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Production of lightweight firebricks by adding porcelainite to white kaolin and bauxite

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ABSTRACT

Lightweight firebricks are critical in many sectors. There is a growing need to develop materials for furnaces, chambers, and burning towers in various construction and non-construction industries. Iraq offers raw materials that can replace imports. This study aimed to manufacture lightweight firebricks by adding porcelanite in different proportions to white kaolin and bauxite. Four raw-material mixtures were prepared with 9 samples were formed from each mixture (36 total) for evaluation. The study was prepared by performing chemical analysis and Atterberg limits, followed by forming firebrick specimens using the semi-dry pressing method. After drying at 105–110 °C, firing was carried out at 1200, 1300, and 1400 °C with a maturation (soak) time of one hour. The fired specimens were then inspected and tested to determine physical, mechanical, and thermal properties. Physical tests included post-firing longitudinal shrinkage, porosity, and total density; mechanical testing measured compressive strength; and thermal conductivity was assessed for the produced bricks. The results met international and Iraqi standard specifications for lightweight refractories.

Keywords: *Lightweight refractory brick, Porcelainite rocks, Thermal conductivity*

1 INTRODUCTION

The production of lightweight clay bricks in Mesopotamia dates back thousands of years, when ancient Iraqi builders utilized them in architecture due to their thermal insulating properties and low weight. The need to develop building materials increased with the rise in construction activity resulting from the country's population growth.

Lightweight firebrick is known as clay blocks with a density ranging from 800 to 1200 kg/m³. This is considered a low density when compared to the density of regular solid bricks, which ranges between 1,600-2,000 kg/m³. Its lightweight and low density confer several advantages. Thermal insulation is superior to that of regular bricks. The material withstands high temperatures while limiting heat loss. It is used in steel and glass manufacturing, as well as in ovens, furnaces, stoves, and chimneys. It helps retain heat without excessive energy consumption. It also reduces shrinkage cracking during drying [1].

To make the firebricks produced in the present research relatively lightweight and with a lower density than normal firebricks, porcelainite rocks were used as additives in varying proportions to the main mixture. Porcelainite is a light-weight rock with a density of 0.9-1.4 g/cm^3 and is considered one of the important industrial sedimentary rocks that consists of at least 50% of opal-CT (opal-cristobalite and tridymite). It can also be known by various names, such as diatomite, diatomaceous earth, kieselguhr, silite, and flatas [2].

2 MATERIALS AND METHODS

The appropriate raw materials for manufacturing lightweight fire bricks were selected from local clays found in the western Iraqi desert, such as white kaolin, bauxite, and porcelainite, which were used as additives to make the product lighter, i.e., relatively low density. Several laboratory tests were conducted, such as Atterberg limits, particle size gradation, and chemical analysis. Then, the study samples were formed and burned at various temperatures, and evaluation tests were conducted, including longitudinal shrinkage, porosity, total density, compressive strength, and thermal conductivity.

2.1 Study area

The deposits of the primary materials used in the current study are located in the western Iraqi desert, which is part of the northeastern Arabian Shield. A group of stratigraphic units ranging in age from the Permocarbonate to the late Eocene is exposed in the region [3]. In the current study, Duwaikhla kaolin clay (Ga'ara Formation) was chosen for use in the manufacture of firebricks, due to its availability in suitable quantities and the presence of a quarry for preparing the necessary quantities from the Ga'ara Formation. The bauxite clays are located between Wadi Al-Hussainiyat and Wadi Hawran within the Ubaid Formation. As for the lightweight silica on which the current study focused, the porcelainite rocks found in Tarifawe and Wadi Al-Jandali within the Digma Formation were used (Figure 1).

2.1.1 Ga'ara formation

White kaolin clays are found in the Ga'ara Formation, which is exposed in the Ga'ara Depression/Tell al-Afayef. The thickness of the formation is not clearly defined [4]]. The exposed thickness of the formation is 140 meters [5]. The formation generally consists of coarse and medium-grained sandstone rocks, and it also contains cross-bedding with kaolin clay rocks [6]. The formation is deposited in a fluvial environment with large meandering rivers.

2.1.2 Ubaid formation

The bauxite clays of the Ubaid Formation can be found in the western desert of Iraq, specifically in the Wadi Hawran area, located northeast of Rutba in western Iraq. As a stratigraphic unit with a thickness of 75 meters [7]. The formation consists of two main parts: the lower member, with a thickness ranging between 25-30 meters, comprises coarse-grained sandstone rocks and multi-colored marly rocks with lenticular layers of iron ore. While the upper member consists mainly of crystalline limestone rocks with large amounts of flint, the thickness of this member ranges between 40 and 50 meters [6]. The formation appears in a belt extending from the southwest to the northeast of the city of Rutba, 10 km east of Wadi Hawran. The formation's lower limit is incompatible with the Zour Hawran Formation and represents a case of marine transgression.

2.1.3 Digma (marbat beds)

The Digma Formation is part of the Early Maastrichtian-Late Maastrichtian sequence. The formation is located 10 km southeast of the Akashat mine. The depositional environment is shallow water, coastal neritic; the lower contact is not compatible with the Messad Formation [5]. The formation is 40 m thick; it is called "Yellow Beds". It is a white to cream limestone, dolostone with a phosphorite horizon and green to yellow foliated mudstone [8].

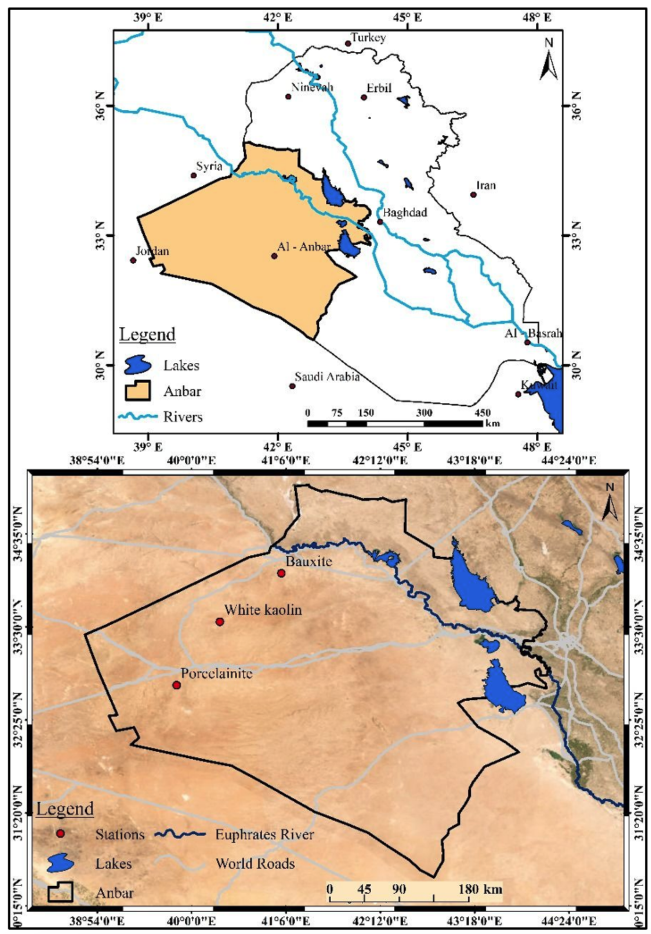

Fig. 1 Geological map of the study area

2.2 Chemical analysis

The raw material samples were chemically analyzed by X-ray fluorescence in the laboratories of the Geology Department, College of Science, University of Baghdad. From Table 1, it was found that the percentage of silicon oxide (SiO_2) in the clay samples ranges between 42.35% and 60.90%. Because silica enters the crystalline structure of clay minerals, this oxide makes up the majority of the clay samples. In addition to free silica present in the form of quartz. As for aluminum oxide (Al_2O_3), it ranges from 1.46% to 51.47% in the study samples. Calcium oxide (CaO) ranges from 0.50% to 11.20% in the clay samples, as calcite and gypsum are the main sources of this oxide. The percentage of ferric oxide Fe_2O_3 ranges between (0-0.86%), while titanium oxide TiO2 ranges between (0.10-3.30%). As for magnesium oxide (MgO), its percentage ranges between 0.18% and 7.0%. As for (Na_2O, SO_3, Cl, K_2O), Clay samples include relatively tiny quantities of these oxides.

Table 1 Main oxides of the study area

Oxides	Porcelainite %	White kaolin %	Bauxite %
Na_2O	0.51	0.43	0.14
MgO	7.0	0.39	0.18
Al_2O_3	1.46	33.97	51.47
SiO_2	60.90	48.86	42.32
Cl	0	0	0.05
TiO_2	0.10	1.0	3.30
Fe_2O_3	0.65	0	0.86
K_2O	0.15	0	0.01
CaO	11.20	0.50	0.57
SO_3	0.31	0.09	0.73

2.3 Index properties

2.3.1 Atterberg limits

It is one of the important tests for soil and represents the percentage of water content that causes a change in the soil, as most types of soil exhibit a clear change in their behavior when the percentage of water content changes [9]. The name Atterberg came from the Swedish scientist who developed it. We observed that the soil transitions from a liquid state to a semi-liquid state, then to a plastic state, and finally to a semi-solid state, before solidifying into a solid state (Figure 2).

The plasticity limit (PL) is the proportion of soil on a dry weight basis that may be twisted into a thin thread with a diameter of 3mm without cracking or breaking the clay thread. Soils were evaluated for flexibility and fluidity using a 425µm sieve, as per the American standard [10]. Non-plastic soil cannot produce threads with a diameter of 3.2mm or smaller, regardless of moisture content. The experiment was performed multiple times until the thread was unbroken and measured 3.2 mm in thickness. The experiment was performed three times to get the average moisture content over three measurements. To calculate the moisture content of the sample, the soil was placed in a small container after taking the empty container's weight. Then, the container and the sample were weighed together. The sample was dried in a drying oven for 24 hours, and its weight was measured after drying. Then, the container and the sample were weighed after drying, and equation (1) was applied to find the moisture content of the sample, as shown in Table 2.

$$W \cdot C\% = [(w2 - w3)/(w3 - w1)] \times 100. \quad (1)$$

whereas : W.C is water content, $w1$ is empty container weight, $w2$ is weight of the container and wet sample, $w3$ is weight of the container and dry sample

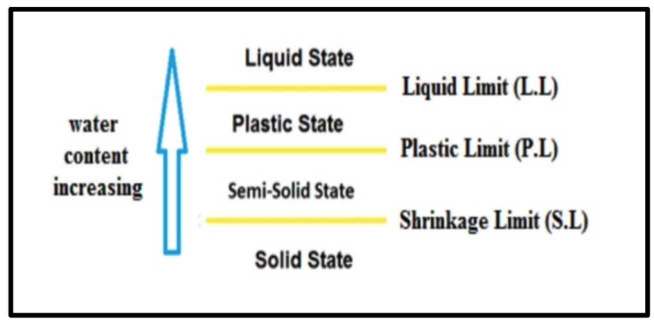

Fig. 2 Sketch shows Atterberg limits [11]

Table 2 Water content

Area	Moisture content at plastic limit %
White kaolin	37
bauxite	29

At this content, the liquid limit (LL) is reached, indicating that the soil is about to become a viscous liquid and has little shear resistance against its flow or fluidity. The Cassagrance Device was used to calculate the liquid limit. The Cassagrance Method was used to measure the liquid limit using the Cassagrance Device to determine the water content.

This experiment was repeated three times for each sample to take the average and represent it graphically on a semi-logarithmic sheet to discover the water content at the number of hits 25 (Table 3).

Table 3 Liquidity limit of the soils used in the study

Area	Moisture content at plastic limit %
White kaolin	37
bauxite	29

The plasticity index is equal to the difference between the plastic and liquid limits. as in the equation (2)

$$\text{P. I.} = \mathbf{L.L - P.L}, \quad (2)$$

Where : $P.I$ is the Plasticity index,
$L.L$is the Liquid limit,
$P.L$ is the Plastic limit.

Comparing the results of the plasticity index shown in Table 4 with the classification of Budinkov [12], shown in Table 5. The white kaolin clays exhibited natural (plastic), meaning these clays are malleable and suitable for brick making, while local bauxite clays showed (moderately plastic).

Table 4 Atterberg limits for the clays used in the study

Area	plastic limit	Liquidity limit	plasticity index
White kaolin	37	57	20
Bauxite	29	38	9

Table 5 Plasticity index on [12]

Plasticity Index	Classification
>25	Super Plastic
15-25	
7-25	
<7	Poorly plastic

2.3.2 Grain size distribution

In this research, the clay samples were ground to a very fine size and then sieved using a 63-micron sieve to separate the sand size from the silt and clay sizes. The particles that did not pass the sieve are the sand size, while the particles that passed the sieve are the silt and clay sizes. The percentage of silt and clay was then calculated using the pipette method. This test was conducted in the German laboratory affiliated with the Department of Earth Sciences / College of Science / University of Baghdad, Table 6.

Table 6 Results of the volume gradation analysis of the clays in the study area

Area	Clay %	Silt%	Sand%
White kaolin	97.6	2.4	0
Bauxite	97.1	2.9	0

2.4 Lightweight firebrick manufacturing

The manufacturing process of fired clay bricks can be divided into four stages, based on the basic principles used for thousands of years: selection and preparation of clay, shaping, drying, and firing [13].

2.4.1 Sample preparation

Several manufacturing operations were carried out on the local raw materials after they were brought in their natural sizes from the selected sites, in order to prepare them for the production of lightweight firebricks. They were crushed using a hammer and then softened in a drying oven at a temperature of 105-110°C, in order to facilitate the grinding process into fine sizes. After that, the samples were ground using a grinding machine. Then, the samples were homogenized by adding 15% distilled water and placed in tightly sealed bags, left to ferment for 24 hours to provide sufficient time for the moisture to become completely homogeneous. A moisture content of 15% was used instead of 8%, specifically in the mixtures containing ground porcelainite, in order to produce sound samples formed by the semi-dry pressing method.

2.4.2 Sample formation

There are numerous ways for producing ceramic samples, including plastic forming, semi-dry pressing, and dry pressing. Each of these methods has a different use. In the current study, samples were prepared using the semi-dry pressing method, which involved wetting the combination components with 15% water and homogenizing them thoroughly by passing the product through a 1.4 mm sieve. The samples were then placed in firmly sealed plastic bags and stored for 24 hours, as shown in Table 7. The samples were formed, and then the mixture components were pressed using a mechanical hydraulic press, applying a pressure of 250 kg/cm^2. Then the drying and burning stages began. The crook was prepared by burning the clay at a temperature of 1200 °C, and then re-ground after burning. It was mixed in specific proportions with raw clays, as this gives the sample the ability to withstand high heat without melting. Samples of bauxite and white kaolin were taken and burned at a temperature of 1200 °C, according to a specified burning timetable, and then re-ground after the combustion process [11].

Table 7 Mixtures used in the study

Mixtures	Firebrick mixes
A	60 Burnt White Kaolin +40 Porcelainite Rocks
B	60 Local Burnt Bauxite +40 Porcelainite Rocks
C	80 Local Burnt Bauxite +20 Porcelainite Rocks
D	80 Burnt White Kaolin +20 Porcelainite Rocks

2.4.3 Drying

Drying After completing the semi-dry pressing process, the mixtures were transferred to a drying oven at a temperature of 105-110 °C for 24 hours to reach a degree of complete dryness, where the moisture resulting from the presence of mixed water in the spaces and pores in the pressed samples is removed, causing an initial longitudinal contraction in size [14]. The drying process strengthens the pressed samples, allowing them to be transferred to burning furnaces without breaking or shattering [15].

2.4.4 Burning

The burning process is one of the most complex and important because it involves several complex physical and chemical processes, including the combustion of organic matter, the evaporation of molecular water from clay minerals, transformations in silica phases, and the disintegration of carbonate minerals [16]. The burning was carried out according to a specific program and had a maturation period of one hour, at temperatures of 1200-1300-1400 °C. The cooling process for the brick samples was rather sluggish, as the samples were left in the oven until the next day, at which point they were removed. The benefit of gradual cooling is that it prevents fractures in burnt samples, which can occur with quick cooling. On the other hand, leaving the samples in the oven after it has been turned off allows for more complete reactions and crystallization of the various mineral phases [15].

3 RESULTS AND DISCUSSION

3.1 Longitudinal contraction after burning

This is a very significant test in the brick business. Longitudinal shrinkage refers to the percentage loss in the original length of a burnt brick sample resulting from fire. The longitudinal shrinkage of the burned brick samples was determined using [17] by measuring the length of the sample before firing (L1) and after firing (L2) using a precise electronic Vernier scale. The amount of longitudinal shrinkage was then calculated, and the following equation was applied (3).

$$\text{Linear Shrinkage (\%)} = \frac{L1 - L2}{L1} \times 100 \qquad (3)$$

Where: $L1$: length before burning (mm) , $L2$: Length after Burning (mm).

It is noted from the results, as shown in Table 8, that the percentage of longitudinal shrinkage increases with the increase in the firing temperature. This shrinkage is attributed to the decrease in porosity, which also leads to an increase in density. The lowest percentage of longitudinal shrinkage was in model (K) at a firing temperature of 1200 °C, reaching 0.09%, and the highest percentage of longitudinal shrinkage at a temperature of 1400 °C, reaching 1.92%, was in model (m). The results of this test showed that the percentage of longitudinal shrinkage of the firebrick samples, in general, and for all burnings (1200, 1300, and 1400 °C), increases with an increase in the burning temperature. At a temperature of 1400 °C, the percentage of longitudinal shrinkage was greater than its percentage at the burning temperature of 1300 °C, which in turn is greater than its percentage at the burning temperature of 1200 °C. The reason for this shrinkage in length is due to the burning process, the occurrence of melting, and the formation of the glassy material that works to close the pores between the grains, thus leading to the shrinkage of the brick sample (since the higher the burning temperature, the more the glassy material is formed) and that this shrinkage is equivalent to the decrease in the percentage of porosity [18].

Table 8 Represents the longitudinal shrinkage values after firing for the produced firebrick samples

Longitudinal shrinkage% 1400°C	Longitudinal shrinkage% 1300°C	Longitudinal shrinkage% 1200°C	Mixtures
0.17	0.13	0.09	A
1.92	1.01	0.66	B
1.66	1.27	0.95	C
0.22	0.17	0.13	D

3.2 Porosity

There are two types of porosity: apparent (open) porosity, which is associated with the exterior surface and has a substantial impact on the mechanical, electrical, thermal, and chemical properties of the ceramic body.

The second kind is closed porosity, which is unrelated to the outside surface and has a negligible impact on the aforementioned properties. Porosity is of tremendous relevance in industry because it allows water vapor and other gases to escape from the brick during various production processes, such as drying and burning [15]. The porosity test was carried out according to the International Organization for Standardization [19, 20] by drying the samples a second time to ensure that no moisture was acquired after burning the brick in an electric oven at a temperature of 105-110 °C. After cooling the samples, the dry weight W1 is measured. After that, the submerged weight of the sample is measured by hanging it with a wire. It is then completely submerged without touching the bottom surface of the vessel, and the weight reading W3 is recorded, which equals the submerged weight. The samples were then submerged in water for 24 hours and wiped with a wet cloth. To remove the water droplets adhering to the surface of the samples, the saturated weight W2 is measured. The porosity of the samples was calculated according to Equation 4.

$$\text{Porosity \%} = \frac{w2 - w1}{w2 - w3} \times 100 \quad (4)$$

Where: $w1$: Dry weight, $w2$: Saturated weight , $w3$: Submerged weight

The results, as shown in Table 9, indicated that the porosity decreases with increasing degree of firing. As a result of the firing process, a glassy phase will be formed that closes the pores of the firebrick, depending on the amount of glassy material formed, which in turn depends on the type of components of the fired material, as well as the size of its grains, firing temperature, firing duration, and maturation duration [21].

Table 9 results of apparent porosity

Porosity% 1400°C	Porosity% 1300 °C	Porosity% 1200 °C	Mixtures
17.91	19.11	21.86	A
18.44	20.51	22.83	B
16.46	18.51	20.69	C
16.01	19.14	17.96	D

3.3 Total density

It is one of the important characteristics when examining the produced bricks, which is positively related to the compressive resistance. The higher the total density, the higher the compressive resistance values [22]. The total density is directly related to porosity and compressive resistance. The lower the porosity, the higher the total density, and thus the higher the compressive resistance values [23].

When density increases, particles grow closer together, resulting in a reduction in porosity. Also, as density increases, so does compressive resistance. The apparent density of the manufactured bricks was determined at temperatures of 1200, 1300, and 1400 °C, as per the American specification [24], using Equation 5.

$$\text{Density} = \frac{w1}{w2 - w3} \times \rho_1 \quad (5)$$

Where $w1$: Dry weight, $w2$: Saturated weight, $w3$: Submerged weight, p1: Water density.

We note from the results shown in Table 10 that the total density values of the samples decrease with an increase in the weight percentage of the porcelainite content. There is also an inverse relationship between the density values and the percentage of longitudinal shrinkage of the samples within the same firing temperature. The lower the density values, the higher the percentage of longitudinal shrinkage. The reason for this is the increase in the apparent porosity percentage, which leads to a decrease in the density values, and the occurrence of the sintering process leads to an increase in the percentage of longitudinal shrinkage, which is not sufficient to close the pores, so the increase in longitudinal shrinkage continues with the increase in porosity and then the decrease in the density values of the firebrick samples [25].

Table 10 Results of the total density test of fire bricks

Total Density 1400°C	Total Density 1300°C	Total Density 1200°C	Mixtures
1.73	1.45	2.24	A
1.61	1.68	1.89	B
1.82	1.88	2.05	C
1.92	2.05	2.37	D

3.4 Unconfined compressive strength

The compressive strength of bricks is one of the most essential mechanical parameters for determining the material's capacity to bear loads and pressure. The value of compressive strength is heavily influenced by the quality of the raw materials, as well as the manufacturing method and firing temperatures. The compressive strength of bricks is an essential feature that determines the material's capacity to bear compressive stresses in construction [26]. The sample was placed on a base in the device, and pressure was slowly applied by a vertical axis of movement (the compressive part). When the compressive part touches the sample, the device's meter begins to calculate the applied pressure. The pressure is applied gradually and slowly until the brick sample collapses, at which point the device's scale stops recording the pressure at the moment of sample collapse, as indicated by the device's reading, in kilonewtons. The stress applied to the sample during collapse is converted to newtons and divided by the sample area (measured in square millimeters). The result is the force applied to the sample (Newtons/square millimeters), according to Equation 6.

$$S = \frac{W}{A} \tag{6}$$

Where S: Compressive strength (nt./mm^2) or (Mega Bascal), W: stress amount applied when the collapse occurs (nt.) A: Sample area (mm2).

The results in Table11 show that the samples' ability to withstand increases with increasing firing temperature, and we conclude that when firing temperature increases, the melting rate of the raw materials that make up those samples increases, and thus larger quantities of the glass phase are formed, which in turn works to bind the grains together, and thus the strength of the samples increases [16].

Table 11 Results of the compressive strength test of the samples

compressive strength(nt./mm^2) **1400°C**	**compressive strength**(nt./mm^2) **1300°C**	**compressive strength**(nt./mm^2) **1200°C**	**Mixtures**
22.59	19.68	17.90	A
24.15	22.03	20.87	B
20.05	18.87	18.11	C
22.36	21.36	19.05	D

3.5 Thermal conductivity

Thermal conductivity is one of the most important thermal tests for insulating materials. There are many different methods for measuring the thermal conductivity of materials, depending on the type of material and the nature of its use. This test was conducted on samples of firebricks burned at a temperature of 1400 °C. In this study, Lee's disc method was used to calculate the thermal conductivity (K), a method commonly employed in thermal insulating materials. The insulating material is placed between two conductive copper plates B, A, and there is a coil called the heating coil connected to the two ends of the battery between the plates C, B. Then a voltage of 6V is applied, and after that the current I was read, then the reading of disc A, disc B, and disc C was taken when the three discs reach thermal equilibrium for a period of time between 0 to 60 minutes, and after measuring each of r, ds, dB, and dA [27], Equation 7 was used.

$$K\left[\frac{T_B - T_A}{d_S}\right] = e\left[T_A + \frac{2}{r}\left(d_A + \frac{d_S}{4}\right) + \frac{1}{2r}d_S T_B\right] \tag{7}$$

Where: I : Passing current (0.4) (Ampere) V: Supply voltage (6) (volt) R: Model radius (mm) E: Amount of thermal energy (k) (w/m2) TC, TB, TA :Disc temperatureABC, respectively. Ds: Model thickness (mm)

Table 12 indicates that the thermal conductivity increases with increasing firing temperature and decreases with increasing apparent porosity of the samples.

Table 12 Thermal conductivity results of the produced firebrick samples

Thermal conductivity (W/m^2.K)	**Mixtures**
0.25	A
0.14	B
0.46	C
0.47	D

4 CONCLUSION

The results of the chemical analysis of the clays showed that they contain a high percentage of silica and aluminum, indicating that the clays from the selected areas are suitable for the manufacture of fire bricks. There is a clear, direct relationship between porosity and thermal insulation, and an inverse relationship between porosity and total density. The best results were obtained when using a firing temperature of 1400 °C. This is because it is the highest value of compressive strength, and at the same time, the total density was not significantly affected by other temperatures. The optimal performance was achieved when using a mixture of 60% clay and 40% porcelainite silica, with 15% water content, at a pressure of 250 kg/cm^2, which resulted in the lowest value of thermal conductivity. The thermal conductivity of bricks is affected by porosity and density. The thermal conductivity values decrease with increasing the percentage of porcelainite rocks. The results are consistent with the international standards values.

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DATA AVAILABILITY

N/A

DECLARATIONS

Conflict of interest

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Consent to publish

All authors consent to the publication of this work. Written informed consent for publication was obtained from the participants.

Ethical approval

N/A

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