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Correlating the thermomechanical indexes of concrete modified with anacardium occidentale nutshell ash using linear model polynomial analysis

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Abstract. This study correlated the thermal and mechanical properties of concrete produced with anacardium occidentale (cashew) nutshell ash (AONA). Cashew nutshells, agricultural waste products, was valorized to obtain AONA. AONA was replaced at 5, 10, 15, and 20 wt% of cement to produce concrete grade 25 MPa. Density, compressive strength, and thermal conductivity of the concrete samples were determined at 28 days curing, and the results were correlated using regression model analysis. The experimental findings revealed that the compressive strength increased with increasing AONA content. Moreover, both density and thermal conductivity reduced as AONA content increased. Besides, the correlation yielded a high precision with 97% "R^2". Thus, AONA has proved to exhibit higher mechanical strength with excellent thermal insulation when utilized as supplementary cementitious material (SCM) in concrete production. The developed model can also be applied to the correlation of thermomechanical properties of concrete incorporating SCMs in that time, energy, and cost in conducting laboratory works would be reduced.

Keywords: supplementary cementitious materials; waste management; sustainability; compressive strength; thermal conductivity; thermal insulation; building comfort; modelling.

1. Introduction

In recent years, scientific research is oriented towards energy consumption and environmental concerns threatening thermally efficient buildings. In the construction sector, efforts are in progress to conserve energy and resources by valorizing waste materials while to improve comfort conditions for thermally efficient buildings [1]. Furthermore, concerted attention has been drawn to the increasing energy costs and climate change due to energy performance and efficiency [2]. Buildings consume about 40-50% supply of energy and waste about 50-60% generation of energy [3]. Consequently, the demand for building comfort conditions has risen. However, more attention is drawn to the aesthetic values of buildings in Nigeria with little or no consideration for the environment, energy efficiency, health, and economy [4]. Thus, previous studies [2, 5] recommended a careful selection of building materials that would improve thermal comfort in buildings, especially in hot or arid climatic condition.

Structural concrete members, beams, slabs, and columns, are the backbone of any structure/building, hence playing the significant role in creating and maintaining buildings' internal environment, apart from block walling components. Therefore, the internal temperature of a building can be maintained at a lower cost when a building is passive (structural members exhibiting thermal insulating characteristics) [6].

A review of previous studies [7-9] revealed that concrete modified with SCMs, blast furnace slag (BFS), silica fume (SF), fly ash (FA), and corncob ash (CCA), were promising thermal insulating materials. However, the study on thermal characteristics of AONA in concrete production is still limited. Anacardium occidentale (cashew) nutshell is an agricultural waste product with about 4.2 million metric tonnes (MMT) of global generation in 2017; from this global generation, about 100 MMT was estimated in Nigeria [10]. Notwithstanding, some of these materials are disposed of as wastes, thus creating environmental concerns.

Therefore, this study filled a gap by recycling the anacardium occidentale nutshells and applying it as SCM for concrete production. Its effects on thermomechanical properties were examined, and the results were correlated using the regression model analysis in Matlab 2017a. In achieving these objectives, concrete grade 25 MPa was selected as mix design proportion due to its widespread uses in the construction sector.

2. Materials and Methods

2.1. Materials

Cashew nutshells were obtained from the Federal University of Agriculture, Abeokuta, Nigeria. After the pyrolysis, about 21 wt% of cashew nutshells was obtained as AONA. The specific gravity (SG) and fineness of AONA and Portland limestone cement (PLC) were obtained by the procedure outlined in *British Standard, BS EN* [11]. The results revealed the SG of 2.80 and 3.15 g/cm^3, and fineness of 8.10 and 7.60% for AONA and PLC, respectively; these results indicated that more volume of AONA and water would be needed when AONA is replaced by wt% of PLC for concrete production due to lower SG and higher fineness [12]. The results of XRF analysis for both AONA and PLC are shown in Table 1.

Table 1. Oxide compositions of the binding materials used

Oxide Composition	CaO (%)	SiO$_2$ (%)	Al$_2$O$_3$ (%)	Fe$_2$O$_3$ (%)	MgO (%)	K$_2$O (%)	Na$_2$O (%)	SO$_3$ (%)	TiO$_2$ (%)	P$_2$O$_5$ (%)	LOI (%)
AONA	2.04	65.02	16.28	10.16	1.53	0.52	0.45	1.32	0.01	0.01	2.95
PLC	64.50	21.55	5.50	3.08	1.52	0.61	-	2.03	-	-	1.20

LOI = Loss of Ignition, determined at 800 °C.

Sharp sand (≤ 4.5 mm) and granite (12.5 mm) were used as both fine and coarse aggregates and obtained from an aggregate dealer in Ota, Nigeria. The physical properties were examined based on *BS EN* [13]'s procedure. The results indicated 2.60 and 2.64 g/cm^3 as specific gravity, 0.7 and 0.8 % as water absorption, and 0.3 and 0.2% as moisture content for both fine and coarse aggregates, respectively.

2.2. Experimental methods and tests

The mix was designed in consonance with the procedure stated in *BS EN* [14]. For the mix, the quantities of binding material (AONA and PLC), fine aggregate, and coarse aggregate were 340, 715, 1035 kg/m^3, respectively, hence indicating the water to binder ratio as 0.62. AONA was replaced at 0, 5, 10, 15, and 20 wt% of PLC, denoting as T0, T1, T2, T3, and T4, respectively.

The mix constituents were prepared in line with *BS EN* [15]'s procedure. The concrete samples were tested at 28 days. Both density and compressive strength (CS) were determined by *BS EN* [16] and *BS EN* [17] methods, respectively. The average temperature and relative humidity (RH) during the test were 28 °C and 65%, respectively. For each mix ID, the mean of three (3) tests was used for the analysis.

The thermal conductivity (TC) test was performed at 28 days curing of samples based on *BS EN* [18]'s procedure. The samples, panels 300 × 300 × 55 mm^3, were oven-dried at 105 °C for 24 h to remove any moisture content. For the induction of interior and exterior temperatures, the samples were placed between the hot plate and cold plate at 40 °C and 18 °C temperatures, respectively. At every 10 min, both hot and cold plates' temperatures were recorded for 24 h. The simplified condition of one-dimensional heat transfer was adopted by this study. Therefore, the concrete TC was obtained using Fourier's law, as indicated in Equation (1).

$$k = \frac{\Phi \times t}{A \times \Delta T} \qquad (1)$$

where k = TC (W/mK)
   Φ = heat flow (J/s)
   t = thickness of specimen (m)
   A = area of the specimen (m^2)
   ΔT = temperature difference between hot and cold plates (°C).

The density, CS, and TC results were correlated using statistical software, Matlab 2017a, setting TC as dependent variable (predictor), and both density and CS as continuous (independent) variables.

3. Results and Discussions

3.1. Chemical compositions of Binders
The oxide compositions, as presented in Table 1, indicated that AONA met 70% minimum requirements of *BS EN* [19] for $SiO_2 + Al_2O_3 + Fe_2O_3$, and 5% maximum specification for LOI. Therefore, the material is desirable for use as SCM.

3.2. Concrete density
The concrete density, as shown in Figure 1, decreased as the AONA content in the mix increased. This may be attributed to the lower SG of AONA, which in turn reduced the interfacial particle of PLC, thus decreasing the concrete density [12]. These results also agreed with the findings from previous studies [20-22] that density decreases with increasing SCMs in the mix. Therefore, the incorporation of AONA in concrete production reduces the dead load and contributes to buildings' lightweight.
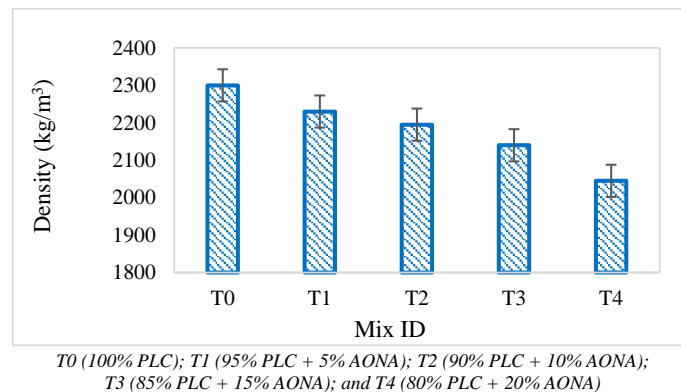

T0 (100% PLC); T1 (95% PLC + 5% AONA); T2 (90% PLC + 10% AONA);
T3 (85% PLC + 15% AONA); and T4 (80% PLC + 20% AONA)
Figure 1. Concrete density at 28 days curing

3.3. Compressive strength
The compressive strength (fc) results, as shown in Figure 2, at 28 days curing showed that the fc increased as AONA content increased. The results further revealed that AONA replacement at 15 wt% of PLC exhibited the highest CS compared with other replacement proportions. The increase in CS with increasing AONA could be associated with the higher contents of silica and alumina oxides in AONA compared with PLC; these oxides reacted with hydrating agents of PLC, resulting in the strengthening paste and bonding improvement in the concrete [12]. However, the strengthening improvement was optimum at 15 wt% AONA compared with 5, 10, and 20 wt% AONA. Ultimately, a 5-20 wt% of AONA could be incorporated for concrete structural applications because they fulfilled the concrete target strength of 25 MPa stipulated by *BS EN* [23].
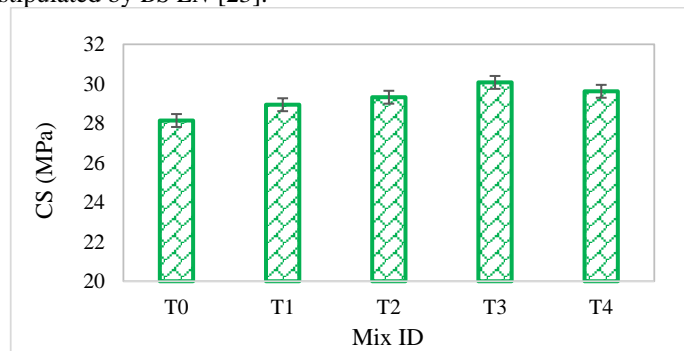

Figure 2. Compressive strengths

3.4. Thermal conductivity (TC)

As shown in Figure 3, the TC reduced as AONA content in the mix increased due to the decrease in density with increasing AONA content. Moreover, less air would be entrapped as AONA content in the blend increased due to its higher fineness compared with PLC, thus reducing the rate of heat transfer through the concrete and subsequently reducing the TC [12]. This result signified that the recycling and incorporation of AONA in concrete production reduce the environmental challenges, improve the thermal insulation, and enhance the building comfort.
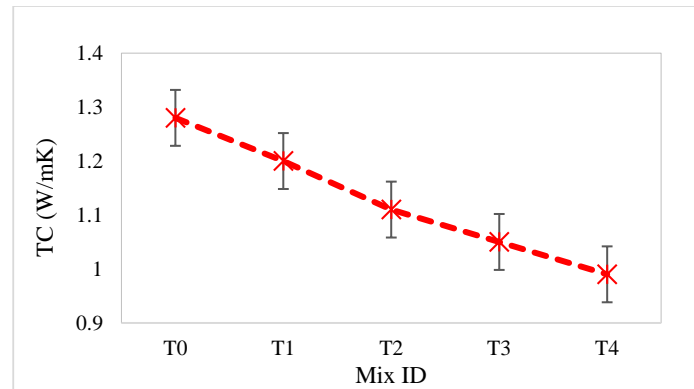

Figure 3. Thermal conductivity of the concrete produced

3.5. Correlation between CS, density, and TC

Following the linear model polynomial of regression analysis, the relationship between TC, density, and CS, as indicated in Figure 4, yielded a strong correlation with 97% coefficient of determination (R^2) at 95% confidence bounds to predict all variables. Moreover, the sum of squared errors (SSE) and root mean squared errors (RMSE) signified that the data fit the regression line because the values were between 0 and 1 [24]. Therefore, the relationship is illustrated in Equation (2), and the model can be used to predict future data trends and enhance data quality on the thermal insulation values in relation with the weight and mechanical cost of concrete modifying with AONA.
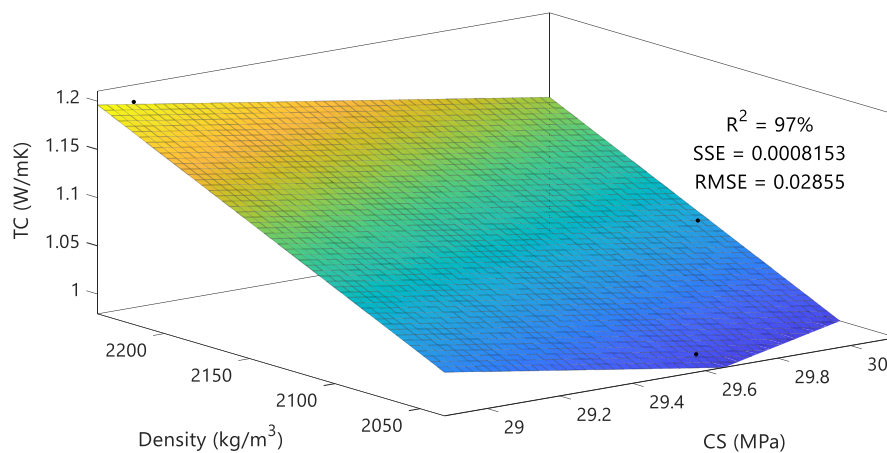

Figure 4. Correlation of CS with density and TC at 28 days curing

$$\lambda = 1.008 - 0.0588 fc + 0.0008423 \rho \qquad (2)$$

where λ is the TC (W/mK),
    fc is the CS (MPa),
    ρ is the concrete density (kg/m^3).

3.6. Validation of the developed model with previous studies

Following the regression model illustrated in Equation (2), Figure 5 presents the relationship between the proposed model equation and the previous studies at 28 days curing. The results, as indicated in Figure 5, showed that both Experimental TC (ETC) and predictive TC (PTC) exhibited a good precision, thus yielding a good relationship with *Gomes et al.* [25], *Demirboga* [7], and TC obtained herein at 52, 87, and 97% R^2, respectively. Therefore, the developed model illustrated in Equation (2) can be applied to the prediction of TC related to concrete strength and weight incorporating SCMs in that *Gomes et al* [25] and *Demirboga* [7] utilized SCMs, fly ash, silica fume, metakaolin, and blast furnace slag, as replacements of Portland cement for concrete production with high and adequate strengths at 28 days curing.
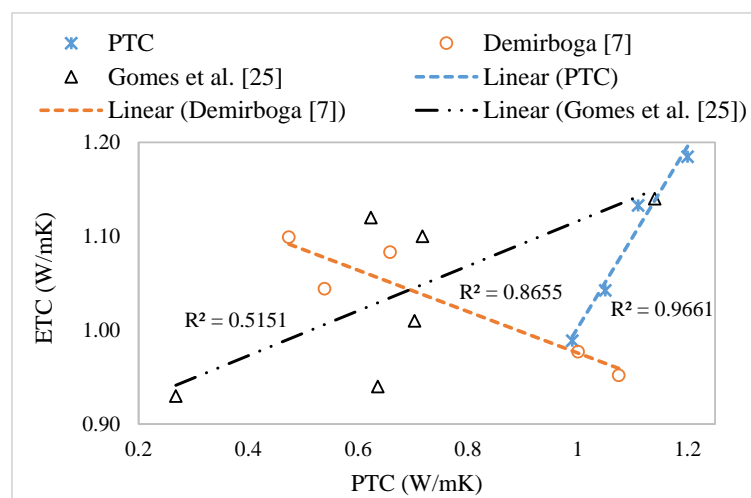

Figure 5: Validation of the proposed model with previous studies

4. Conclusions

This study correlated the concrete TC with CS and density, and the results obtained are promising:
  i.   At 28 days curing, there was about a 6% decrease in TC at every 5 wt% increase of AONA in the mix. Moreover, about 6-23% decrease in TC was obtained as AONA increased from 5-20% compared with the control concrete.
  ii. There was nearly a 1.5% increase in CS at every 5 wt% increase in AONA content at 28 days curing, but maximum CS occurred at 15 wt% of AONA's substitution.
  iii. The concrete becomes lighter with increasing AONA content in the mix. There was about 3-4% decrease in concrete density at every 5 wt% of AONA replacement in the combination.
  iv. A strong correlation exists between the concrete TC, and CS and density with 97% R^2 at 28 days curing.

Acknowledgement

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