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Effect of Coal Fly Ash Incorporation on the Physical and Mechanical Properties of Terracotta Bricks Based on Grey Clay

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Abstract

This study was part of the framework that contributed not only to the improvement of thermal comfort in housing but also to the decarbonization of the construction and building materials industry. For this purpose, terracotta brick seems to meet these needs. Thus, the objective of this work was to evaluate the influence of the incorporation of coal fly ash from a thermal power plant on the physical and mechanical properties of fired bricks from grey clay in the Thicky area of Senegal. The coal fly ash was incorporated into the raw clay material in proportions of 0, 5, 10, and 15 % by weight. These two raw materials were first characterized by X-ray fluorescence spectroscopy (XRF). The XRF analyses showed that the most abundant oxides in clay were SiO_2 (55.034%) and Fe_2O_3 (10.155%). In coal fly ash, SiO_2 (38.574%) is predominant. The ash also contained Al_2O_3 (7.717%) and alicano-earthy melting oxides such as CaO (9.271%) and MgO (7.298%) etc. These melting oxides were necessary to facilitate the formation of the liquid phase when baking platelets. The latter, when burned at a temperature of 880°C, were characterized by determining the number of physico-mechanical parameters, such as linear shrinkage during cooking, water absorption, fire loss and compressive strength. A Hierarchical Ascending Classification of these different parameters was performed and three classes were obtained. Class 1 with better compressive strength (6.358 MPa), was in sample A (5%). Class 2 consisted of sample D (reference) and had a higher plasticity index (28.51%) and water absorption rate (11.19%). Finally, class 3, which included samples B (10%) and C (15%), had very high shrinkage and fire losses compared to other platelets. These results highlighted the possibility of using up to 5% of the coal fly ash in the production of new fired bricks with good performance.

Keywords

Grey Clay, Coal Fly Ash, Terracotta Bricks, Construction, Greenhouse Gases

1. Introduction

Today, strong demographic growth and the gradual expansion of cities pose challenges that humanity must face. Among these challenges is access to housing for a larger segment of the population. Thus, due to this growth of urban communities, the construction sector is experiencing a rapid explosion. Currently, cement is the most widely used material in the construction of buildings all over the world. However, the building sector is booming in terms of energy consumption and is a significant source of greenhouse gases [1]. The cement industry is the third largest CO_2 emitting industry in the world [2]. Indeed, cement manufacturing is responsible for approximately 7 to 8% of total CO_2 emissions on a global scale [3]. Projected urbanization over the next 50 to 100 years indicates that the demand for cement will continue to increase, thus requiring strategies to limit its environmental impact [4]. Furthermore, climate change and environmental degradation pose a fundamental threat to humanity [5]. In order to face these scourges and protect our environment, it is necessary to review current construction methods and practices. One of the solutions to the problems caused by cement is the valorization of clay raw materials [6]. This is what justifies the use of clay in the development and implementation of new high-performance construction materials with low environmental impact and lower energy and economic costs [7]. In addition, clay is an available, abundant, non-toxic, recyclable, inert material (resistant to chemical agents and biological attacks), low cost and offers thermal comfort [7] [8]. The clay-based brick sector is thus positioned as one of the key solutions to meet this challenge. However, there is still a problem of resistance of structures built with this material, which is linked to its sensitivity to water [9]. However, its combination with other adjuvant materials (inert-non-plastic elements), would make it possible to obtain better quality bricks. These materials not only increase the bonding between particles but also help lower the melting temperature by acting as a flux [10]. The recycling of certain residues as a possible replacement has attracted considerable interest in recent years. Thus, research has focused on the development of means of stabilization by the incorporation of residues of reusable or recyclable materials to improve the performance of bricks in the construction sector [6]. Numerous works have studied the effects of a number of additions such as biomass ashes (sugar cane bagasse and rice husks) [11] [12], sewage sludge [13], paper mill waste [14], sawdust [15], pyrrhotite ash [16] etc. Coal fly ash from power plants is one of the most well-known wastes and promised feedstocks for construction and building materials. Coal-fired power plants produce a significant amount of ash through the combustion of coal [17]. The amount of coal generated worldwide is estimated to be 800 million tons per year [18]. Thus, these wastes can be recycled in the production of clay bricks to improve their performance. Furthermore, recycling is part of the waste treatment strategy [19]. These ashes could be used as supplementary cementitious materials (SCMs). In addition, it would be a promising way to reduce the dangers associated with the impact of this type of waste on the environment, to reduce the exploitation of clay resources and to reduce energy consumption and carbon dioxide emissions [11].

Thus, the objective of this study aims to investigate the effects of the incorporation of coal fly ash from a thermal power plant on the physico-mechanical properties of terracotta bricks. The performance of the designed bricks was evaluated by determining a number of parameters such as water absorption rate, compressive strength, plasticity, loss on ignition, shrinkage, etc. A principal component analysis (PCA) was also performed.

2. Material and Methods

2.1. Raw Materials

The raw materials used in this study were gray clay from the Thicky deposits, located in the Thies region, in western Senegal at 14˚50'N, 17˚06'W, and coal fly ash, which came to us from a power station. Some physical and particle size parameters of these raw materials are presented in (**Table 1**). The chemical characteristics of the clay and ash were determined using an X-ray fluorescence spectrometer (XRF) of the Malvern Panalytical type (Epsilon1). The chemical element results expressed in % were the average of three readings.

Table 1. Physical and granulometry parameters of the clay and coal fly ash.

Physical parameters	Clay	Coal fly Ash
Apparent density (kg/m^3)	1399.57	1357.03
Specific surface (m^2/g)	183.00	167.00
Porosity (in%)	46.00	67.00
Average diameter (in µm)	<2 µm	24 µm

2.1. Pad Design

Clay platelets containing 0; 5; 10 and 15 wt% coal fly ash were designed. The compositions of each mixture are given in (**Table 2**).

Table 2. Physical and granulometry parameters of the clay and coal fly ash.

Mixtures	Percentage of coal fly ash (%)	Percentage of gray clay (%)
A	5	95
B	10	90
C	15	85
D	0	100

The different quantities of each constituent were mixed using a BMF type mixer. The quantity of water used during mixing represented 19% of the total mass of the two raw materials. Indeed, this quantity of water corresponded to the appropriate humidity for shaping by molding. This shaping was carried out using a VERDES type extruder where the material came out with a certain cross-section continuously, which was subsequently cut into sized plates (length 150 mm; width 85 mm and thickness 15 mm). In the wet state, the wafers were weighed and measured with a caliper to control the shrinkage that would occur after drying and cooking. After shaping, the wafers were placed in a Memmert type oven at a temperature equal to 40˚C and which was gradually increased every 2 hours by 20˚C. The temperature of the oven was subsequently set at 105˚C for a period of 24 hours. After drying the wafers, they were put in an oven for 3 days to cook. To avoid cracking problems and to eliminate all residual water, cooking was done gradually from 100˚C to 880˚C. 880˚C was the maximum temperature that allowed the bricks to perform well. Thus, for reasons of energy savings, it was not necessary to exceed 880˚C. The cooked platelets are presented in (**Figure 1**). The physical and mechanical properties of the platelets were determined by standard methods. For each analytical parameter, 3 tests were carried out to get closer to the normal value. The apparent density and the loss on ignition were determined respectively according to the standards NF EN 1936 [20] and NF EN 15169 [21]. The plasticity index before cooking was determined according to the ASTM D4318 standard [22]. The Atterberg plasticity index (PI) is given by equation 1. The compressive strength properties were carried out according to the ASTM-C674 standard [23]. Water absorption was determined according to the ABNT NBR 15270-2 standard [24]. Shrinkage after drying (Rs) was calculated by applying Equation 2.

$$I_P = W_L - W_P \tag{1}$$

with:

W_P: the plasticity limit (LP);

W_L: The liquidity limit.

$$\mathrm{Rs} = \frac{\mathrm{Lh} - \mathrm{Ls}}{\mathrm{Ls}} * 100 \tag{2}$$

with:

$\mathrm{R_S}$: Shrinkage after drying;

Lh: Length of wet pads;

Ls: Length of dry platelets.

2.3. Statistical analyzes

A principal component analysis (PCA), which is the most widespread of the factorial methods, was carried out in order to highlight the information carried by the platelets according to the physico-mechanical properties. Therefore, all analyzes were carried out with R software (version 4.1.1, 2021).

Figure 1. Specimens of platelets made from waste coal fly ash and gray clay.

3. Results and Discussion

3.1. Chemical Characterization of Clay and Coal Ash

The results of X-ray chemical characterization of gray clay and coal fly ashwere presented in **Figure 2**, and **Figure 3**, respectively.

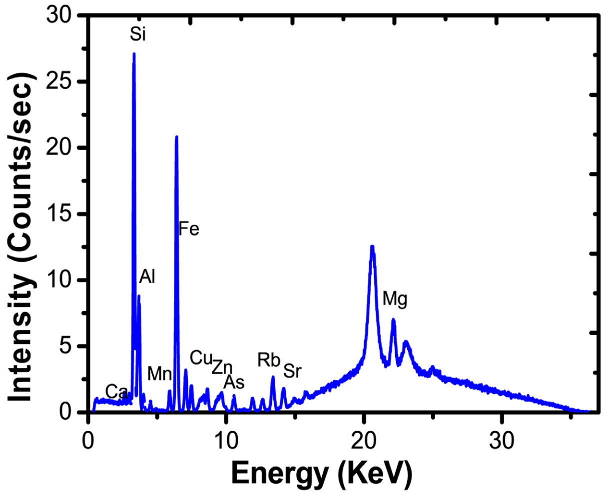

Figure 2. EDXRF X-ray fluorescence spectrum Niton XLT900s gray clay at 35 KV.

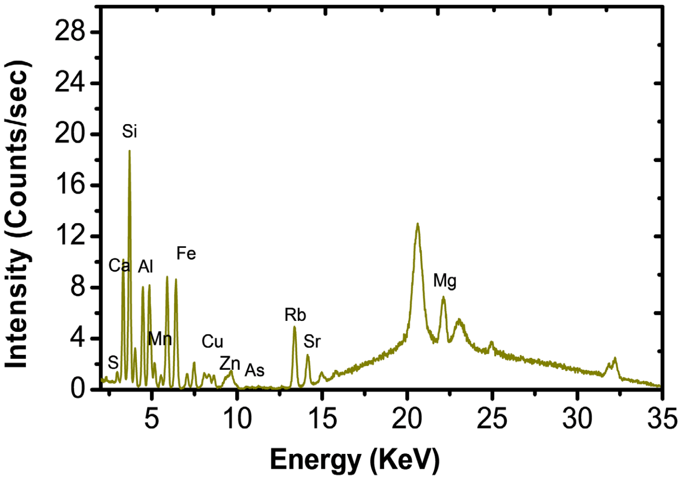

Figure 3. EDXRF X-ray fluorescence spectrum Niton XLT900s coal fly ashat 35 KV.

The results of (**Figure 2** and **Figure 3**) showed that in clay, the most abundant oxides were respectively SiO_2, Fe_2O_3, MgO and Al_2O_3 with contents estimated at 55.034; 10.155; 7.560 and 4.109%. While in coal ash, SiO_2 is predominant followed by CaO, Al_2O_3, MgO and Fe_2O_3. The respective contents of these oxides in the coal fly ash were estimated at 38.574; 9.271; 7.717; 7.298 and 6.293%. The higher SiO_2 content in the clay than in the coal fly ash indicates a greater presence of quartz in the clay. On the other hand, the very high ratio (13.39) of SiO_2/Al_2O_3 in the clay shows that this material contained a greater quantity of kaolinite compared to the ash. In general, the oxides of Si and Al are mainly associated, thus forming the structures of aluminosilicates such as kaolinite [23]. However, kaolinitic clay very often contains a small quantity of fluxing oxides, which leads to the slow formation of the liquid phase of the designed bricks. Thus, the addition of alkaline oxides or alkaline earth oxides such as MgO and CaO which are fluxing oxides is necessary to facilitate the formation of the liquid phase during the baking of the wafers [25]. Thus, the relatively satisfactory CaO content (9.271%) in the coal fly ash could play the role of facilitator of the formation of this liquid phase. Note also that the two raw materials had relatively high iron oxide (Fe_2O_3) contents. The latter are mainly responsible for the reddish color of the bricks after firing. In addition, the clay and coal fly ash used in this study do not present dangerous elements and are chemically stable. The combination of these two materials would increase the bond between the particles, thus ensuring weather resistance.

So, these two materials could be used well in making clay bricks. This ability is confirmed by the presence of kaolinite, quartz and iron oxides in these materials.

3.2. Physico-Mechanical Characteristics of Platelets

The results of the physico-mechanical characterization of the platelets are presented in **Table 3**.

Table 3. Characteristics of the wafers after cooking.

Mixtures	A	B	C	D
Compressive strength (MPa)	6.358	3.486	1.206	5.005
Plasticity index	26.76	25.65	24.29	28.51
Withdrawal (%)	0.04	0.32	0.3	0.26
Fire loss (%)	5.39	6.51	7.72	5.13
Absorption (%)	10.45	11.00	11.11	11.19

According to (**Table 3**), the mechanical strengths of the different plates varied from 1.206 MPa for plate C (15% ash) to 6.358 MPA for plate A. The latter thus presents the best compressive strength. On the other hand, beyond 5% by weight of coal ash, we found that the resistance had decreased. This result could be explained by the fact that a progressive increase in the coal content breaks the bonds of the clay material but also reduces the plasticity of the material [26]. This hypothesis was confirmed by the plasticity indices, which also decreased with the increase in coal fly ash content. However, these strength values comply with Adobe legislation, which certifies the acceptance of compressive strength between 1.2 and 2.1 MPa [27]. These results on compressive strength are better than those obtained in the work of (Monica Castoldi *et al.* 2019) [24] and (Mekbel, Debieche *et al.* 2023) [28].

Withdrawal tests were also carried out. Indeed, shrinkage is an important parameter that could cause tensions thus generating defects likely to compromise the quality of the bricks during the cooking and drying process [29]. The shrinkage results gave values between 0.04 to 0.32%, respectively for wafers A and D. Thus, wafer A (5% coal ash) lost less organic matter.

These results also showed that the loss on ignition in the different chips increased with the addition of coal ash. This trend could be explained by the volatilization of organic matter present in coal fly ash [30]. On the other hand, plates (A) and (D) had practically the same loss on ignition values. The latter were evaluated at 5.39 and 5.13%, respectively. The difference is not significant. Thus, they lost less material during cooking compared to the others.

Concerning water absorption, it is a very important parameter for the durability of terracotta bricks and depends largely on the firing temperature. Furthermore, to improve the density and decrease the water absorption of clay bricks, the firing temperature should be increased [30]. According to the sintering phenomenon of ceramic firing, when the temperature increases, the porosity between the seeds decreases, so the absorption rate also decreases. From (**Table 3**), the water absorption rates of different platelets were approximately equal and ranged from 10.45 to 11.19%. In addition, the wafers were all fired at the same temperature and on the same wagon, which could explain the small difference between these values. However, the reference wafer (D) had the greatest absorption rate compared to the others. This characteristic constitutes an advantage because the plates, without addition, absorb a large part of this water and cause the brick to crumble, thus leading to poor adhesion. These values are also lower than the ASTM C62 specifications, which stipulate that the absorption rate should not exceed 17% [31]. Previous studies [12], carried out on rice husk ash and sewage sludge as degreasers, have given somewhat similar compressive strengths but with higher water absorption rates compared to the incorporation of coal fly ash as a degreaser. Thus, the long-term exposure of these bricks to adverse weather elements such as water could reduce their performance. In addition, compared to coal fly ash, sewage sludge could also contain dangerous chemical contaminants, such as heavy metals, that could have adverse effects on the environment.

Thus, from all these results, it appears that plate A (5% by weight of ash) presented the best physico-mechanical properties.

3.3. Statistical Studies

3.3.1. Principal Component Analysis (PCA)

To better appreciate the quality of the designed wafers, the data obtained from the physical and mechanical characterization were processed in the form of principal component analysis (PCA). The latter also made it possible to calculate the eigenvalues, the variances expressed for each factor and their accumulation (**Table 4**). The analysis on the Dim1-Dim2 factorial plan highlighted the general trends. Indeed, dimension 1 (Dim 1) has an expressed variance of 71.1%, the largest, followed by dimension 2 (Dim 2) with 27.3% of the expressed variance. The cumulative variance expressed is 98.4% for the two dimensions. These factorial axes retained for this statistical analysis were supposed to be representative of the variance of the entire data set (**Figure 4**). The correlation coefficients obtained between the different physical parameters of the platelets are grouped in (**Table 5**). The latter had shown on the one hand a good correlation between shrinkage and the water absorption coefficient ($R^2 = 0.91$), a positive correlation between the resistance of the platelets and the plasticity index which is acceptable ($R^2 = 0.78$) and a fairly weak positive correlation between loss on ignition and removal of platelets. On the other hand negative correlations were observed, this is the case of the loss on fire with the resistance and with the plasticity index ($R^2 = -0.94$) and the water absorption coefficient with the resistance ($R^2 = -0.636$).

Table 4. Eigenvalues and percentages expressed for the main axes.

	F1	F2
Own value	3.49	1.99
% Total variance expressed	71.1	27.3
Cumulative expressed variance (%)	49.86	78.36

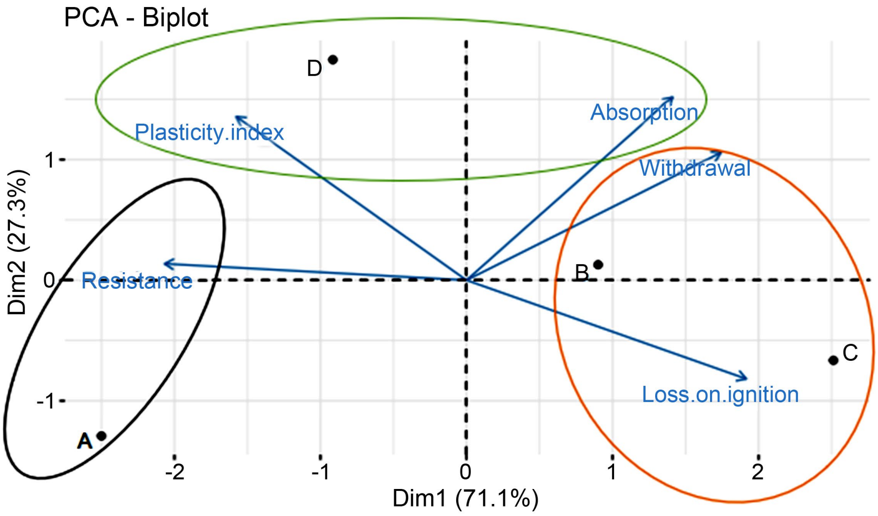

Figure 4. Analysis in the space of variables (factorial design Dim1 - Dim2).

Table 5. Correlation matrix between the different variables.

Variables	Compressive strength	Withdrawal	Loss.on.ignition	Absorption	Plasticity.index
Compressive strength	1				
Withdrawal	−0.77	1			
Loss.on.ignition	−0.94	0.558	1		
Absorption	−0.636	0.91	0.34	1	
Plasticity.index	−0.78	−0.318	−0.94	−0.029	1

3.3.2. Ascending Hierarchical Classification (CHA) and Establishment of Classes (Clustering)

In order to classify the different variables under different groups, an Ascending Hierarchical Classification (AHC) was carried out, and this made it possible to observe three groups of variables through the dendrogram obtained (**Figure 5**). These three groups are, on the one hand, the resistance (I), the plasticity index and the water absorption (II), and on the other hand, the shrinkage and loss on ignition (III). The k-means clustering obtained from (**Figure 6**) allowed us to

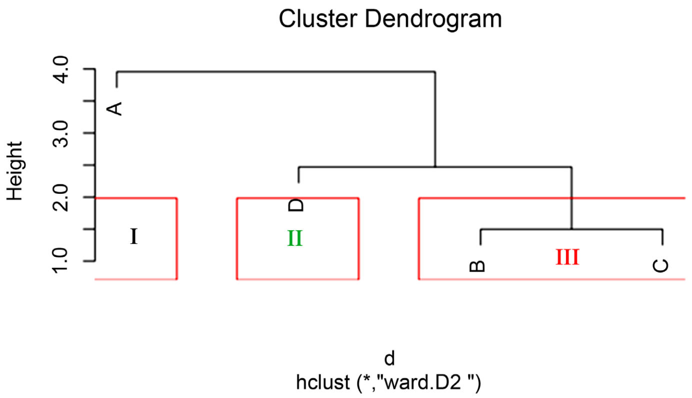

Figure 5. Dendrogram of the physical parameters of the designed platelets.

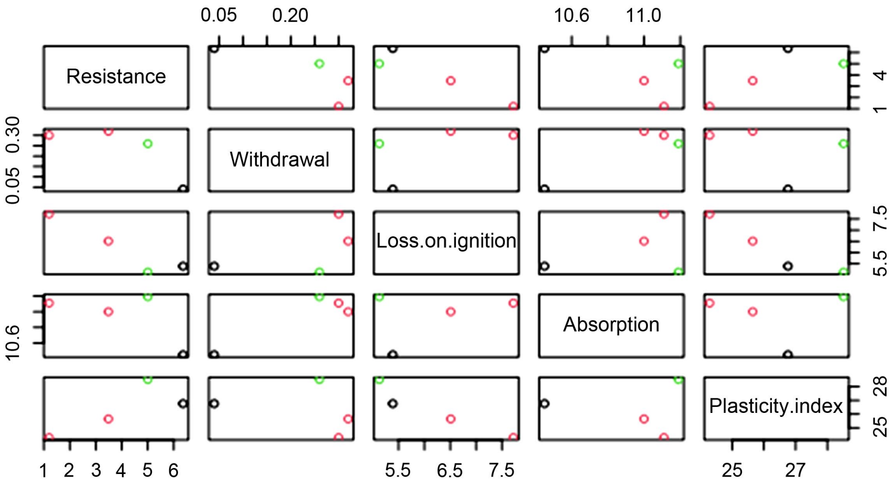

Figure 6. K-means clustering.

have three classes. Class 1 consisted of sample A (5% by weight ash) with the highest compressive strength. Class 2 formed by sample D (reference) had a greater plasticity index and water absorption coefficient and finally class 3 which grouped samples B and C. This class was mainly made up of platelets with very high shrinkage and loss on ignition compared to other classes. Thus, this ascending hierarchical classification confirmed that wafer A (with 5% by weight of coal ash) presented the best physico-mechanical qualities.

4. Conclusion

This work was part of the general policy of recovering certain waste in the production of terracotta bricks. The objective was to develop environmentally friendly construction materials and find a solution to the growing problem of waste materials. Thus, terracotta plates based on gray clay with the addition of coal fly ash in proportions of (0, 5, 10 and 15% by weight) were manufactured and characterized, in order to know if the ash could be used as a degreaser. Thus, it was concluded that the addition of coal fly ash to the bricks allowed the reuse of this by-product and reduced the consumption of clay which is a non-renewable resource, while respecting the minimum standards of compressive strength, water absorption, loss on ignition and shrinkage. In addition, the wafer with 5% additions presented the best results with a compressive strength of 6.358 MPa and water absorption of 10.45% compared to 5.005 MPa and 11.19%, respectively, for the reference wafer. Thus, the study suggested that it could be beneficial to incorporate waste coal fly ash into the production of fired bricks, thereby reducing the use of natural resources and energy consumption during production and decreasing the carbon footprint. In addition to reducing energy and clay consumption, these bricks also meet the requirements of thermal regulations. Indeed, they can offer very good thermal comfort. After optimizing the incorporation of coal fly ash as a degreaser, the next step would be to manufacture so-called G bricks with cells. This could further improve the energy efficiency of buildings. Other special bricks could be developed by injecting polystyrene into the cells, further improving thermal performance.

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Conflicts of Interest

The authors declare that they have no conflict of interest.

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