacement level. Also, the effectiveness of Metakaolin (MK), Fly Ash (FA), and Silica Fume (SF) as SCMs on HSC was assessed by [21]. Under compression, the combinations outperformed the control mix.

Table 1. Summary of nominated previous studies using LPBA as reported in literature

			Summary of Findings							
No.	Authors	% Replacement	HSC	Compressive Strength	Flexural Strength	Tensile Strength	Sulphate Resistance	Thermal Resistance	Water Absorption	Remarks
1	[16]	0, 5, 10 and 15%	X	√	X	X	X	X	X	Decreased compressive strength.
2	[27]	0, 10, 15, 20 and 30%	X	√	X	X	X	X	X	Increased compressive strength up to 15% replacement.
3	[24]	0, 5, 10, 15 and 20%	X	X	√	X	X	X	X	Increased flexural strength with curing time.
4	[33]	0, 5,10,15 and 20%	X	X	X	X	X	X	X	Increased consistency.
5	[34]	0, 5, 10 and 15%	X	√	X	X	X	X	X	Reduction in compressive strength with increase in curing age.
6	[28]	0, 40, 50 and 60%	X	√	X	√	X	X	√	Increased strength.
7	[35]	0, 2.5, 5, 7.5, and 10%	X	√	√	X	X	X	X	Increased strength with curing age.
8	Current Research	0, 5,10,15, and 20%	√	√	√	√	√	√	√	Presented in this paper.

LBPA obtained from calcination of the African Locust Bean (Parkia biglobosa); a perennial tree species native to the west African Savannah has been utilized in production of concrete and mortar [22]–[24]. Figure 1 shows locust bean tree, ripe locust bean fruit, LBP, LBPA, LBPA concrete and Universal Testing Machine.

The utilization of LBPA as SCM has been examined in numerous studies aimed at ensuring effective waste management, construction cost reduction and conservation of the environment [22], [24], [25]. Available literature reveals that concrete made with LBPA exhibits an appreciable level of strength and durability hence, it can be used to produce structural light weight concrete. In their study, [26] observed a progressive rise in strength with curing time. They found that the highest compressive strength of 28.44 N/mm^2 was realized at 28 days when using 5% of LBPA, compared with the control mix which had a strength of 22.27 N/mm^2. Similarly, [27] found an increase in strength of LBPA mortar up to 15% and thence a decline. In the same vein, [28] also discovered that the tensile strengths of 20 and 40% LBPA concrete were higher than that of OPC concrete. The observed increase in strength can be attributed to the substantial surface area of LBPA, which facilitates the pozzolanic reaction leading to the formation of C-S-H gel. Additionally, [29] reported an improvement in flexural strength as the curing period progressed. Some blends had greater strength than the control. Similarly, the utilization of LBPA has been demonstrated to enhance the performance of concrete in various aspects, including water absorption, sulphate resistance, shrinkage, and chloride permeability [28], [30]–[32]. A summary of selected works utilizing LBPA are in Table 1.

Despite its vast potential and the extensive experimental work carried out to determine the properties of LBPA concrete, there is paucity of literature on the performance of LBPA in HSC as well as prediction models. This study is an attempt to assess the performance of LBPA on the properties of HSC. The impact of LBPA on properties of HSC comprising slump, compressive, tensile and flexural strengths as well as water absorption, resistance to sulphate attack and elevated temperatures were examined. Furthermore, the mechanical properties of the concrete were statistically modelled using Regression analysis. This study is expected to cause a reduction in construction cost, greenhouse gases, and cement consumption while ensuring efficient agricultural waste management and sustainability.

2. Materials and Methods

2.1. Materials

The ordinary Portland cement (BUA brand, Nigeria, specific gravity: 3.15) conforming to BS EN 197 [36] was used in this research. The LBP was obtained from Makurdi, Benue state, Nigeria and thermally processed to ash (LBPA, specific gravity: 2.18, bulk density: 875 kg/m^3 and moisture content: 1.58%) in a furnace (600°C for 2 hours) and allowed to cool to room temperature before being sieved (75μm). The chemical compositions of OPC and LBPA was determined via XRF analysis (RaynyEDX-700/800, Shimadzu Corporation, Tokyo, Japan) at Umaru Musa Yar'Adua University, Katsina, Nigeria (Table 2). Sand collected from Benue River in Yola, Nigeria (passing through 4.75mm sieve, specific gravity: 2.67, bulk density: 1,626.04kg/m^3 and moisture content: 2.48%) was used as fine aggregate. Crushed granite (maximum size 12.5 mm, specific gravity: 2.70, moisture content: 1.31% and bulk density: 1883.0 kg/m^3) was used as coarse aggregate. SIKAMENT NNR which conforms to ASTM C494 [37] was the superplasticizer used.

Table 2. Chemical composition of OPC and LBPA

Chemical Composition	OPC	LBPA
SiO_2	20.05	37.03
Al_2O_3	5.27	3.11
Fe_2O_3	3.54	2.67
CaO	61.18	5.10
MgO	0.93	5.85
Na_2O	1.01	0.00
K_2O	0.07	9.94
SO_3	1.24	2.99
P_2O_5	-	3.53
TiO_2	-	-

2.2. Methods

Table 3 displays the mix design and slump values for the concrete. The LBPA as cement replacement material was evaluated (control mix, L00: 0%, L05: 5%, L10: 10%, L15: 15%, L20: 20%). The slump test was conducted on the freshly mixed concrete to determine its workability (BS EN 12350) [38].

Table 3. Mix design for LBPA concrete

Mix No.	OPC (kg/m^3)	LBPA (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)	Slump (mm)
L00	350	-	525	875	105	10.5	105
L05	332.5	17.5	525	875	105	10.5	97
L10	315	35	525	875	105	10.5	85
L15	297.5	52.5	525	875	105	10.5	45
L20	280	70	525	875	105	10.5	26

2.2.1. Mechanical Properties

2.2.1.1. Compressive Strength

An evaluation of the concrete's compressive strength was carried out (BS EN 12390-4) [39]. Forty-five samples were cast in 100 mm steel cube moulds and cured in water (3, 7, and 28 days). Three samples were crushed at the conclusion of each curing procedure using the Civit Test Hydraulic Universal Testing Machine of 1000 kN capacity and at constant rate of 15 kN/s and the average taken.

2.2.1.2. Flexural Strength

The flexural strength of the concrete was evaluated (BS EN 12390-5) [40]. A total of forty-five concrete specimens were cast in steel beam moulds (100 x 100 x 400mm long) and kept in water (3,7, and 28 days). Three samples were crushed at the conclusion of each curing regime.

2.2.1.3. Splitting Tensile Strength

Splitting tensile strength was determined (BS EN 12390-2) [41]. Forty-five concrete samples were cast in cylindrical moulds of 100mm diameter by 200mm long and cured in water (3, 7, and 28 days).

2.2.2. Durability of LBPA Concrete

The durability of concrete is its ability to withstand deterioration caused by physical, mechanical or chemical factors during its service life in the form of acid attack, carbonation, alkali-aggregate reaction, freezing-thawing, leaching, sulphate attack among others [42]. To ensure that the HSC will be able to withstand the environmental conditions that it will be exposed to, the durability of the concrete was determined in terms of water absorption, resistance to sulfate and elevated temperatures.

2.2.2.1. Water Absorption

The standards of ASTM C642 [43] were followed in order to conduct the water absorption test for the concrete. After 28 days at a temperature of 25 ± 2˚C, the concrete cubes (15) were cured. After heating the specimens in an oven at 110˚C for twenty-four hours, their weights (W1) were determined, and then they were immersed in water for twenty-four hours. After the specimens were brought out, the surfaces of the specimens were dried, and their weights were measured once more (W2). The formula for calculating the proportion of water absorbed was:

$$WA\ (\%) = \left|\frac{W2 - W1}{W1} \times 100\%\right| \tag{1}$$

2.2.2.2. Resistance to Sulphate Attack

The cubes (60) underwent a curing process in water at ambient temperature (28 days). The sample cubes were thereafter soaked in 10% Magnesium sulphate ($MgSO_4$) solution, adopted from works by [44]–[46]. At 7, 14, 21, and 28 days, samples' compressive strength was evaluated.

2.2.2.3. Effect of Elevated Temperature

The concrete specimens (90) were cured in water at 25 ± 2˚C (28 days). The samples were brought out of water and allowed to dry for 24 hours before being subjected to various elevated temperatures. Three concrete cubes were exposed for 2 hours to temperatures of 100˚C, 200˚C, 300˚C, 400˚C, 500˚C, and 600˚C in a furnace, adopted from previous works by [47], [48]. After exposure to the required temperature range, the concrete samples were permitted to settle to room temperature before crushing them to determine their residual compressive strength.

2.3. Model Optimization

Concrete's compressive strength is regarded as the foremost significant mechanical characteristic, typically ascertained subsequent to a curing period of 28 days [49]–[51]. Because the widely used compressive strength factor is only available after 28 days, determining the strength of concrete requires time, preparation, and resources [52]. The development of a strength prediction model was based on the experimental findings depicted in Figure 2, utilizing the Statistical Package for Social Sciences (SPSS) Version 29. Multiple regression analysis is a statistical technique used to predict the value of a dependent variable based on a set of known independent variables. Multiple regression analysis provides evidence that the dependent variable Y is influenced by one or more independent variables (x_1, x_2, x_k) [53]. The association between the anticipated dependent variable (Y) and the independent predictor variables (x_1, x_2, ..., x_k) is expressed as:

$$Y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots\ldots \beta_k x_k + E\ldots\ldots\ldots \tag{2}$$

Where:

α = constant on Y axis

Y = dependent variable

x_1 and x_2 = independent variables

α is the intercept, representing the value of Y on the regression plane when are both zero. β_1, β_2, and β_k are the regression coefficients representing marginal change in Y associated with a unit change in the corresponding x variable, if the other x variable remains unchanged. For validation of the models, the percentages of error between experimental and predicted values of response variables were evaluated using Equation 3.

$$Error\ (\%) = \left|\frac{Experimental\ Value - Predicted\ Value}{Experimental\ Value} \times 100\%\right| \tag{3}$$

3. Results and Discussion

3.1.1. Slump

The slump values of the LBPA concrete exhibited a decline as the LBPA content increased. This finding is consistent with [22]. Because LBPA particles have a wide surface area, it is possible that their absorption of some water contributed to the decrease in workability. The decrease in workability can also be ascribed to the permeable characteristics of LBPA resulting from the existence of macro and meso-pores situated both internally and externally on the material, hence contributing to its substantial specific surface area [27]. During the process of mixing, the LBPA undergoes water absorption on its surface, resulting in a decrease in the amount of free water and a corresponding decrease in the slump value [54]. This is not only attributed to the particle size distribution of the LBPA, but also to its mean particle size and geometric shape.

3.1.2. Compressive Strength

The result presented in Figure 2 illustrates the compressive strength of LBPA HSC. The compressive strength improved with inclusion of LBPA and curing age. Concrete containing 5% LBPA was the strongest at 3-, 7- and 28-days having strength of 7.8%, 11.1%, and 13.1% better than the control respectively.

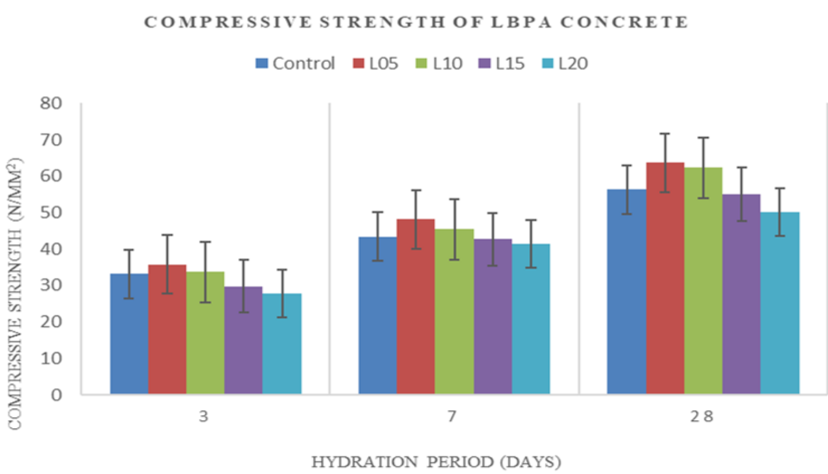


Fig. 2. Compressive strength of LBPA concrete

The aforementioned outcome aligns with the discoveries made by [55] and [56] who stated that pozzolan mixes develop higher strength with curing age. The change in strength gains between the LBPA concrete and the control is due to the pozzolanic interaction between LBPA and Ca $(OH)_2$, which results in the creation of more C-S-H gel [42]. The strength declined beyond 10% replacement. The 28-day compressive strength of L15 and L20 were 5.7 and 10.8 % lower than that of the OPC concrete with L20 having the lowest strength. The reduction in compressive strength at higher level of LBPA may be as a result of clinker dilution effect [57]. The optimum replacement level is 10% in agreement with [19] and [58] who utilized RHA and (MK) in HSC respectively.

3.1.3. Flexural Strength

The flexural strength behavior of LBPA HSC is similar to that of compressive strength (Figure 3). The result indicates that flexural strength increased with curing age consistent with [24], [29]. The flexural strength of L05 and L10 were 6.4 and 5.2% higher than control concrete at 28 days with L05 showing the best performance. The observed improvement in low-level LBPA substitution can perhaps be attributed to the heightened pozzolanic reaction and enhanced particle packing capacity of LBPA particles [59]. Beyond 10% substitution, the flexural strength declined. The lower flexural strength at higher LBPA content could be attributed to low pozzolanic reaction of LBPA. The observed reduction in flexural strength as the LBPA content increases can be attributed to two factors: the diluting effect of OPC and the poorer formation of C-S-H gel due to the pozzolanic reaction of LBPA [60].

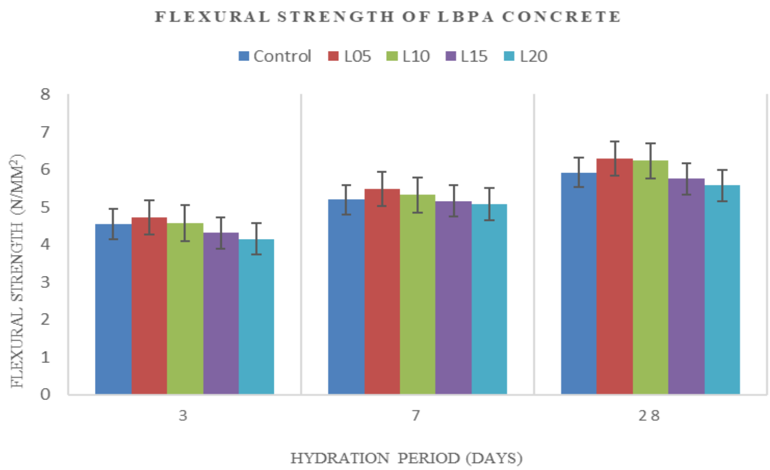


Fig. 3. Flexural Strength of LBPA concrete

3.1.4. Splitting Tensile Strength

Both the curing age and the LBPA content contributed to an increase in the splitting tensile strength. It was observed that at 28 days, the tensile strength of L05 and L10 were 7.1 and 5.9% higher than the control concrete. [28] obtained similar result. The 28-day tensile strength of the reference sample was 4.24 N/mm^2 whereas that of LBPA concrete ranged between 94 and 106% of the control with concrete containing 5% and 20% LBPA content having the highest and least strengths, respectively. The observed improvement in low-level LBPA substitution can perhaps be attributed to the heightened pozzolanic reaction and enhanced particle packing capacity of LBPA particles [59]. The optimum substitution was found to be 10%, same reported by [58] using MK blended mix.

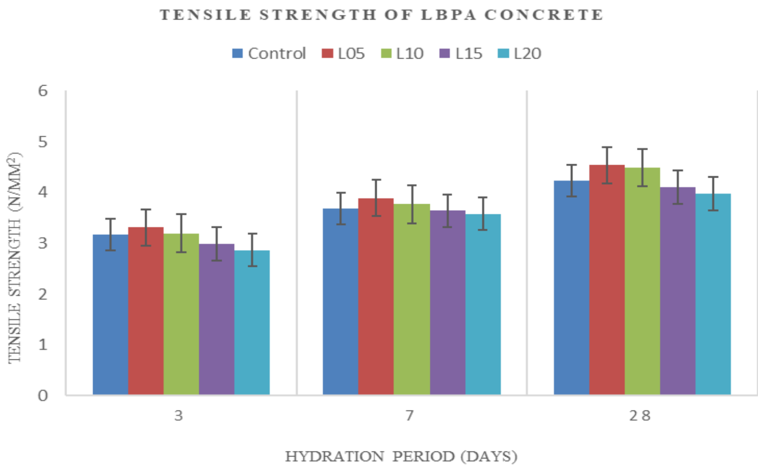


Fig. 4. Tensile Strength of LBPA Concrete

3.2. Durability Properties

3.2.1. Water Absorption

The water uptake of LBPA concrete is between 2.2% and 3.8% with 5% LBPA contributing to the lowest water absorption (Table 4). The rise in LBPA level was accompanied by an increase in the water absorption. However, given that the quantity of water consumed is less than 10%, all of the concretes fall within the category of high-quality concrete [2]. The inclusion of LBPA content led to a reduction in water migration into the concrete, resulting in a decrease in porosity and an increase in impermeability compared to the control sample. This was accomplished by the process of infilling the spaces, resulting in a decrease in potential pathways for the intrusion of water [28]. The resistance to water intrusion is due to the secondary C-S-H gel that develops during the pozzolanic reaction and covers the gaps within the LBPA structure, resulting in denser and more impermeable concrete. The decreased water absorption value reflects the diminished porosity and restricted pore connectivity of the LBPA concrete [61]. [62] also reported less water absorption in ternary concrete containing MK and FA. Similarly, [63] found that concrete made from palm oil fuel ash (POFA) and MK concrete absorbs less water than OPC concrete. Thus, inclusion of pozzolans reduces the water uptake of concrete.

Table 4. Water Absorption of LBPA Concrete

Mix Designation	Water Absorption (%)
L00	3.2
L05	2.2
L10	2.6
L15	3.3
L20	3.8

3.2.2. Resistance to Sulphate Attack

The LBPA concrete showed better resistance to $MgSO_4$ than the control concrete (Figure 5) with LB05 demonstrating the highest resistance. The compressive strength decreased by 18.12%, 11.46%, 14.45%, 13.94%, and 16.53 % for L00, L05, L10, L15 and L20 respectively after 28 days' immersion $MgSO_4$ solution. The resistance may be attributed to the silicate gel produced during hydration processes which coats and binds the matrix together and prevents the detrimental effects of sulphate on the concrete construction [28]. Another reason could be that the pozzolanic reaction caused by LBPA results in the production of extra binding gel, which leads to the formation of concrete that is more compact. The pozzolanic reaction may have been responsible for the consumption of calcium hydroxide, which may have led to the formation of ettringite, which ultimately had an effect on the concrete [64]. This is because pozzolans are known to enhance concrete's resistance against Sulphate attack [65].

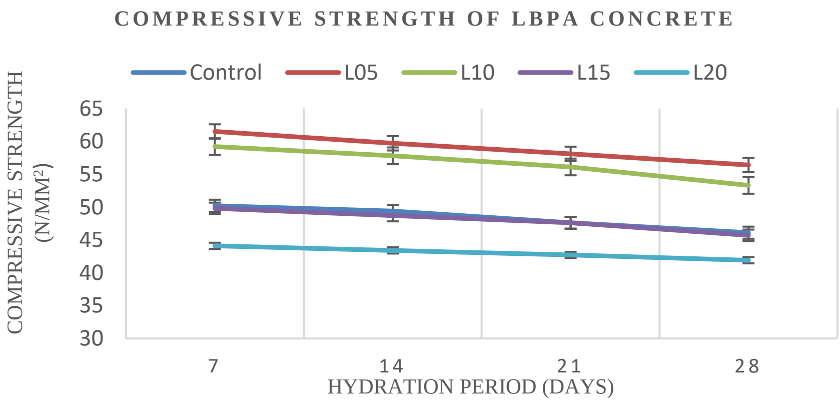


Fig. 5. Compressive strength of LBPA Concrete after Immersion in $MgSO_4$.

3.2.3. Performance Against Elevated Temperature

The correlation between compressive strength and temperature is illustrated in Figure 6. There was a variable change in the compressive strength of LBPA concrete as the temperature increased. The study observed a sharp decline in compressive strength at 100˚C, thence an increase at 200 ˚C. As temperatures rise, water in the concrete dissipates, exposing a greater proportion of the cementitious components and resulting in a decrease in binding strength between the binder and aggregates.

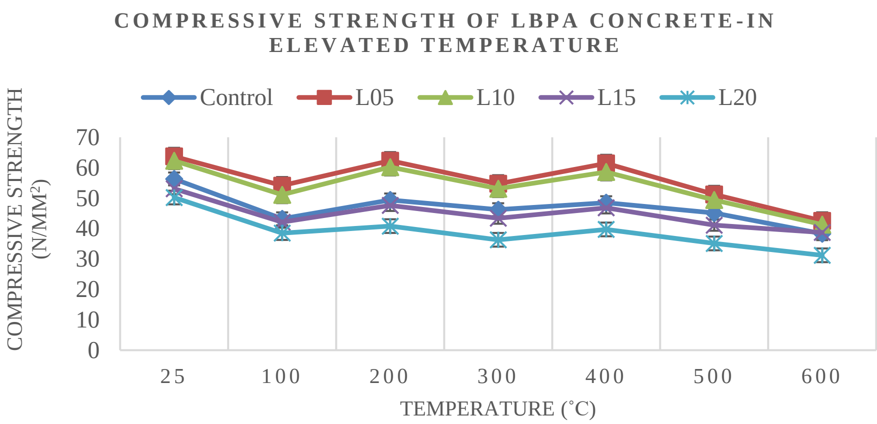


Fig. 6. Compressive Strength of LBPA concrete at elevated temperature

During the dehydrating process, there is an initial decrease in compressive strength followed by an increase [66]. Generally, it was observed that the specimens had better performance at 200 and 400˚C with increase in strength while the worst performance was recorded at 600˚C. L05 had the best performance at temperature of 400˚C with a 68.21% increase in compressive strength from 300˚C. This observation is consistent with the one made by [47] who had the best performance at 200˚C and 400˚C with a drastic strength loss at 800˚C when they subjected MK blended cement paste to elevated temperatures. The low content of the LBPA was responsible for the thermal stability of the composite. This may be attributed to the chemical decomposition of the already depleted C-S-H in the blends [67]. The specimens recorded lower compressive strength at 100˚C and 600˚C. Therefore, the thermal stability of LBPA concrete could be achieved at 10% replacement respectively.

3.3.1. Evaluation of Statistical Model

Equations 4, 5, and 6 show the regression equations for the compressive, flexural, and splitting tensile strengths of LBPA concrete models.

$$F_{CS} = 36.665 - 0.329\,(x_1) + 0.875\,(x_2) \tag{4}$$

$$F_{FS} = 4.774 - 0.020\,(x_1) + 0.051\,(x_2) \tag{5}$$

$$F_{TS} = 3.345 - 0.015\,(x_1) + 0.040(x_2) \tag{6}$$

Where:

F_{cs}= concrete compressive strength the concrete

F_{FS} = flexural strength

F_{TS} = concrete splitting tensile strength

x_1 = percentage replacement of cement by LBPA

x_2 = curing age

The multiple regression analysis findings are presented in Table 5. According to the coefficient of determination (R^2) values of 82.2, 80.1, and 80.6% for the compressive, flexural, and tensile strengths, respectively, the differences in LBPA content and curing age have a considerable impact on the variation in concrete strengths indicating a strong correlation.

Table 5. Results of the multiple regression analysis.

Strength Property	Model	R	R-squared	Adjusted R-squared	Std. error of the estimate
Compressive	1	0.907	0.822	0.792	5.1376
Flexural	2	0.895	0.801	0.768	0.32256
Tensile	3	0.898	0.806	0.773	0.24814

The p-value presented in Table 6 provides an assessment of the overall statistical significance of the model. At a significance level of 0.05, the P-value is less than 0.001 for both LBPA content and age of curing of concrete. This indicates that both variables are highly significant (P < 0.05), suggesting that the variation in the concrete compressive, splitting tensile, and flexural strengths can be attributed to the LBPA content and age of curing. The emerged model indicates that 82.2, 80.1, and 80.6% of the variation in compressive, flexural and tensile strengths of LBPA concrete can be explained by the two variables (LBPA content and curing age).

Table 6. Analysis of variance (ANOVA) showing the significance of the regression model.

	Model		Sum of squares	df	Mean Square	F	Sig.
Compressive	1	Regression	1461.314	2	730.657	27.681	< 0.01
		Residual	316.742	12	26.395		
		Total	1778.056	14			
Flexural	2	Regression	5.021	2	2.511	24.130	< 0.001
		Residual	1.249	12	0.104		
		Total	6.270	14			
Tensile	3	Regression	3.064	2	1.532	24.883	< 0.001
		Residual	0.739	12	0.062		
		Total	3.803	14			

The coefficients of the independent variables in the regression equation are shown in the B-column of Table 7. The statistical analysis of the Table reveals that both the LBPA content and curing age have a substantial impact on the anticipated strengths. This is supported by the fact that the p-value for curing age is less than 0.001. The t-values quantify the degree of influence that each variable has on the projected strengths. Hence, the t-values and corresponding p-values provide evidence about the statistical significance of the effects of LBPA content and curing age on the predictive capability of LBPA concrete strength.

Table 7. Coefficients of the independent variables in the regression equation.

			B	Std. error	Beta	T	p-value
Compressive	1	Constant	36.665	2.762		13.276	< 0.001
		% Replacement	-0.329	0.188	-0.23	-1.752	0.105
		Curing Age	0.875	0.121	0.881	7.231	< 0.001
Flexural	2	Constant	4.774	0.173		27.532	< 0.001
		% Replacement	-0.020	0.012	-0.219	-1.698	0.115
		Curing Age	0.051	0.008	0.868	6.736	< 0.001
Tensile	3	Constant	3.345	0.133		25.080	< 0.001
		% Replacement	-0.015	0.009	-0.217	-1.707	0.114
		Curing Age	0.040	0.006	0.871	6.845	< 0.001

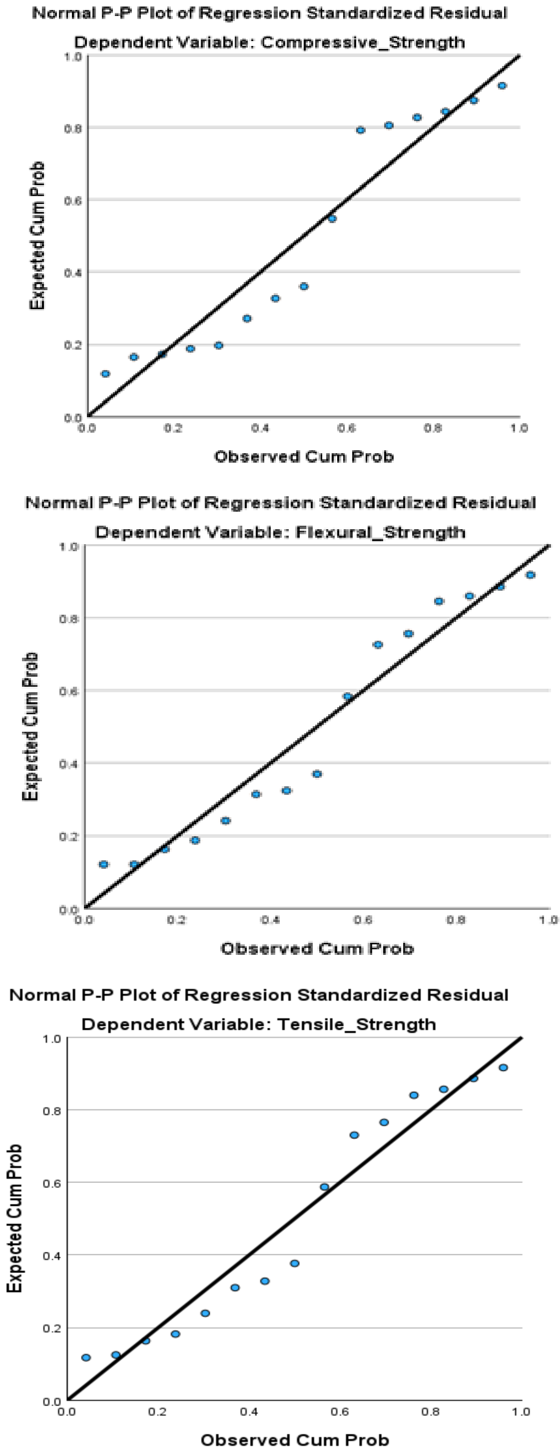


Fig. 7. Normal probability plot for a. Compressive strength b. Flexural strength c. Tensile strength

Figure 7 is the Normal Probability plot for the strength (compressive, flexural and tensile) models of LBPA concrete. The data points exhibit a close proximity to the linear regression line, suggesting that the residuals follow an approximated normal distribution.

3.3.2. Validation of the Model

The optimized model's validity is displayed in Table 8. In engineering contexts, a 20% margin of error is considered to be acceptable [68], [69]. From the table, all the response variable are within the acceptable limits with L15 having the best accuracy for compressive and flexural strengths respectively while L05 had the highest accuracy for tensile strength. This shows that all the optimized prediction models in relation to percentages of LBPA are adequate for design prediction.

Table 8. Validation of optimized models.

Replacement Level	Compressive Strength (N/mm^2)		Percentage Error (%)	Flexural Strength (N/mm^2)		Percentage Error (%)	Tensile Strength (N/mm^2)		Percentage Error (%)
	Experimental	Predicted		Experimental	Predicted		Experimental	Predicted	
0	56.3	61.17	8.65	5.92	6.20	4.73	4.24	4.47	5.42
5	63.7	59.52	6.56	6.30	6.10	3.17	4.54	4.40	3.08
10	62.3	57.88	7.10	6.23	6.00	3.69	4.49	4.32	3.77
15	53.1	56.23	5.89	5.75	5.91	2.78	4.11	4.24	3.16
20	50.2	54.59	8.75	5.58	5.80	3.94	3.98	4.17	4.77

4. Conclusions

The performance of HSC containing LBPA as cement replacement was investigated in this study. The LBPA was obtained by thermal digestion of LBP at 600°C for 2 hours. The slump, strengths, water absorption, resistance to sulphate, and the effects of elevated temperatures were assessed, after initial curing in water for 28 days. Results from the study revealed that slump values decrease with increase in LBPA content in the HSC with the lowest value of 26mm for the 20% replacement. The strength (compressive, flexural and tensile) of concrete improved by 13.14%, 6.42% and 7.08% respectively over the control samples at 5% replacement level. Additionally, LBPA improved the durability of concrete in terms of water absorption, resistance to sulphate action and elevated temperatures. Water absorption decreased with increase in LBPA content recording the lowest value of 2.2% over control samples at 5% replacement level. The compressive strength decreased by 18.12%, 11.46%, 14.45%, 13.94%, and 16.53% for L00, L05, L10, L15, and L20 respectively after 28 days' immersion in $MgSO_4$; implying that LBPA improves the resistance of concrete against $MgSO_4$. The compressive strength of LBPA concrete fluctuated with increase in temperature; providing a better resistance at temperatures of 200°C and 400°C compared to OPC concrete as a result of low pozzolanic activity. The optimized model of L15 had the highest accuracy with percentage errors of 5.89% and 2.78% for compressive and flexural strengths respectively while L05 had the highest accuracy for tensile strength with percentage error of 3.08%. The study concludes that LBPA can be used successfully as an SCM in HSC. Thus, 10% optimum replacement amount is recommended. The findings of the study are comparable with previous work carried out by [70], [71] utilizing POFA and bamboo leaf ash in HSC respectively. The study further recommends that the effect of the use of additional pozzolans together with LBPA in HSC be studied. Additionally, the performance of LBPA in geopolymer and self-compacting concrete should be studied. Finally, the environmental impacts and the economic aspects of using LBPA should be investigated.

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