ARID ZONE JOURNAL OF ENGINEERING, TECHNOLOGY & ENVIRONMENT

AZOJETE September 2026. Vol.22(3):560-571
Published by the Faculty of Engineering, University of Maiduguri, Maiduguri, Nigeria.
Print ISSN: 1596-2490, Electronic ISSN: 2545-5818
https://doi.org/10.63958/AZOJETE/2026/22/03/001
www.azojete.com.ng

ORIGINAL RESEARCH ARTICLE

OPTIMIZATION OF PERIWINKLE SHELL ASH AND SAWDUST MIXTURE AS ADDITIVES IN FIRED CLAY BRICK USING GREY RELATIONAL ANALYSIS IN TAGUCHI METHODOLOGY

S.O. Jimoh[1], F.O. Anafi [1,2], A.M. Na'inna[3*]

[1]Department of Mechanical Engineering, Ahmadu Bello University Zaria, Nigeria
[2]TETFund Centre of Excellence in Pedagogy, Ahmadu Bello University Zaria, Nigeria
[3]Armament Engineering Department, Air Force Institute of Technology Kaduna, Nigeria
**Corresponding Author's email: abdulmajid.nainna@airforce.mil.ng*

ARTICLE INFORMATION

Received: 27th March 2026
Revised: 27th July 2026
Accepted: 29th July 2026

Keywords:
Periwinkle shell ash
Sawdust
Fired brick
Optimum mixture
Grey relational analysis
Taguchi methodology

ABSTRACT

The use of additives remains one of the methods of enhancing compressive strength and thermal conductivity of a clay bricks used for various applications in the construction industry. However, obtaining the right mixtures of additives remain a concern by most researchers. In this study, an experimental and modelling approaches were used to determine optimum mixture of periwinkle shell ash (PSA) and sawdust (SD) additives at 5-20 % by weight at 900-1100°C firing temperature on fired bricks. The objective of the study was to evaluate the thermo-mechanical properties of the additives with a view to minimizing thermal conductivity and enhancing compressive strength. Consequently, an optimal thermal conductivity of 0.3486 W/mK was obtained for the additives using a control factor setting of $SD_{10}PSA_{15}FT_{1100}$. In case of an optimum value for a compressive strength, a value of 8.2234 MPa was obtained employing a control factor setting of $SD_{10}PSA_{10}FT_{1100}$. The estimated values obtained in the present study aligned with the suggested thermal conductivity of less than 0.6 W/mK and the proposed minimum compressive strength of at least 7 MPa. This fulfils the "Lower the Better" and "Higher Better" criterion for thermal conductivity and compressive strength respectively. In addition, a close relationship between predicted and experimental values of thermal conductivity affirmed the acceptance of the prediction model with an R-squared value of 96.25%. Conversely, as for the compressive strength, the predicted and experimental values exhibited a close relationship where the prediction model also boasts an R-squared value of 89.93%, signifying its strong acceptability for accurate predictions. The present study will be utilized in optimizing the quantity of additives used in the production of clay fired bricks for various industrial heat containment and eco-friendly applications.

© 2026 Faculty of Engineering, University of Maiduguri, Nigeria. All rights reserved.

1.0 Introduction

Globally, clay minerals are widely used in brick production in the construction industry with about 3 billion m³ of clay reserves used yearly to make 1.5 billion bricks (Mohajerani *et al.*, 2019). Fired bricks especially refractory bricks are broadly applied in bakery ovens due to its ability to retain and resist heat. Some technical properties of fired bricks include water absorption, contraction, permeability, bulk density, thermal conductivity and compressive strength (Sarani, *et al.*, 2023). Hence, understanding and optimizing these properties are essential for selecting, designing and utilizing refractory materials effectively in various industrial processes. Generally, a compressive strength is referred to as the highest severe load or pressure a material could bear before it breaks, cracks or bends eternally. According to Sutcu (2016), a minimum compressive strength of 7 MPa and more is suggested for bricks utilized in the construction of standard building. However, a compressive strength of below 5 MPa is applied for non-structural functions such as non-load bearing constructions (Adazabra, 2023). Also, for thermal conductivity, it is an inherent ability of an object such as bricks to transmit or conduct heat via a direct contact. Nevertheless, low thermal conductivity values are required as they signify a lesser heat increase or loss, thus, improved insulating bricks. Therefore, most fired bricks have thermal conductivities in the range of 0.6 to 1.4 W/mK reliant upon firing temperature, mineral configuration and technique of construction (Gualtieri, *et al.,* 2010; Oyediran, *et al.,* 2024).

Currently, there is increased desire to exploit unused materials as clay alternatives in the production of bricks in the construction industry primarily due to fast exhaustion of clay reserves and increase in the quantity of waste produced globally (Lawanwadeekul, *et al.,* 2024; Al-Fakih, 2019). Interestingly, the wastes utilized as additives in manufacturing fired bricks are mostly grouped into four, namely; ash, mineral wastes, biological wastes and sewage slush (Velasco, *et al.,* 2014). It is noteworthy that the most prominent additive is organic (biological) type such as sawdust (SD) because it is cheaply available and burns off throughout the course of firing, thus creating openings that reduce the bricks' thermal conductivity (Arslan, *et al.,* 2021; Rao, *et al.,* 2024). Although the utilisation of sawdust is beneficial in fired bricks, it could also lead to a decrease in compressive strength and perchance improved water absorption (Beal *et al.,* 2019; Cultrone *et al.,* 2020; Alabduljabbar *et al.,* 2021). To ameliorate this, a periwinkle shell ash (PSA) as a waste additive could improve the compressive strength of the fired bricks when fused into the clay mix (Abdullahi and Sara, 2015; Ruslan *et al.,* 2021).

To attain optimum gains of additives on fired clay bricks, two or more additives are mixed together. For instance, Okunade (2008) studied the implications of mixing sawdust and wood ash to a laterite-clay. The additives were incorporated in numerous blends of quantity from 0 to 10 % by volume. It was discovered that the prime influence of the sawdust is the reduction in the dry density of the manufactured fired brick from 1755 kgm^3 to 1512 kgm^3 for the control mix without additives and for a mix with 10% sawdust content respectively. The wood ash mixture with intrinsic pozzolanic nature, was able to assist in achieving stronger bricks with advanced compressive strengths of 19.15 MN/m^2 for 10% wood ash and 18.42 MN/m^2 for the control mix devoid of additives. Also, Njoku *et al.,* (2024) studied the influence of substituting normal Portland cement with PSA and river sand with quarry dust (QD) on the mechanical and physical features of concrete using diverse weight configuration ranging from 0 to 100 percent. The control sample offered a superlative compressive strength of 22.9 N/mm^2, more than those that were partly swapped, spanning between 18.8 and 15.1 N/mm^2. Hence, it was inferred that fractional replacements with PSA and QD yielded concrete appropriate for structural and non-structural bearing uses.

Presently, there exist a knowledge gap in optimizing the quantity of SD with strength-enhancing additives like PSA using design software to assurance that appropriate additive quantities and firing temperatures are designated to realise good heat conduction and permeability devoid of declining compressive strength (Akpomie, *et al.,* 2025). Consequently, this paper seeks to determine an optimum mixture of periwinkle shell ash and sawdust additives for enhanced compressive strength and thermal conductivity of a fired brick using Grey relational analysis in Taguchi methodology.

2. Materials and Method

2.1 Materials

The three major materials used in the study are clay (Kaolin), periwinkle shell and sawdust, all sourced within Zaria, Nigeria. The clay material was initially cleansed to eliminate undesirable particles using gravity sedimentation after a day water immersion, followed by sifting. Consequently, the clay was sun-dried for three days and thereafter oven-dried at a temperature range of 50-110°C. A periwinkle shell (PS) as an additive was exposed to a treatment process equivalent to that of the clay to remove harmful materials. Thereafter, the PS was washed, sun-dried for 2 days, and then oven-dried at 110°C to guarantee in-depth removal of moisture. Subsequently, the PS underwent calcination at a temperature of 800°C in order to induce the disintegration of the PS into Periwinkle shell ash (PSA). This gave way for the material to be crushed and sieved to attain a fine particle size of 0.5mm. The sawdust equally underwent a process of removing unwanted particles using soaking in it in water. Afterward, the sawdust was subjected to sun-drying for 3 days followed by grinding and sieving to achieve finely sized particles within the range of nearly 1mm.

2.2 Method

2.2.1 Design of experiment using Minitab Software Program (Taguchi)

An experimental design for this study involved the use of a Minitab 21 Software version with an inherent capacity to optimize products and processes by making them robust and hardy against background interference such as noise. The developmental factors for the design purpose were percentage composition of SD, PSA and the firing temperature. The statistical analysis of the laboratory responses was conducted through data analysis, and the best performing combination was validated through experimental means. Within the Taguchi optimization technique, the notion of signal-to-noise ratio entails quantifying the deviation between the measured effect and the desired values. In this context, the thermal conductivity was evaluated with the criterion of "the lower, the better," while the compressive strength was assessed with the principle of "the higher, the better." The Signal-to-Noise (S/N) ratio for the aforementioned responses as defined by Sylajakumari *et al.,* (2018) using Equation 1 and Equation 2 respectively as:

$$\left(\frac{S}{N}\right)_{LTB} = -10 * log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} yi^2\right) \quad 1$$

$$\left(\frac{S}{N}\right)_{HTB} = -10 * log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{yi^2}\right) \quad 2$$

2.2.2 Grey relational analysis

Grey Relational Analysis (GRA) was applied as the goal involves a multi-response optimization objective, this is a fitting approach for the current research where samples are enhanced to realise both low thermal conductivity and relatively high compressive strength. The Grey Relational Grade (GRG) is obtained from the gauged and processed results in the GRA. This GRG undergoes refinement through the application of the Taguchi optimization technique to attain the most favourable results. In this optimization process, all measured responses were amalgamated into a singular response known as the GRG. The Signal-to-Noise (S/N) ratio for these responses was computed, and the Grey Relational Coefficient (GRC) was obtained after the normalization of data.

Normalization of the responses for thermal conductivity and compressive strength was done by Tzeng and Huang (2011) using Equation 3 and Equation 4 respectively. For thermal conductivity, the objective was to minimize, and for compressive strength, the objective was to maximize.

$$x_i^*(k)_{LTB} = \frac{max_{xi}(k) - x_i(k)}{max_{xi}(k) - min_{xi}(k)} \quad 3$$

$$x_i^*(k)_{HTB} = \frac{x_i(k) - min_{xi}(k)}{max_{xi}(k) - min_{xi}(k)} \quad 4$$

where $x_i^*(k)$ is the order after the data computing i.e. for the ith trial and the kth response and $x_i(k)$ was the equivalence sequence. Reference sequence $(x_0^*(k) = 1)$ was taken as one for all the responses. Thus, the standardisation procedure reduced the inconsistency between the data.

The confidence Interval C.I for thermal conductivity (k) was calculated using Equations 5 and 6.

$$C.I = \sqrt{F_{\propto}(1, F_e)V_e\left[\frac{1}{\eta_{eff}} + \frac{1}{\eta_{ver}}\right]} \quad 5$$

where $F_{\propto}(1, F_e)$ = F ratio needed for α; α = Risk; F_e = degree of freedom of error; η_{ver} = number of trials for confirmation. η_{eff} = replications, and this could be obtained using Equation 6 as:

$$\eta_{eff} = \frac{N}{1 + [Total\ degree\ of\ freedom\ of\ controlled\ factors]} \quad 6$$

$F_{\propto}(1, F_e)$ = $F_{0.05}(1, 2)$ = 18.51 $(from\ Statistical\ table)$, V_e = error variance = 0.000753 (from ANOVA Table), N = replications * runs = 27, total degree of freedom of controlled factors = 6,

therefore η_{eff} = 3.85 and thus, $C.I_{(k)}$ = 0.091.

Also, the confidence interval for the compressive strength (σ) was calculated with Equation 5 and 6. $F_{\propto}(1, F_e)$ = $F_{0.05}(1, 2)$ = 18.51 $(from\ Statistical\ table)$, V_e = error variance = 0.2443 (from ANOVA Table), N = replications * runs = 27, total degree of freedom of controlled factors = 6,

therefore, η_{eff} = 3.85 and thus, $C.I_{(k)}$ = 1.64.

A confirmation test was conducted on the optimized sample, consisting of 10% SD, 10% PSA, and heated at a temperature of 1100°C. The experimental results for thermal conductivity and compressive strength were attained as 0.4074 W/mK and 7.83 MPa, respectively.
Predictive value – C.I < experimental value < predictive value + C.I.
The C.I. for both thermal conductivity and compressive strength were obtained from Equation 5.

- For thermal conductivity; 0.091 < 0.4074 < 0.4079 + 0.091

< 0.4074 < 0.4989
For compressive strength;

- 1.64 < 7.83 < 7.615 + 1.64

< 7.83 < 9.255

The confirmatory test results for the thermal conductivity and compressive strength for the optimized samples revealed that the experimental value fell within the confidence interval range. Additionally, a mathematical model was formulated to predict the behaviour of thermal conductivity, compressive strength, and grey relational grade in the insulation refractory lining with the aid of a Minitab 21 software. The regression model for the thermal conductivity, compressive strength and GRG is given by Equations 7, 8 and 9 respectively which can be used for prediction of the output response of any combination run.

$$\text{Thermal Conductivity} = 2.637 + 0.00150\ SD - 0.00606\ PSA - 0.001985\ FT \quad 7$$

$$\text{Compressive Strength} = 10.08 - 0.3510\ SD - 0.0660\ PSA + 0.00155\ FT \quad 8$$

$$GRA = 3.80 - 0.098\ SD - 0.184\ PSA - 0.00369\ FT - 0.00466\ SD * PSA + 0.000126\ SD * FT + 0.000261\ PSA * FT \quad 9$$

Table 1 presents the variable parameter and the parameter settings for the present experiment. The optimization process takes into account of quantity of SD, PSA and FT factors, and their corresponding levels.

Table 1: Valuable parameters and corresponding levels

S/N	Variable parameter (factors)		Variable levels	
1	wt% of SD	10	15	20
2	wt% of PSA	5	10	15
3	Firing Temperature (°C)	900	1000	1100

A Minitab 21 software version used Equation 10 to generate the minimum number of experimental runs necessary to conduct on a laboratory scale.

$$N_{Taguchi} = 1 + N\,(L - 1) \quad 10$$

In Equation 10, N represented the number of factors and L was the number of levels, and denoted the minimum number of runs. Utilizing the Minitab software, an orthogonal array was subsequently employed.

Table 2: Orthogonal array of sawdust, periwinkle shell ash and firing temperature.

Sample No.	Weight (%) SD	Weight (%) PSA	FT (°C)
1.	10	5	900
2.	10	10	1000
3.	10	15	1100
4.	15	5	1000
5.	15	10	1100
6.	15	15	900
7.	20	5	1100
8.	20	10	900
9.	20	15	1000

2.2.3 Laboratory sample preparation

Following the completion of the sample preparation phase for kaolin, sawdust, and periwinkle shell as outlined by Jimoh (2024), the subsequent step involved laboratory characterization, where X-ray powder diffraction analysis using X-ray Diffractometer (XRD) (Rigaku Mini Flex 300 – Japan) was conducted on purified raw materials and additives to ascertain the various mineralogy and phase distribution. Thereafter, Thermo Gravimetric Analysis (TGA) was employed to evaluate the heat features of the samples. The sample mass was placed in the TGA machine and subjected to a peak temperature of 1000°C at a 10°C/min. The sample mass degradation was measured with the reference sample (crucible) material of the machine.

A greenware sample was prepared on a small scale of 10g bricks, utilizing clay material and mixture proportions of PSA and SD at various FT as indicated in Table 2. The PSA served as a pozzolanic material because when adequately burnt (calcinated) and milled, its substantial silica (SiO_2) and alumina (Al_2O_3) contents allowed it to chemically react with the calcium hydroxide in the clay to produce enhanced binding compound in the clay brick. The addition of the SD aided in the creation of pores, consequently reducing thermal conductivity.

The composition was mixed to achieve desired homogeneity, employing a laboratory mixer for mechanical blending of the mixture. The prepared greenware mix was thoroughly combined with a 10wt% sodium silicate binder and water to attain a workable plasticity as outlined by Andic- Cakir*, et al.,* (2021). The incorporation of sodium silicate in the mixture would aid in effective bonding. The binder reacted with the silica present in the matrix, enhancing the processes of polymerization and coagulation. This culminated in the formation of a water-stable silica gel. The dryness of the silica gel and the merging of the structural matrix contributed to strengthening of the bond, leading to the formation of a durable dense material.

The mixture was subsequently pressed using the Universal Testing Machine (WDW 100 Model – China) with a compressive force of 12kN in the Department of Metallurgical Engineering, ABU Zaria to form pellets for laboratory testing purposes. The laboratory trials were subjected to dryness for 24 hours at room temperature, followed by an additional 48 hours of oven drying in an electric oven at 110°C to eliminate significant dampness content as shown in Plate 1.

Subsequently, an Electric Furnace (Nabertherm LH 120/14 Model - Germany) from Department of Chemical Engineering ABU Zaria was used for calcination and firing of the sample bricks produced as shown in Plate 2 at various temperatures as outlined in Table 2 at 10°/min. The fired samples as indicated in Plate 3 were subjected to laboratory testing to evaluate their thermo-mechanical properties, with the objective of minimizing thermal conductivity and maximizing compressive strength. The responses of the produced samples were subsequently analysed using Minitab software to identify the optimal mixture for the bulk production of fired bricks to be used for oven lining.

Plate 1: Oven air-dry samples after forming the pellet

(a) Samples to be fired at 900°C

(b) Samples to be fired at 1000°C and 1100°C

Plate 2: Loaded samples in an electric furnace for firing

Plate 3: Samples after firing

Thermal conductivity tests on the produced bricks were carried out using Thermal Conductivity Device (Lee's Disc Apparatus Model - India) in accordance to ASTM C201 Standard. Also, the fired bricks' compressive strengths were measured using Universal Testing Machine (WDW-100kN model - China) in line with EN 772-1 Standard. The two tests were conducted in Department of Physics and Department of Metallurgical Engineering both at ABU Zaria respectively.

3. Results and Discussion

3.1 Design and Optimization Results

Table 3 is a response of mean and S/N ratio for thermal conductivity and compressive strength. It was discernible from Table 3 that the average mean and S/N ratio of thermal conductivity were 0.6142 W/mK and 4.5982 dB while that of compressive strength were 5.7033 MPa and 14.7597 dB respectively.

Also, Table 3 showed an obvious interchange between thermal and mechanical performances. Sample 1 attained a peak mechanical strength of 7.47 MPa which was considered good for building a structural component and Sample 3 realising 0.350 W/mK as the smallest thermal conductivity which is ideal for building an insulator.

Table 3: The response table of mean and S/N ratio for thermal conductivity and compressive strength.

Sample No.	Thermal Conductivity		Compressive Strength	
(-)	Mean (W/mK)	S/N ratio (dB)	Mean (MPa)	S/N ratio (dB)
1	0.821037	1.71275	7.47	17.4664
2	0.645424	3.80310	7.35	17.3257
3	0.350355	9.10983	7.38	17.3611
4	0.676341	3.39669	5.88	15.3875
5	0.433422	7.26178	6.66	16.4695
6	0.739792	2.61781	4.92	13.8393
7	0.407445	7.79862	3.96	11.9539
8	0.821429	1.70860	4.68	13.4049
9	0.632796	3.97473	3.03	9.6289
Mean	**0.614227**	**4.598211**	**5.7033**	**14.7597**

3.2 Influence of Thermal Conductivity on the Fire Clay Bricks with Additives

Figure 1 shows the impact of varying weight percentages of SD, PSA, and firing temperature on the thermal conductivity of firebricks.

The inclusion of Sawdust to the insulation brick matrix showed a relatively small rise in the heat conductivity of the material as the SD inclusion was increased. Level 1 (see Table 1) representing the lowest level of sawdust inclusion of 10%, Level 2 which was the medium representing 15% and Level 3 was the highest represents 20%. However, the lowest thermal conductivity was identified at the first level, specifically at 10% weight percentage of SD. This signified that the optimal minimal thermal conductivity of 0.6165 W/mK was achieved with a 10% weight percentage of SD in the matrix mix factors. The observed surge in thermal conductivity from 0.6165 W/mK to 0.6206 W/mK with higher weight percentages of sawdust could be attributed to various factors such as incomplete combustion of SD, leading to the presence of residual carbon or char in the composite. The residual carbon, having higher thermal conductivity of about 0.20 -1.40 W/mK compared to other matrix components (hydrogen, 0.18 W/mK; oxygen, 0.026 W/mK and nitrogen, 0.024 W/mK) contributed to increased thermal conductivity (Bullen *et al.,* 2000).

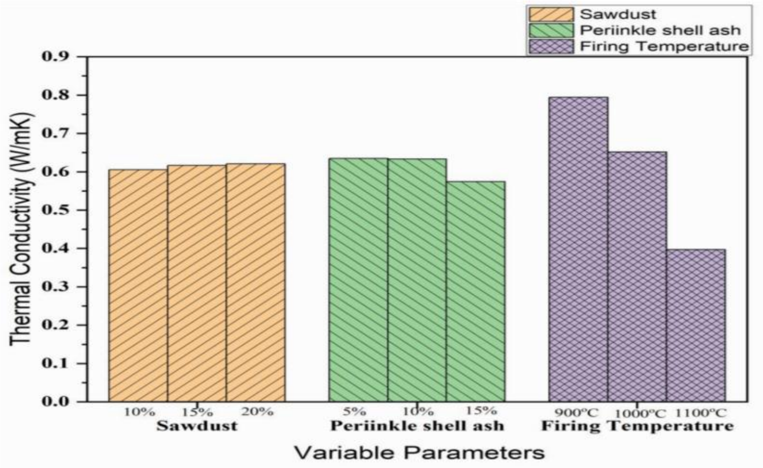

Figure 1: The effect of inclusion of SD, PSA and firing temperature on thermal conductivity of the insulation bricks

The effect of inclusion of weight percentage of PSA on the thermal conductivity of insulation firebricks is also shown in Figure 1. A distinct reduction in thermal conductivity (from 0.6349 to 0.5743 W/mK) was noticed with a rise in the weight of PSA (from 5% to 15%). This was attributed to the composition of PSA, which shared similarities with clay, particularly in terms of high SiO_2, CaO, and MgO contents. These constituents contributed to the low thermal conductivity properties exhibited by PSA. The third level of the second factor (weight percentage of PSA) demonstrated the optimal condition for achieving the lowest thermal properties of the insulation bricks.

Figure 1 also illustrates a discernible trend in the mean thermal conductivity, showcasing a consistent decrease (0.7941 to 0.3971 M/mK) with an increase in firing temperature (900°C to 1100°C). This observed behaviour aligned with discoveries by Kumar *et al.,* (2017) and Velasco*, et al.,* (2014), providing appreciated understanding into the impact of firing temperature on the thermal features of the material. The reduction in thermal conductivity with rise in temperature could be ascribed to multiple factors associated with the firing process. These include the elimination of volatile matter, including components such as SD and water, phase transition within the material matrix, marked by the decomposition of organic material (SD) and enhanced sintering and bonding leading to the creation of pores in the brick matrix.

Using the "Lower the Better" criterion for thermal conductivity it became apparent that the best combination for reducing thermal conductivity was 15% SD, 10% PSA, and 1100°C FT ($SD_{15}PSA_{10}FT_{1100}$). This set of parameters represented a promising outline for the manufacture of insulation bricks with good thermal insulation properties.

3.3 Influence of Compressive Strengths on the Fire Clay Bricks with Additives

Figure 2 indicates the influence of percentage weight of SD, PSA and firing temperature on the compressive strength of insulation fired bricks.

Figure 2 revealed that the compressive strength of firebricks experienced a notable decline (7.40 MPa to 3.89 MPa) with an increase in the percentage of SD (10% to 20%). This phenomenon was attributed to the unique characteristics of SD as an additive in the block matrix. The burning off of SD during firing introduced pores into the fire bricks, contributing to their enhanced insulation properties while concurrently reducing compressive strength. SD was less dense than clay and PSA which formed the whole brick matrix thus a reduction in overall density of the material which was attributed to reduced compressive strength due to the loose and weaker bonding. However, a SD percentage of 10% by weight (level 1) yielded the most favourable response in terms of compressive strength. This discovery underscores the importance of carefully balancing the composition of insulation fire bricks to achieve a synergistic combination of insulation properties and mechanical strength.

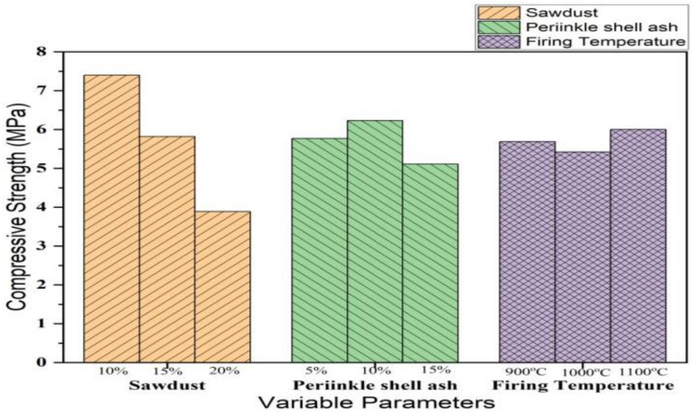

Figure 2: The effect of inclusion of SD, PSA and firing temperature on compressive strength of the insulation bricks

The effect of increasing the percentage of PSA on the compressive strength of fired bricks is also evident in Figure 2. For a percentage of 10% by weight, the pozzolanic reaction between PSA and clay was is balanced, leading to the formation of a robust Calcium-Silicate-Hydrate gel that positively impacted the compressive strength of the firebricks to a value of 6.23 MPa. The sharp decrease in compressive strength (5.11 MPa at 15% weight) beyond the optimal level of PSA incorporation was attributed to the dissolution effect. This dissolution effect underscores the importance of carefully controlling the PSA percentage to maintain the desired balance between compressive strength and other material properties.

Also, in Figure 2, the impact of firing temperature on the compressive strength of insulation fire bricks was evident. A notable observation was the rise in compressive strength with elevated firing temperatures. However, a relatively modest decline was noted from level 1 (5.69 MPa) to level 2 (5.42 MPa) firing temperatures of 900°C and 1000°C respectively. This decline was attributed to the complete combustion of low melting point compounds at higher temperatures. The overall surge in compressive strength (6.00 MPa) at elevated firing temperature (1100°C) was primarily attributed to consolidation and fusion of the material matrix. Higher firing temperatures contributed to the minimization of porosity and the formation of more compact particles. This was achieved through increased C-S-H formation, directly improving compressive strength. Thus, utilizing the "larger the better" processing S/N ratio for compressive strength, the optimal parameter combination was identified as 10% SD, 10% PSA, and a firing temperature of 1100°C ($SD_{10}PSA_{10}FT_{1100}$). This combination ensured a favourable balance of factors that positively contributed to achieving enhanced compressive strength in the produced insulation fire bricks.

3.4 Estimating the Optimal Grey Relational Grade

Approximating an optimum GRG is importance since it alters multifaceted, multi-objective problems into a single and direct optimization index. Optimized mean charts illustrating the Grey Relational Grade (GRG) for both thermal conductivity and compressive strength responses are presented in Figure 3.

The GRG was exploited as it had been applied to combine the multiple response to a lonely response. Thus, leading to the optimal parameter setting for achieving low thermal conductivity and relatively high compressive strength at 10% SD, 10% PSA, and a firing temperature of 1100°C. As depicted in Figure 3 these values represent level 1, level 2 and level 3 of SD, PSA and the firing temperature respectively.

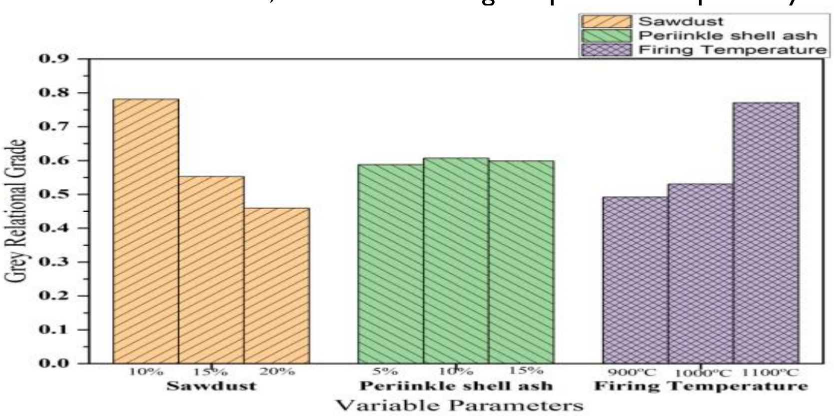

Figure 3: Optimized mean for Grey Relational Grade

Utilizing the optimal control factor settings ($SD_{10}PSA_{10}FT_{1100}$) illustrated in Figure 3 which correspond to 0.7812 at 10% sawdust weight percentage, 0.6068 at 10% PSA weight percentage, and 0.7709 at a firing temperature of 1100°C and GRG means of 0.5978 obtained from Figure 3, an optimum GRG for the brick was calculated via Equation 11 as:

$$T_{opt} = T_m + \sum_{k_n}^{k-1} [(T_{ik})_{min} - T_m] \qquad 11$$

where T_m is the optimum control factor for the variables, n is the quantity of performance features, which is the number of k or number of responses. k_n is the number of core design factor influencing the responses namely thermal conductivity and compressive strength. The T_{ikmin} was obtained from the response table of mean or S/N ratio in which for each parameter on the table, the lowest number among the levels was the T_{ikmin} and the highest number among the levels was the T_{ikmax}. Hence, the optimum thermal conductivity was;

T_{opt} = 0.5978+ (0.7812 – 0.5978) + (0.6068 – 0.5978) + (0.7709 – 0.5978)

T_{opt} = 0.9633

3.5 Confirmation Test

Figure 4a demonstrated a close relationship between predicted and experimental values of thermal conductivity for all runs, affirming the acceptance of the prediction model with an R-squared value of 96.25%. Regarding compressive strength as in Figure 4b, it predicted and experimental values which exhibited a close association and prediction model also boasts an R-squared value of 89.93%, signifying its strong acceptability for accurate predictions. Moreover, Figure 4c illustrated the experimental grade alongside the predicted grade. The model also boasts an R-squared value of 97%. From Figures 4 (a to c), experiment run 3 was notable in term of lower thermal conductivity, relatively high strength and optimal GRG. Using a regression model for the thermal conductivity, compressive strength and GRG as respectively outlined in Equations 7, 8 and 9, a prediction of the impact of interactions between considered factors (SD, PSA and firing temperature) was made as shown in Figure 5 (a)-(c).

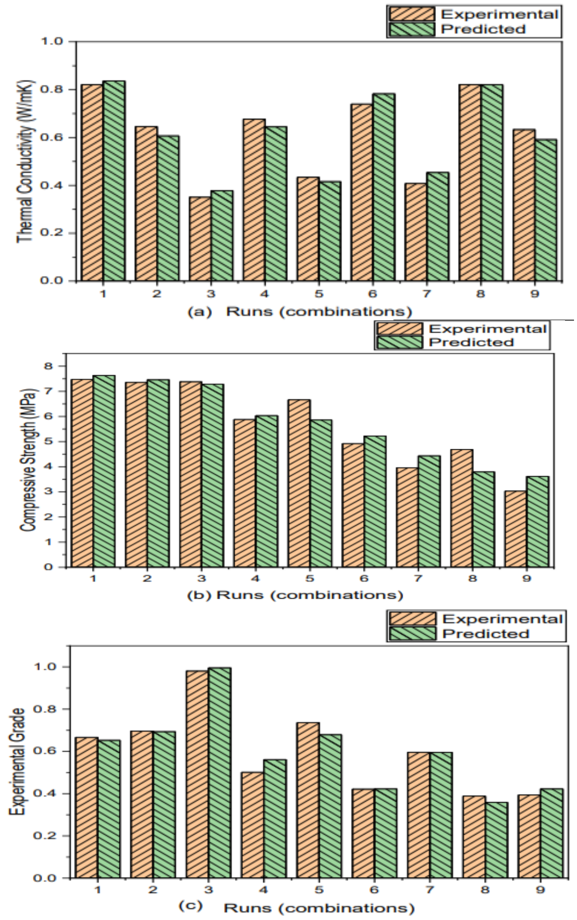

Figure 4: Experimental and predicted value of thermal conductivity, compressive strength and GRG.

Corresponding author's email address: abdulmajid.nainna@airforce.mil.ng

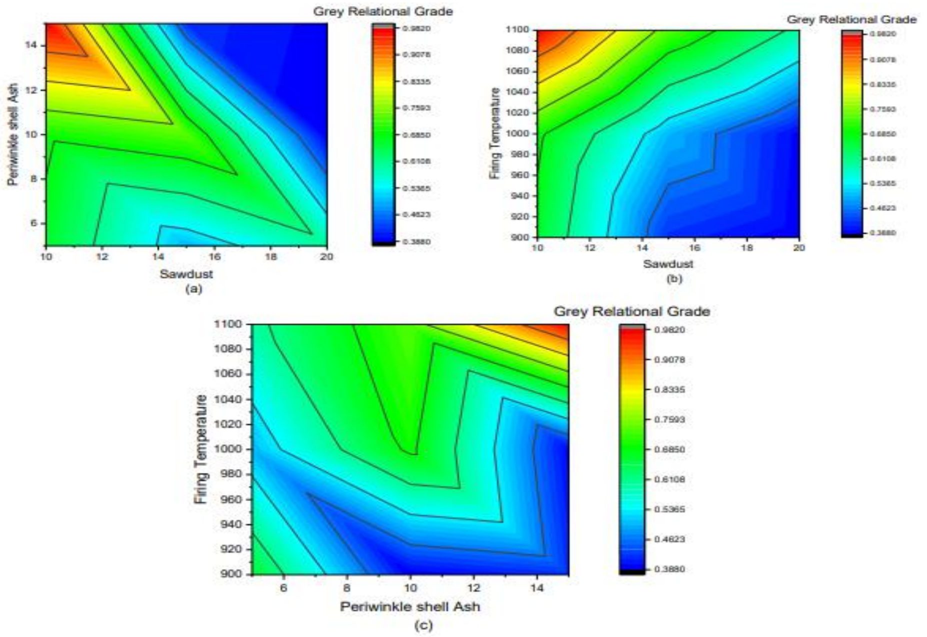

Figure 5: (a) Surface plot interface between SD and PSA (b) Surface plot interface between SD and FT (c) Surface plot interaction between PSA and FT

In Figure 5 (a), the GRG was high when PSA content was elevated to about 15%wt, coupled with a lower quantity of SD of about 10%wt, resulting in a corresponding high grade. Furthermore, Figure 5 (b) demonstrated that the grey relational grade increased with an increase in firing temperature to about 1100°C, albeit under the condition of a lower quantity of sawdust of about 10%wt. The corresponding rise in GRG was observed in plot (c) of Figure 5, where a surge in firing temperature to about 1100°C alongside a rise in PSA content to 15% by weight led to a higher grey relational grade. High firing temperature with lower PSA content yielded a lower grade.

4. Conclusion

The present study determined an optimum mixture of PSA and SD additives for enhanced compressive strength and thermal conductivity of a fired brick using both experimental and modelling approach (Grey relational analysis in Taguchi methodology). A mixture proportion between 5-20 % weight of PSA and SD at 900-1100°C firing temperature was used.

Utilizing the best control factor settings of $SD_{10}PSA_{15}FT_{1100}$ has yielded a thermal conductivity of 0.6056 W/mK, 0.5743 W/mK 0.3971 W/mK for 10 % weight of SD, 15% weight of PSA and a firing temperature of 1100°C respectively. Thus, an estimation of the material's optimal thermal conductivity, T_{opt} was obtained as 0.3486 W/mK. For a compressive strength, an optimal control factor setting of $SD_{10}PSA_{10}FT_{1100}$ was realized. The values were 7.400 MPa for SD weight percentage of 10, 6.230 MPa for PSA weight percentage of 10, and 6.000 MPa at a firing temperature of 1100°C. Hence, an estimation of the material's optimal compressive strength of 8.2234 MPa was obtained.

A close relationship between experimental and predicted values of thermal conductivity affirmed the acceptance of the prediction model with an R-squared value of 96.25%. Regarding compressive strength, the predicted and experimental values exhibited a close association as evident with an R-squared value of 89.93%, signifying its strong acceptability for accurate predictions. The outcome of the present study will contribute to fill in the existing knowledge gap in optimizing the quantity of SD and PSA mixtures for an enhanced mini fired brick. Consequently, the optimum blend identified through analysis and experimentation will be employed for the large-scale production of refractory bricks intended for oven evaluation.

References

Abdullahi, I. and Sara, SG. 2015. Assessment of periwinkle shells ash as composite materials for particle board production. International Conference on African Development Issues: Materials Technology Track Assessment, 158-163.

Adazabra, AN. and Viruthagiri, G. 2023. Use of waste husk from millet grain cultivation in the production of fired clay bricks. International Journal of Ceramic Engineering & Science, 5(4):1-16.

Alabduljabbar, H., Benjeddou, O., Soussi, C., Khadimallah, MA. and Alyousef, R. 2021. Effects of incorporating wood sawdust on the firing program and the physical and mechanical properties of fired clay bricks. Journal of Building Engineering, 35 (3): 102106.

Al-Fakih, A., Mohammed, BS., Liew, MS., and Nikbakht, E. 2019. Incorporation of waste materials in the manufacture of masonry bricks: An update review. Journal of Building Engineering, 21: 37-54.

Akpomie, KG., Akpotu, SO., Ohoro, CR., Omotola, EO., Amaku, JF., Olisah, C., Malloum, A., Adegoke, KA., Conradie, J., and Okeke, ES. 2025. Effect of biomass-based additives on the thermal, physical, and mechanical properties of fired clay bricks: a review. International Journal of Thermophysics, 46 (5).

Andic- Cakır, O., Son, AE., Sürmelioğlu, S., Tosun, E. and Sarıkanat, M. 2021. Improvement of traditional clay bricks' thermal insulation characteristics by using waste materials. Case Studies in Construction Materials, 15: e00560.

Arslan, C., Gencel, O., Borazan, I., Sutcu, M., and Erdogmus, E. 2021. Effect of waste-based micro cellulose fiber as pore maker on characteristics of fired clay bricks. Construction Building Material, 300: 124298.

Beal, B., Selby, A., Atwater, C., James, C., Viens, C., and Almquist, C. 2019. A comparison of thermal and mechanical properties of clay bricks prepared with three different pore-forming additives: vermiculite, wood ash, and sawdust. American Institute of Chemical Engineers, 38(6): e13150.

Bullen, AJ., O'Hara, KE., Cahill, DG., Monteiro, O. and von Keudell, A. 2000. Thermal conductivity of amorphous carbon thin films. Journal of Applied Physics, 88: 6317–6320.

Cultrone, G., Aurrekoetxea, I., Casado, C. and Arizzi, A. 2020. Sawdust recycling in the production of lightweight bricks: How the amount of additive and the firing temperature influence the physical properties of the bricks. Construction and Building Materials, 235:117436.

Gualtieri ML., Gualtieri, AF., Gagliardi, S., Ruffini, P., Ferrari, R. and Hanuskova, M. 2010. Thermal conductivity of fired clays: effects of mineralogical and physical properties of the raw materials. Applied Clay Science, 49(3):269-275.

Jimoh, SO. 2024. Investigation of the effects of sawdust and periwinkle shell ash additives on fired-bricks oven and students learning of thermal insulation. Master of Engineering Dissertation. Department of Mechanical Engineering Ahmadu Bello University, Zaria, Nigeria.

Kumar, MA., Ranjan, VH., and Sinha, O.P. 2017. Utilization of aluminium plant's waste for production of insulation bricks. Journal of cleaner production, 162: 949-957.

Lawanwadeekul, S., Srisuwan, A., Phonphuak, N., and Chindaprasirt, P. 2024. Addition of spent coffee grounds and waste glass to enhance the physical–mechanical and thermal properties of fired clay bricks at reduced temperatures. Innovative Infrastructure Solutions, 9(206).

Mohajerani, A., Ukwatta, A., Jeffrey-Bailey, T., Swaney, M., Ahmed, M., Rodwell, G., Bartolo, S., Eshtiaghi, N., and Setunge, S. 2019. A proposal for recycling the world's unused stockpiles of treated wastewater sludge (biosolids) in fired-clay bricks. Buildings, 9(1): 14.

Njoku, CE. Ekeleme, AB., Ekwueme, BN. Onuoha, C., Onuzulike, EP., Chibundu, W., Okon, K. and Ozoh, CC. 2024. Utilization of quarry dust and periwinkle shell ash in concrete production. Advanced in Waste Recycling and Environmental Technology, 32: 29957–29966

Okunade, EA. 2008. The effect of wood ash and sawdust admixtures on the engineering properties of a burnt laterite-clay brick. Journal of Applied Sciences, 8(6): 1042-1048.

Oyediran, AO., Balogun, OA., Balogun, RB., Mosuru, SG., Akinwande, AA., and Akinradewo, OI. 2024. Optimization and modelling of the insulating and mechanical properties of fired ceramics for sustainable construction. Hybrid Advances, 7:100310.

Rao, AU., Bhandary, RP., Tantri, A., Narayana, S., and Kamath, M. 2024. Low carbon multi-binder composite using lithomargic soil, biomass, and calcined seashell powder for sustainable bricks. Discover Sustainability, 5:192.

Ruslan, HN., Muthusamy, K., Syed Mohsin, SM., and Kirgiz, MS. 2021. Periwinkle shell as mixing ingredient in concrete: a review. Construction, 1(2): 21-30.

Sarani, NA., Abdul Kadir, KA., Md Din, MF., Farhanah, S., and Johan, SM. 2023. Physical-mechanical properties and thermogravimetric analysis of fired clay brick incorporating palm kernel shell for alternative raw materials. Construction and Building Materials, 376(1):131032

Sutcu, M., Ozturk, S., Yalamac, E., and Gencel, O. 2016. Effect of olive mill waste addition on the properties of porous fired clay bricks using Taguchi method, Journal of Environment Management, 181: 185-192.

Sylajakumari, PA., Ramakrishnasamy, R. and Palaniappan, G. 2018. Taguchi grey relational analysis for multi-response optimization of wear in co-continuous composite. Materials, 11(1743): 1-17.

Tzeng, GH. and Huang, JJ. 2011. Multiple Attribute Decision Making: Methods and Applications. Publisher. Taylor and Francis Group, Florida.

Velasco, PM, Ortiz, MPM, Giro, MAM, and Velasco, LM. 2014. Fired clay bricks manufactured by adding waste as sustainable construction material - a review. Construction and Building Materials, 63: 97–107.