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Strength Prediction of Millet Husk Ash Concrete Exposed to Elevated Temperature Using Artificial Neural Network

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Abstract
The rising demand for cement has significantly impacted the environment due to the high energy consumption and emission of harmful gases during cement production. To reduce cement usage, energy demand, and environmental degradation, researchers are exploring the incorporation of agricultural waste materials with cementitious properties. Millet husk ash (MHA), an agricultural byproduct, has emerged as a potential supplementary cementitious material (SCM) for sustainable concrete production. This study investigates the effects of partially replacing cement with MHA at 0%, 5%, 10%, and 15%. A total of 96 concrete samples were prepared and cured for 7, 14, and 28 days. Laboratory tests were conducted to evaluate setting time, workability, density, compressive strength and thermal stability at temperatures up to 800 °C. After 28 days, concrete with 5% MHA achieved the highest compressive strength (30.59 N/mm²) and a density of 2338 kg/m³, surpassing the control mix (30.14 N/mm², 2347 kg/m³). At 800 °C, the control mix lost 7.16% of its mass, while MHA blends showed slightly higher losses up to 7.42%. These reductions in mass and density were attributed to moisture loss, pore expansion, and decomposition of hydration products at elevated temperatures. Residual compressive strength declined with increasing temperature. At 800 °C, the control mix lost 41.29% of its strength, compared to 46.21%, 48.17%, and 57.46% for mixes containing 5%, 10%, and 15% MHA, respectively. Visual inspection after fire exposure indicated that mixes with up to 5% MHA retained better structural integrity, showing minimal surface damage up to 600 °C and only fine cracks at 800 °C. Furthermore, an artificial neural network (ANN) model was developed to predict compressive strength under thermal stress. The model demonstrated excellent predictive accuracy with an R^2 value exceeding 0.998. The findings confirm that low level MHA replacement (especially at 5%) enhances concrete performance while promoting sustainable practices through the beneficial reuse of agricultural waste.
***Keywords**: Millet husk ash, Artificial Neural Network, Strength property, Cement replacement, Elevated temperature.*

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I. Introduction

The rapid growth of the construction industry has led to shortages of raw materials and environmental degradation. Concrete, composed of ordinary Portland cement (OPC), aggregates, and water, relies heavily on OPC, the most carbon intensive component (Nwaobakata & Eme, 2018; Ibedu, Akinola, & Omole, 2023). In Nigeria, cement consumption rose from 20 million metric tons in 2015 to 30 million in 2023, driven by urbanization and infrastructure demands (Dangote Cement, 2023; Cardinal Stone, 2024). Cement production contributes significantly to greenhouse gas emissions around 8% globally due to CO_2, SO_2, and NO_x releases (World Economic Forum, 2022; Etim et al., 2021).

Mitigation strategies like carbon capture and alternative fuels are still emerging in Nigeria. Reducing clinker content and using Supplementary Cementitious Materials (SCMs) have gained attention. Researchers have explored agricultural wastes such as maize cob ash, locust bean pod ash, and millet husk ash (MHA) as partial cement replacements to reduce OPC use and enhance concrete strength (Patel & Shah, 2020; Ogunbode et al., 2019).

Millet is widely cultivated in countries like India, Nigeria, and Niger, producing 3 to 5 million metric tons annually in Nigeria alone (Ogunbayo et al., 2020). MHA, rich in silica, exhibits pozzolanic activity that enhances concrete strength and durability (Kumar, Sinha, & Singh, 2018). Studies show up to 20% MHA replacement yields optimal results with minimal strength loss (Prasad & Reddy, 2017; Singh et al., 2021). Despite its benefits, challenges remain in standardizing MHA quality and processing methods (Zhang et al., 2019).

Machine learning (ML) techniques have improved predictions of concrete properties, outperforming traditional methods in accuracy. Algorithms like neural networks and decision trees can model complex relationships in concrete behavior, aiding sustainable mix design and performance forecasting (Nath et al., 2021; Shi et al., 2020; Ahmad et al., 2019). As data quality improves, ML's role in optimizing MHA concrete is expected to grow.

This study evaluates the properties of MHA concrete and develops machine learning based predictive model for enhanced performance forecasting.

II. Materials and Methods

2.1 Materials

In this research work, the basic materials for concrete production were used. These materials include cement, fine aggregate, coarse aggregates, water and Millet husk ash (MHA) was also used as a partial replacement for cement.

2.2 Methods

2.2.1 Concrete Mix Design

The DoE method of mix design was adopted for this study to design a 30 N/mm^2 concrete grade. The process of mix design is established on the procedure followed according to BS EN 1008-2002:1983 with particular emphasis on strength properties. The procedure for mix design begins with selecting the targeted concrete strength, followed by choosing the slump level to ensure appropriate workability for the specific application. Next, the nominal maximum size of coarse aggregate was determined, impacting the mix's density and durability. Cement content is then calculated to achieve the desired strength, followed by estimating the amount of coarse aggregate for proper density balance. Finally, fine aggregate content is estimated to complete the mix proportions, ensuring a balanced and workable concrete mix.

2.2.2 Production of Concrete Samples and Preparation

The casting of the cubes was carried out immediately after the workability test. The mould was lubricate with an engine oil to allow for easy removal of the concrete, the concrete was casted in 100mm moulds, the moulds was filled and compact in three layers and tampered 25 times at each layer, and after casting the cubes were left for 24hours before de-molding. A total number of 96 cubes were casted as shown in the Table 1. As soon as the cubes are de-molded, they were put into a curing tank full of water and cure for 7, 14, and 28 days respectively. At the end of each curing period, three (3) specimens for each mixture and each percentage were tested for compressive strength, density and fire resistance.

Table 1: Concrete Samples for Different Percentages of MHA

Replaced % of Cement by MHA (by volume)	0%	5%	10%	15%	Total
Compressive strength test at 7, 14, and 28 days of size 100x100x100mm.	9	9	9	9	36
Density at 7, 14 and 28 days of size 100x100x100mm.	3	3	3	3	12
Compressive strength and density of fired cubes at 200, 400, 600 and 800^{o}c.	12	12	12	12	48
Total number of samples = 96					

2.2.3 Testing of Concrete Samples

All the laboratory work was conducted according to BS standard. The tests procedures are explained in the following sub-headings.

2.2.3.1 Slump Test

Slump test is an empirical test that measures the workability of fresh concrete and was done in accordance to BS EN 12 350-2:2009.

2.2.3.2 Density Test

The density of hardened concrete is of interest to the parties involved for numerous reasons including its effect on durability, strength and resistance to permeability. The test was carried out according to BS EN 12390-7:2019. The concrete density test was carried out at 7, 14 and 28 days. The densities of the concretes are expected to reduce over time because the specimens were subjected to air drying at room temperature after demolding until days of testing. The density of concrete specimens was calculated, using Equation (1).

$$D = \frac{M}{V} \quad \text{---} \quad (1)$$

Where D is the density of the concrete specimen in kg/m³, M is the mass of the specimen and V its volume.

2.2.3.3 Compressive strength

The determination of compressive strength test, which is before crushing of cubes. The cubes were brought out of water and kept for about 30 minutes for the water on the cube surface to drip off before carrying out the test. The cubes were crushed in accordance with BS EN 12390-3: 2002. After the cubes are crushed, the result of the load applied by the crushing machine were recorded. The compressive stress was obtained by the ratio of applied load to the cross-sectional area of the specimen that was in contact with the compression plates. The compressive stress was then calculated by dividing this maximum load, averaged across three identical specimens, by the area of one cube face calculated using Equation (2).

$$Compressive\ strength\ (N/mm^2) = \frac{\text{load(N)}}{\text{surface area }(mm^2)} \quad \text{---------------------------------- (2)}$$

2.2.3.4 Fire Resistance

The fire resistance test was done to measure the performance of concrete in terms of fire incidents in accordance to section 4 of BS 8110-2 (1985). 100x100x100 mm concrete cubes containing Guinea corn husk ash as a partial replacement of cement at 0%, 5%, 10%, and 15% were used for the experiment. These cubes were cast in molds and cured in water for 28 days. Post-curing, the cubes were subjected to fire resistance testing in accordance with BS standard. The cubes were heated to target temperatures of 200°C, 400°C, 600°C, and 800°C in a kiln located at the Industrial Design Department lab at Abubakar Tafawa Balewa University, Bauchi. Physical observations, compressive strength, and density tests were conducted post-heating. Data were analyzed to assess the effects of millet husk ash on thermal properties of MHA concrete.

2.2.4 Artificial neural networks (ANN) model development and validation

This study developed an Artificial Neural Network (ANN) model to predict the strength of concrete using millet husk ash (MHA) as a partial cement replacement under thermal stress, with MHA replacing cement at 0%, 5%, 10%, and 15% by volume. The study involved twelve (12) variables including material properties and compressive strengths were used as inputs in a feed forward ANN with ReLU activated hidden layers and a linear output layer to predict residual compressive strength under thermal stress. ANNs, with their ability to capture complex, non-linear relationships in data, outperformed traditional models in predicting the properties of MHA concrete, making them highly suitable for this research (Afshari, Alagha, & Rafiei, 2021).

Pre-processing steps included min-max normalization, data augmentation via CTGAN to expand the dataset, and a 70/30 ratio for train/test split with 5-fold cross-validation for parameter tuning. The training utilized Mean Squared Error (MSE) as the loss function and the Adam optimizer, with early stopping after 1,000 epochs to prevent over fitting. Model performance was evaluated using metrics like R^2, Mean Absolute Error (MAE), and MSE, highlighting the model's accuracy and its suitability for predicting the impact of WGP on concrete durability. To evaluate the performance of the ANN model, the following metrics were utilized (Alkadhim et al. 2022).

2.2.4.1 Coefficient of Determination (R^2)

Coefficient of Determination measures the proportion of the variance in the dependent variable predictable from the independent variables, with values ranging from 0 to 1, where 1 indicates perfect prediction. The equation gives it:

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \quad \text{-- (3)}$$

2.2.4.2 Mean Absolute Error (MAE)

MAE measures the average magnitude of errors in predictions without considering their direction, indicating how far off predictions are from actual outcomes on average. MAE provides an idea of how far off predictions are from the actual outcomes, on average.

The equation gives it:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \quad \text{-- (4)}$$

2.2.4.3 Mean Squared Error (MSE)

MSE measures the average of the squares of errors, giving more weight to larger errors, thus providing a measure sensitive to outliers. The equation gives it:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \quad \text{-- (5)}$$

Where SS_{res} is the sum of squares of the residuals, $\sum(yi - \hat{y}i)^2$

$SStot$ is the total sum of squares, $\sum(yi - \bar{y})^2$

y_i are the actual values

$\hat{y}_i$ are the predicted values

$\bar{y}$ is the mean of the actual values

n is the number of observations.

III. Results and Discussion

3.1 Physical Properties of Materials

The specific gravities and bulk densities of the materials used are presented in Table 2. The fine aggregate (sand) had an adjusted average specific gravity of 2.61, while the coarse aggregate (gravel) recorded 2.73 both within the standard range of 2.4 to 2.9 specified by BS 882:1992 and BS EN 1097-6:2013, respectively, and supported by recent studies (Mohammed et al., 2021; Bheel et al., 2023; Michael et al., 2024). Millet husk ash (MHA) had a specific gravity of 2.36, closely matching the 2.25 reported by Michael et al. (2024), indicating consistency with existing research. The bulk densities of the fine aggregate were 1366 kg/m³ (uncompacted) and 1540 kg/m³ (compacted), while those of the coarse aggregate were 1421 kg/m³ and 1714 kg/m³, respectively. All bulk density values fall within the 1200 to 1800 kg/m³ range specified in BS 1881, confirming compliance with standard requirements.

Table 2: Physical Properties of Materials

Materials	Bulk Density(Kg/m^3)		Specific Gravity
	Compacted	Uncompacted	
Sand	1525	1340	2.59
Crushed Stone	1727	1398	2.71
MHA	-	-	2.36

3.2 Slump Test

The workability of concrete mixes incorporating Millet Husk Ash (MHA) as a partial replacement for Ordinary Portland Cement (OPC) was assessed using the slump test. The results, presented in Table 3 and illustrated in Figure 1, indicate a clear trend of decreasing slump values with increasing MHA replacement percentages. Specifically, the slump values recorded were 15 mm for the control mix (0% replacement), 9 mm for 5% replacement, 5 mm for 10% replacement, and 0 mm for 15% replacement. These results demonstrate that higher MHA content leads to a reduction in the workability of the concrete mixes compared to the control. This observed decrease in workability is likely attributed to the pozzolanic activity of MHA, which appears to reduce the concrete's flowability. This finding is consistent with the observations reported in previous studies (Mohammed *et al.*, 2021; Bheel *et al.*, 2023).

Table 3: Workability of Concrete Made with OPC/ MHA (Slump)

Mixes	Slump (mm)	Degree of workability
Control (0%)	15	Low workability
10% (MHA)	9	Low workability
20% (MHA)	5	Low workability
30% (MHA)	0	Low workability

Source: Laboratory Research Work (2025)

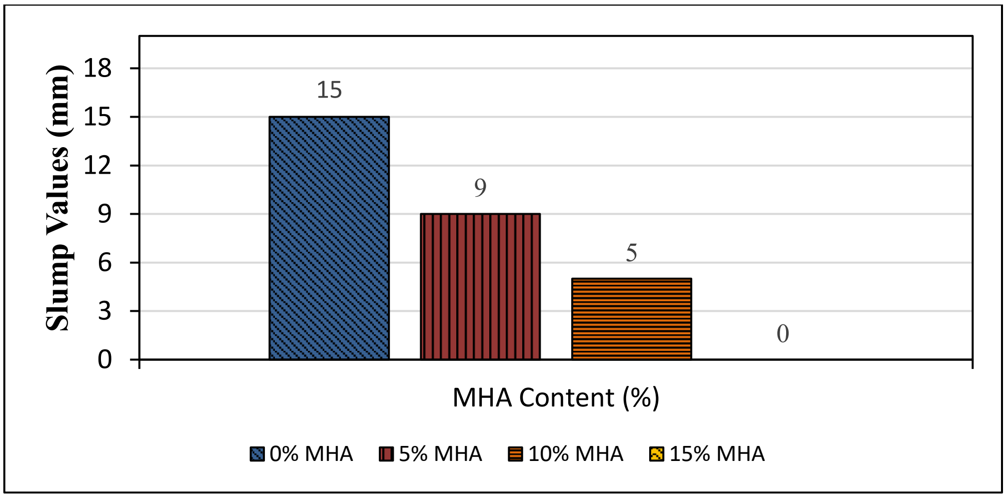

Figure 1: Slump result of concrete containing MHA

3.3 Concrete Density with Millet Husk Ash

Table 4 and Figure 2 demonstrate a gradual increase in the density of concrete samples made with Ordinary Portland Cement (OPC) and Millet Husk Ash (MHA) as they cured for longer durations, starting at 2308 kg/m³ and reaching 2347 kg/m³. After 28 days of water curing, the densities of concrete with 5%, 10%, and 15%

MHA were 2338 kg/m³, 2329 kg/m³, and 2308 kg/m³, respectively. This was lower than the control sample (0% MHA), which had a density of 2347 kg/m³. These results indicate density decreases of about 0.38%, 0.77%, and 1.66% when compared to the control mix. This density reduction is likely due to the inclusion of MHA, which dilutes the cement content, and its pozzolanic activity. This activity leads to ongoing hydration and filling of voids, making the internal structure of the concrete finer over time (Bheel *et al*., 2023). Furthermore, the production of additional calcium silicate hydrate (C–S–H) from the reaction between the amorphous silica in MHA and the calcium hydroxide released as OPC hydrates helps to make the concrete structure denser. This effect becomes more significant as the curing period increases, especially at 7, 14, and 28 days (Mohammed *et al*., 2021; Bheel *et al*., 2023).

Table 4: Densities of MHA Concrete Samples in kg/m³ at 7,14 & 28 days

Sample Type	3 cubes 7 days			3 cubes 14 days			3 cubes 28 days		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Control mix	2295	2292	2287	2305	2301	2298	2307	2283	2335
Average		**2291**			**2301**			**2308**	
5% MHA	2263	2272	2254	2276	2265	2281	2273	2256	2317
Average		**2263**			**2274**			**2282**	
10% MHA	2244	2238	2251	2243	2256	2252	2281	2243	2262
Average		2244			2250			2262	
15% MHA	2221	2218	2222	2225	2230	2223	2238	2225	2245
Average		**2220**			**2226**			**2236**	

Source: Laboratory Research Work (2025)

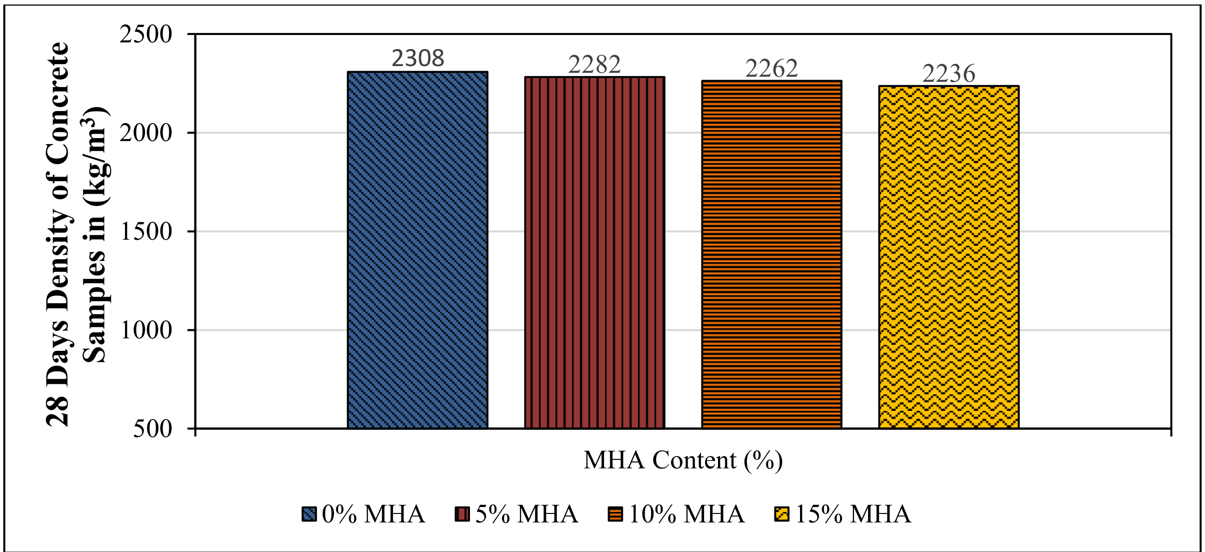

Figure 2: Average 28 days Density of Concrete Samples

3.4 Compressive Strength of MHA Concrete Samples

From the results shown in Table 5 and Figure 3 depict the compressive strength performance of concrete incorporating varying levels of Millet Husk Ash (MHA) as a partial replacement for Ordinary Portland Cement (OPC), assessed at 7, 14, and 28 days of curing. After 28 days, concrete specimens with 5%, 10%, and 15% MHA recorded compressive strengths of 30.59 N/mm², 26.87 N/mm², and 24.44 N/mm², respectively, while the control mix (0% MHA) achieved 30.14 N/mm². Among the tested mixes, only the 0% and 5% MHA blends met the 30 N/mm² minimum compressive strength threshold outlined in BS EN 197-1 (2000) for 28-day cured concrete. The reduced performance of the 10% and 15% mixes may be attributed to the higher levels of MHA, which can dilute the cementitious content and slow early strength gain. Additionally, the generally lower compressive strengths across the board may stem from the use of manual compaction during casting. This method often fails to achieve the level of consolidation needed to maximize concrete strength, unlike mechanical compaction, which is recommended by the standard to ensure uniformity and optimal performance (Mohammed *et al*., 2021; Michael *et al*., 2024).

Table 5: Compressive Strength of cubes cured at 7, 14 and 28 days

Sample Type	3 cubes 7 days			3 cubes 14 days			3 cubes 28 days		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Control mix	19.09	20.36	20.25	22.56	24.05	23.35	30.22	30.05	30.15
Average		**19.9**			**23.32**			**30.14**	
5% MHA	23.69	23.37	23.95	24.77	24.39	23.95	29.8	30.92	31.05
Average		**23.67**			**24.37**			**30.59**	
10% MHA	19.93	20.65	20.45	24.4	24.7	25.05	25.95	27.7	26.95
Average		20.34			24.72			26.87	
15% MHA	17.52	18.29	18.55	19.51	20.08	20.03	24.71	24.05	24.56
Average		**18.12**			**19.87**			**24.44**	

Source: Laboratory Research Work (2025)

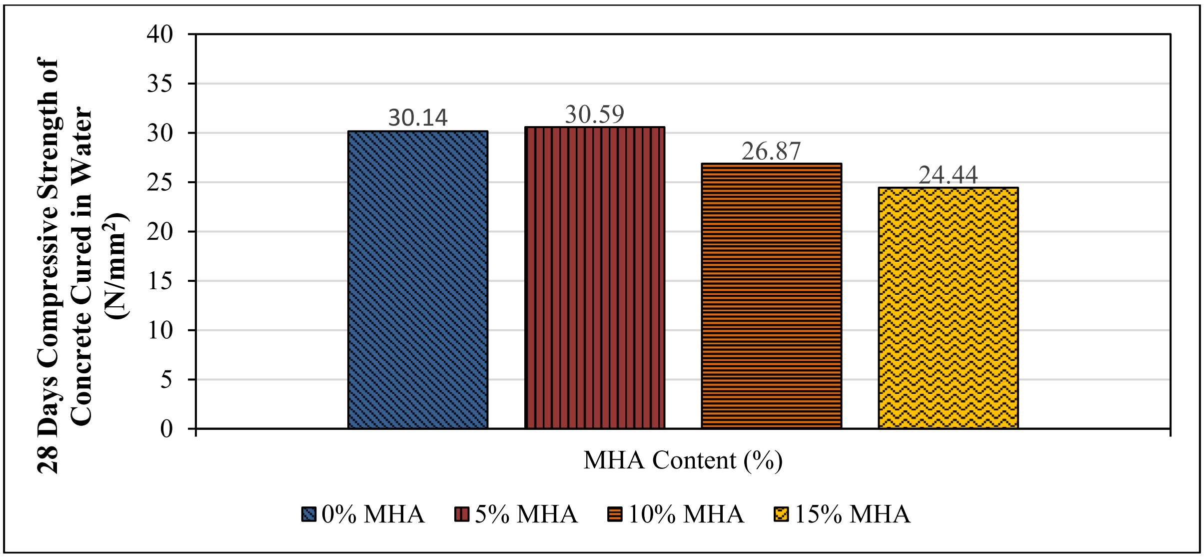

Figure 1: Average 28 days Compressive Strength of Concrete Samples

3.5 Fire Resistance

Concrete structures exposed to elevated temperatures, such as during fire outbreaks, experience significant changes in their physical and mechanical properties. To assess the fire resistance of MHA-blended concrete, a series of tests were conducted on 100x100x100 mm concrete cube specimens cured for 28 days and subsequently exposed to controlled heating at 200°C, 400°C, 600°C, and 800°C. The parameters evaluated included residual density, percentage weight loss, residual compressive strength, and visual inspection for surface cracking, discoloration, and spalling.

3.5.1 Density and Mass Loss of Concrete Cubes Subjected to Elevated Temperatures

Figure 5 present the average densities and weight changes of concrete specimens subjected to elevated temperatures. For the control samples, the average mass before exposure to fire was 2310g, reducing to 2144g after thermal treatment indicating a 7.16% weight loss at 800°C. This aligns with recent findings that thermal degradation leads to progressive loss of physically bound and chemically bound water, especially above 400°C (Chen, Wu & Wang, 2020; Yusuf, Saleh & Musa, 2022).

Specifically, the control mix experienced mass reductions of 0.50%, 0.59%, 5.42%, and 7.16% at 200°C, 400°C, 600°C, and 800°C, respectively, while samples containing 5%, 10%, and 15% Millet Husk Ash (MHA) exhibited weight losses of 6.85%, 7.01%, and 7.42% at 800°C, respectively. The increased weight loss in higher MHA content samples suggests greater moisture expulsion and less thermal stability. This is consistent with the view that pozzolanic-rich blends may form less thermally durable hydrates compared to pure Portland cement systems (Afolayan & Ogunbiyi, 2021). The decline in density with rising temperature was attributed to pore expansion, moisture evaporation, and decomposition of hydration products. Notably, $Ca(OH)_2$ begins to decompose at 400°C, releasing water and leaving behind CaO, which increases porosity. At temperatures exceeding 600°C, the breakdown of C–S–H gel becomes prominent, leading to structural weakening (Liu, Wang & Zhang, 2023).

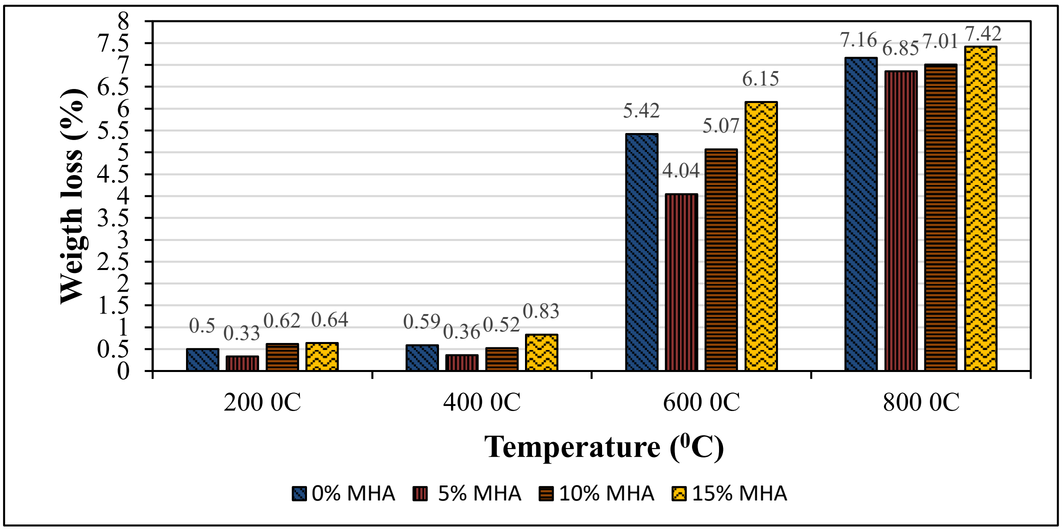

Figure 5: Percentage weight decrease for fired cubes Between 200 to 800 °C

3.5.2 Residual Compressive Strength of Fired MHA Concrete

Figure 6 presents the residual compressive strengths of concrete specimens exposed to elevated temperatures. The results indicate a notable decline in mechanical performance across all mixes, particularly at higher thermal exposures. For the control mix, the compressive strength decreased from 30.14 N/mm² (ambient condition) to 17.70 N/mm² after exposure to 800°C, amounting to a 41.29% strength loss. Intermediate losses were recorded as 0.94% at 200°C, 2.68% at 400°C, and 4.58% at 600°C. This progressive deterioration is consistent with findings that high-temperature exposure leads to evaporation of free and bound water, microcrack propagation, and decomposition of hydration products, particularly calcium silicate hydrate (C–S–H) (Afolayan & Ogunbiyi, 2021; Yusuf *et al*., 2022).

In comparison, concrete samples with 5% MHA, 10% MHA, and 15% MHA at 800°C experienced compressive strength losses of 46.21%, 48.17%, and 57.46%, respectively. These higher losses suggest that while MHA contributes to pozzolanic reactivity at ambient conditions, its influence on thermal durability may be limited, especially at extreme temperatures. The more porous microstructure of MHA-blended matrices likely exacerbates thermal degradation through accelerated internal moisture movement and weakened interfacial transition zones (Chen *et al*., 2020; Liu *et al*., 2023). According to BS EN 1992-1-2 (2004), concrete exposed to 800°C is expected to retain at least 50% of its original compressive strength. While the control, 5% and 10% MHA mixes marginally meet this requirement, the 15% MHA samples fall short, suggesting the need for careful dosage optimization of MHA in thermally exposed structures.

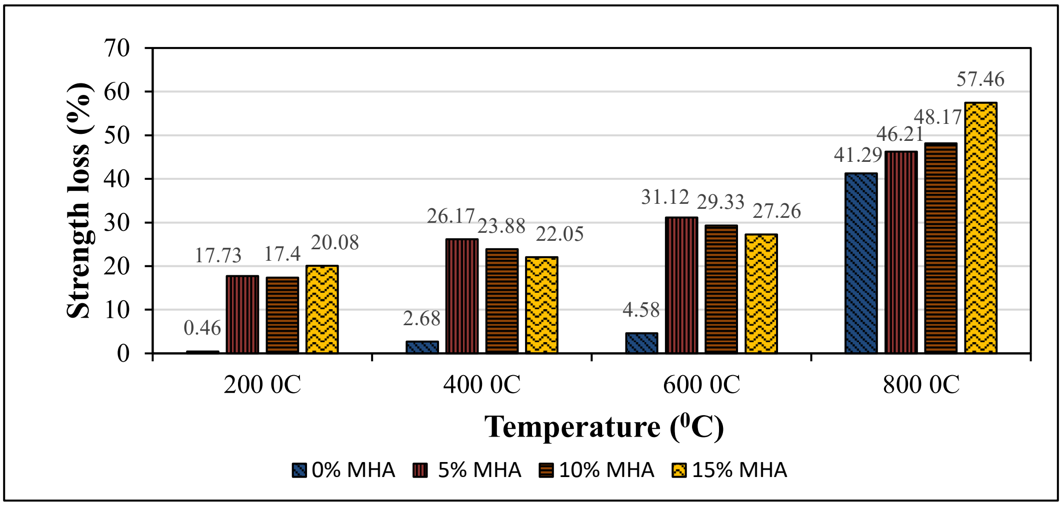

Figure 6: Residual compressive strengths of fired samples cured at 28 Days

3.5.3 Visual Fire Resistance Observations

Table 6 presents the results of the visual assessment following fire exposure. Concrete cubes were subjected to a controlled heating regime in a kiln, gradually raised from ambient temperature to 800°C. During exposure up to 600°C, both the control and 5% MHA specimens retained their structural integrity with no significant visible damage, while the 10% and 15% MHA samples developed initial hairline cracks. Upon reaching 800°C, the control and 5% MHA samples exhibited the formation of fine, elongated cracks, but remained largely intact. In contrast, the 10% and 15% MHA specimens developed multiple pronounced hairline cracks, leading to structural failure and complete surface disintegration.

The firing process lasted 165 minutes, during which the specimens were observed at key temperature intervals. Up to 600°C, the control and 5% MHA mixes remained visually stable, demonstrating superior resistance to thermal degradation. However, with further heating to 800°C, all samples showed varying degrees of cracking, with the higher MHA content specimens (10% and 15%) suffering the most severe deterioration.
These observations suggest that concrete containing up to 5% MHA exhibits enhanced fire resistance compared to higher MHA replacement levels, likely due to better matrix cohesion and reduced internal porosity at elevated temperatures.

Table 1: Visual Fire Resistance Observations of MHA Concrete Samples

Sample Type	T (°C)	Crack Formation	Visual Condition	Remarks
Control	600	None	Stable	No visible damage
5% MHA	600	None	Stable	No visible damage
10% MHA	600	Hairline cracks	Slight cracking	Early signs of distress
15% MHA	600	Hairline cracks	Slight cracking	Early signs of distress
Control	800	Thin, elongated cracks	Partial surface cracking	Moderate degradation
5% MHA	800	Thin, elongated cracks	Partial surface cracking	Moderate degradation
10% MHA	800	Multiple hairline cracks	surface cracking	Severe degradation
15% MHA	800	Multiple hairline cracks	Failed	Severe degradation and spalling

3.6 Predicting the Compressive Strength of MHA Concrete Exposed to Elevated Temperature and Validation of the ANN Model

The artificial neural network (ANN) model developed to predict the compressive strength of concrete incorporating millet husk ash (MHA) as a partial replacement for cement demonstrated excellent performance across a range of elevated temperature exposures specifically 200 °C, 400 °C, 600 °C, and 800 °C. Table 7 and Figures 7 to 14, the model produced consistently high coefficients of determination (R^2) for both the training and testing phases across all temperature conditions. The R^2 values obtained from the ANN model for both the training and testing datasets were 0.9998, 0.9989, 0.9999, and 0.9999 at 200 °C, 400 °C, 600 °C, and 800 °C, respectively, indicating excellent predictive accuracy across all thermal exposure conditions.

These results indicate that the model was able to capture over 99.8% of the variance in the experimental data across all thermal exposure levels, signifying strong learning and generalization capabilities. The accuracy and reliability of the model are further reinforced by the low error metrics. The mean absolute error (MAE) and mean squared error (MSE) across all temperatures remained minimal. For instance, the MAE values ranged between 0.0004 and 0.0006, while the MSE values were between 0.0001 and 0.0003, indicating negligible discrepancies between the predicted and actual compressive strength values. These metrics affirm the model's robustness and effectiveness in capturing the nonlinear behavior of MHA concrete subjected to high thermal stress. Collectively, the results show that MHA blended concrete retains substantial compressive strength even after exposure to elevated temperatures, demonstrating its potential suitability for structural applications in fire-prone or thermally aggressive environments. This conclusion is supported by recent studies such as Ahmadi *et al.*, (2017) and Kumar *et al.*, (2024), which also highlighted the resilience of pozzolanic-based concrete composites under thermal degradation.

Table 7: Statistical Assessment of Error in the Developed ANN Model at Various Elevated Temperatures

Temperature (°C)	Dataset	R^2	MAE	MSE
200	Training	0.9998	0.0004	0.0001
	Testing	0.9998	0.0004	0.0001
400	Training	0.9989	0.0004	0.0001
	Testing	0.9989	0.0004	0.0001
600	Training	0.9999	0.0004	0.0001
	Testing	0.9999	0.0004	0.0001
800	Training	0.9999	0.0004	0.0001
	Testing	0.9999	0.0004	0.0001

Regression Equations: For 200 °C, y_pred (N/mm²) = 1.00 × X + 0.0002 ($R^2 = 0.9998$)
For 400 °C, y_pred (N/mm²) = 1.00 × X + 0.0005 ($R^2 = 0.9989$)
For 600 °C, y_pred (N/mm²) = 1.00 × X + -0.0000 ($R^2 = 0.9999$)
For 800 °C, y_pred (N/mm²) = 1.00 × X + 0.0001 ($R^2 = 0.9999$)
Where: y_pred = Predicted compressive strength of MHA concrete exposed.
X = Linear combination of independent variables defined as:
$X = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \varepsilon$
$X_1, X_2, \ldots, X_n$ = Input features (such as, cement content, MHA %, water-cement ratio, etc.)
$\beta_0, \beta_1, \ldots, \beta_n$ = Regression coefficients
ε = Model residual (error term)

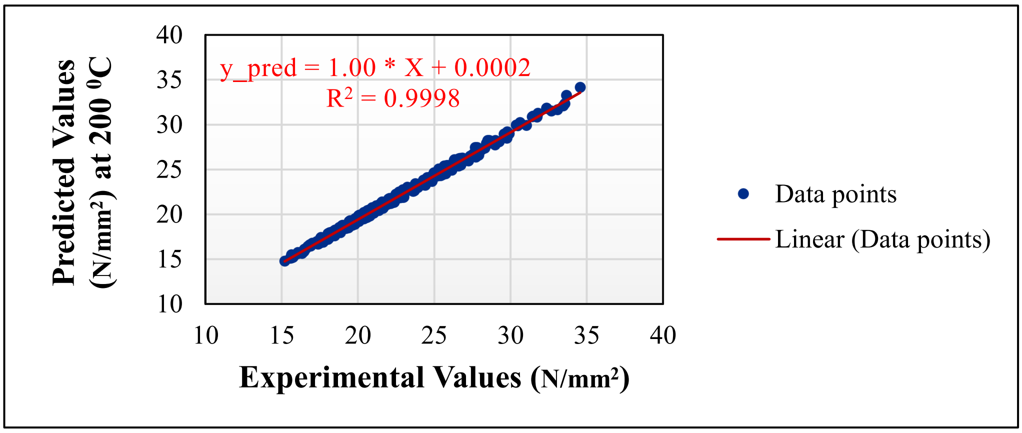

Figure7: Correlation between Experimental and Predicted Compressive Strength of MHA Concrete after Exposure to 200 °C

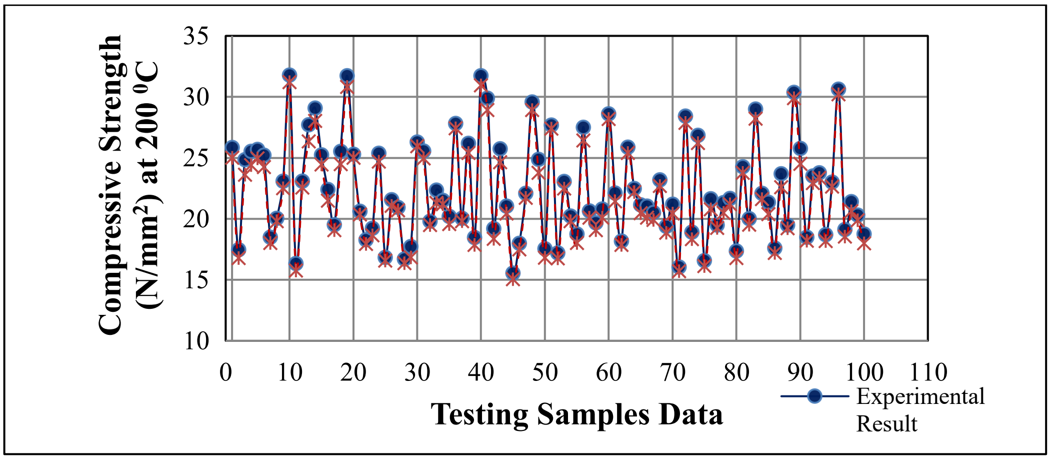

Figure 8: Representation of Experimental, Predicted, and Error Values

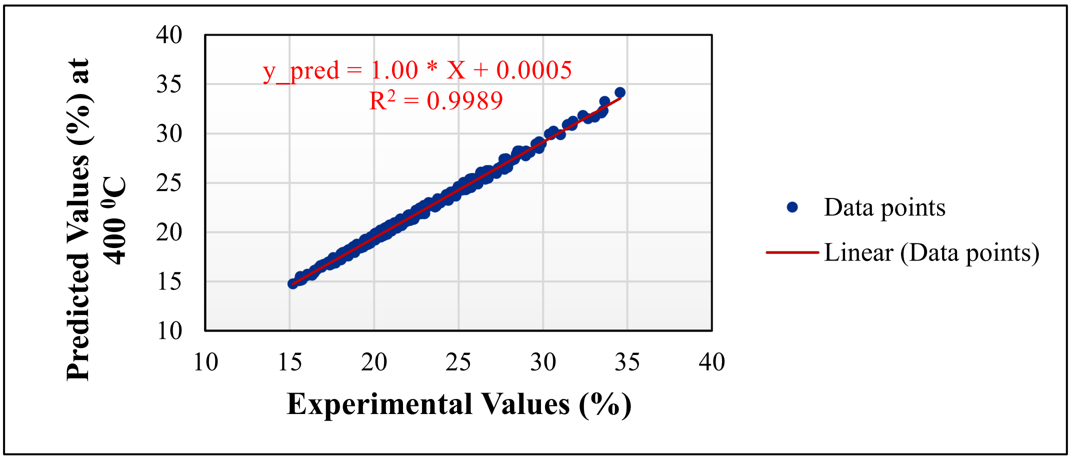

Figure 2: Correlation between Experimental and Predicted Compressive Strength of MHA Concrete after Exposure to 400 °C

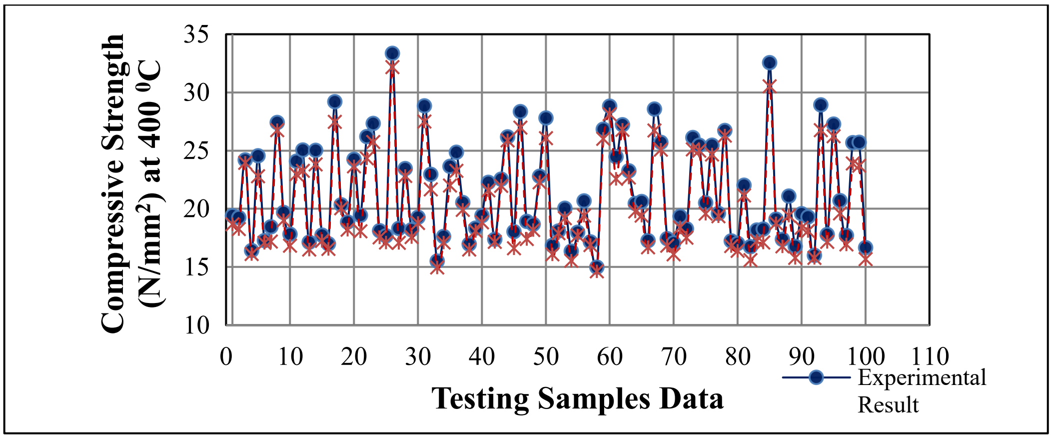

Figure 3: Representation of Experimental, Predicted, and Error Values

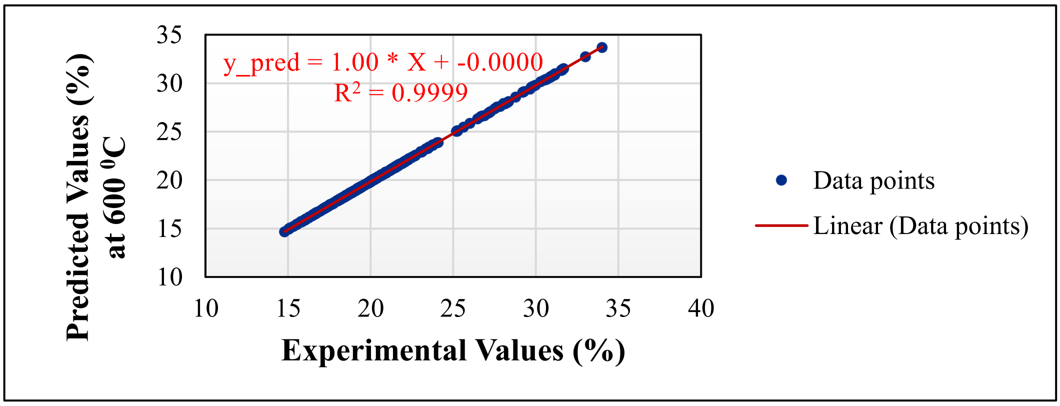

Figure 11: Correlation between Experimental and Predicted Compressive Strength of MHA Concrete after Exposure to 600 °C

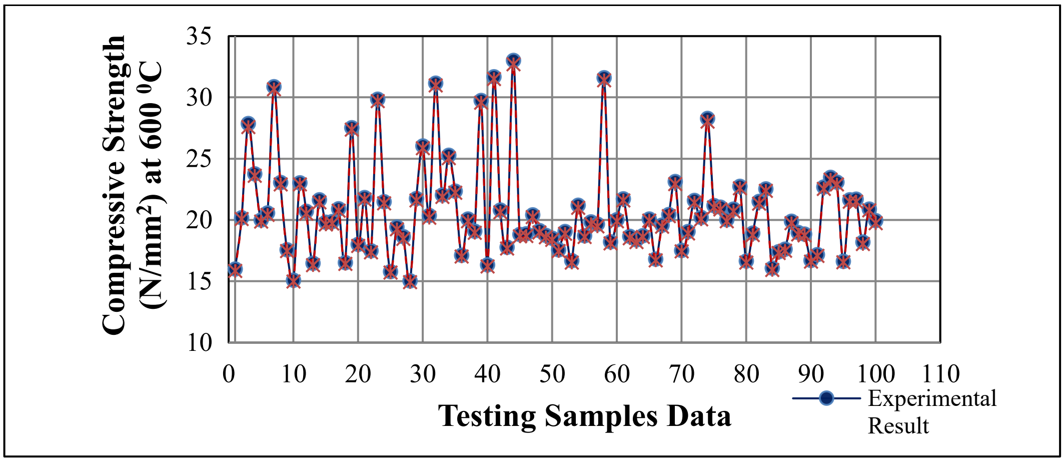

Figure 4: Representation of Experimental, Predicted, and Error Values

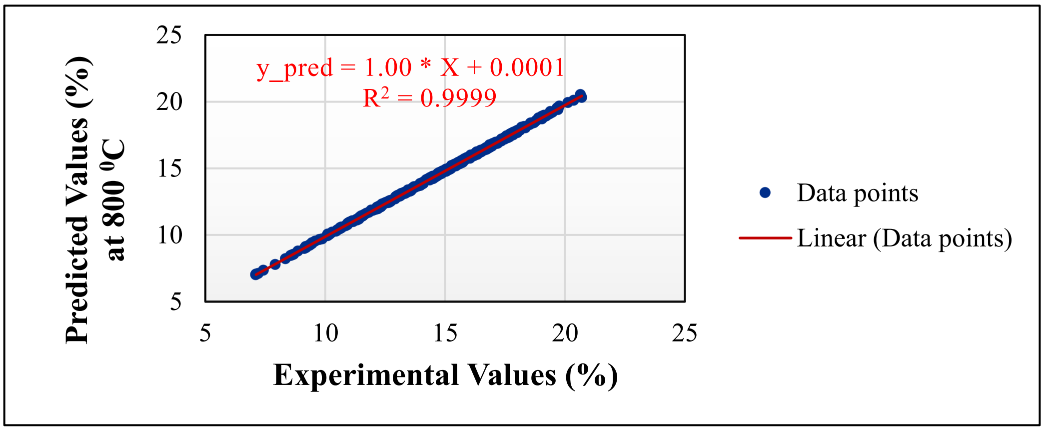

Figure 5: Correlation between Experimental and Predicted Compressive Strength of MHA Concrete after Exposure to 800 °C

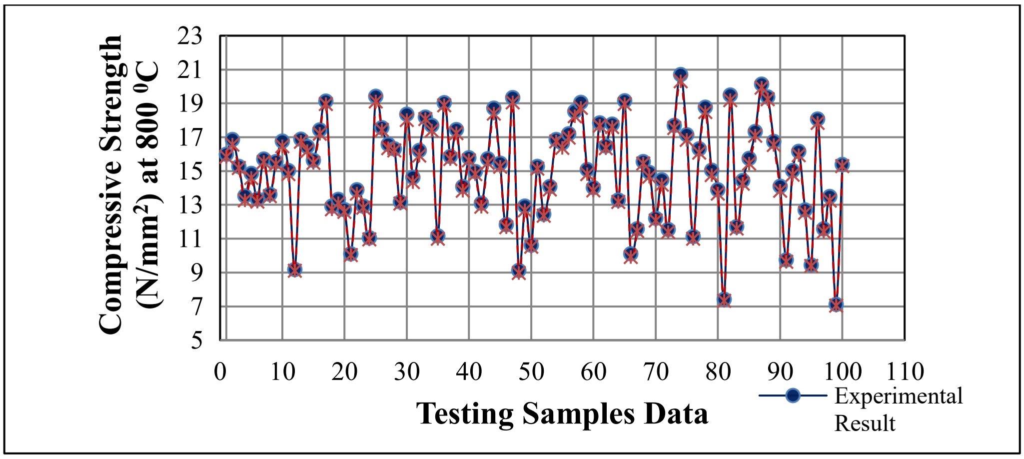

Figure 6: Representation of Experimental, Predicted, and Error Values

IV. Conclusion

The use of millet husk ash (MHA) as a partial cement replacement in concrete exposed to elevated temperatures and ANN based predictive modeling offers a viable approach to producing sustainable concrete. The study reveals that MHA confirmed as a Class F pozzolanic material, meeting BS EN 197-1:2011 standards. At 28 days, 5% MHA replacement improved compressive strength by 1.5%, while 10% and 15% replacements led to 11% and 19% strength reductions, respectively, with only 5% and 10% meeting minimum strength requirements. Elevated temperature exposure caused reductions in mass, strength, and structural integrity across all mixes, with 5% and 10% MHA exhibiting greater thermal degradation than the control, though still compliant with fire resistance standards up to 800°C. Visual inspections showed better integrity for 5% MHA mixes under thermal stress. The developed ANN model accurately predicted compressive strength under thermal exposure with coefficients of determination (R^2) exceeding 0.998, validating its use for performance forecasting of MHA concrete in thermally aggressive environments.

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