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Research Article

Evaluation of bentonite suitability as a binder on the physico-mechanical and thermal properties of insulating bricks produced from quartz deposit

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Abstract

The study developed insulating refractory bricks from quartz with varied percentages of bentonite as a binder was subjected to physico-mechanical and thermal investigations. The produced bricks were dried and then sintered at 1200^{o}C. To examine the refractory performance of the material, analyses were done on the bulk density, apparent porosity, shrinkage test, loss on ignition (LOI), cold crushing strength (CCS), water absorption (WA), and microstructural examination using scanning electron microscope and energy dispersive X-ray spectroscopy (SEM-EDS). The tested bricks' average apparent porosity of 43, 46, and 48%; water absorption of 0.98, 1.70, and 1.86%; bulk density of 1644, 1516, and 1324 kg/m^3; shrinkage value of 1.71, 0.20, and 0.66%; cold crushing strength of 2.165, 1.381, and 1.088 MPa; loss on ignition of 0.98, 1.70, and 1.86%; and refractoriness of 1571.68, 1568.53, and 1565.39 ^{0}C were obtained for varying the percentage of the bentonite to 5, 10, and 15%, respectively. These results were within the range of values considered typical for refractories suggesting their suitability for high temperature applications. Additionally, the microstructural examination demonstrated homogeneity and the distribution of silicon throughout the brick structure. These denote consistent qualities and good thermal and mechanical capabilities. Meanwhile, the bonding materials were observed to significantly affect the refractory bricks produced.

1. Introduction

Refractory materials (RMs) have shown exponential growth in industrial applications over time, which can be attributed to the rising need for high-temperature materials [1-3]. The exponential growth in industrial applications of refractory materials (RMs) over time can be attributed to the increasing demand for high-temperature materials. This demand arises from various industries where RMs are essential, such as pyrometallurgy, where they are used in furnaces, kilns, incinerators, and other high-temperature environments. RMs exhibit properties like thermomechanical stability, resistance to thermal decomposition, pressure loads, physical wear, and chemical attack, making them indispensable in these applications [1-3].

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Meanwhile, bentonite, a clay mineral renowned for its unique properties such as high-water absorption capacity, swelling ability, plasticity, and thixotropy, plays a significant role in various industrial applications. Its properties make it an excellent binder in the production of building materials like bricks and ceramics [4]. In recent researches, bentonite has been reported to improve sintering mechanism when used as the bonding material [5,6]. Also, the high thermal stability of bentonite is another favorable property. Apart, from the resistance to high temperature, the chemical composition and the content of Montmorillonite of bentonite makes it favourably sorted after for binding in high temperature applications [7-9].

Due to the properties of RMs, they are vastly used in the process of the pyrometallurgical field as part of the structure constituents (pre-eminently inlays) in incinerators, furnaces, ovens, kilns, as well as areas of operation where thermo-mechanical durability is of primary concern for example fire or combustion indicator mechanism for rocket take off supports and re-entry temperature shield used in spacecraft [10, 11]. The predominant of RMs are non-metallic, polyphase, and inorganic materials that also exhibit permeability, non-homogeneity, and polycrystallinity. Hence, these materials are naturally composed of elements like aluminum (Al), silicon (Si), zirconium (Zr), magnesium (Mg), and others, either as oxides or non-oxides. They could be described as consisting of bonding agent phases, additives, and heat resistance composite minerals. Additionally, some metals with melting points higher than 1850 °C, such as tungsten (W), which has a fusion or melting point of 3422 °C, and niobium (Nb), which has a liquefaction phase with 2477 °C, are also regarded as RMs [10 - 12]. The bonding material to be used for the binding of RMs during production needs to also exhibit excellent thermal properties. However, several studies have explored the mineralogical and thermal properties of bentonite, highlighting that it has stable thermal properties [13, 14].

Generally speaking, RMs are materials that retain their mechanical integrity, dimensional stability, and chemical identity when subjected to elevated heat above 538 °C and are mechanically resilient to thermal decomposition, applied force, mechanical deterioration, or chemical degradation such as corrosion [11, 15]. Insulating materials consist primarily of a binder phase, a thermally stable mineral aggregate, and additives. They are non-metallic inorganic materials. Insulating bricks are made to withstand a variety of abrasive and corrosive particles, liquids, or gases as well as exposure to extremely high temperatures [16]. The primary fundamental materials utilized in manufacturing the refractories include silicon oxides SiO_2, calcium (Ca), magnesium (Mg), aluminum (Al), and zirconium (Zr) as well as other non-oxide compounds including borides, nitrides, carbides, silicate, and graphite [17]. Due to the industrial applications of refractories, mechanical strength is critical to be able to resist thermal shock and deformation when in use. Dense refractory materials, such as fireclay and high-alumina bricks, are used for their high mechanical strength. In this light, there are basic requirements a material should meet before it can be used as refractory material [18-20]. Meanwhile, the strength of most refractory materials is extremely reliant on the bonding agent [21], binders are very critical for the production of refractory.

Overall, refractory materials are essential for many high-temperature industrial processes and are however required to perform the following basic functions: act as a thermal insulation; act as a chemical barrier that prevents corrosion; and provide mechanical stability [23]. As demand for these materials continues to grow, the development of new, innovative refractory materials is likely to hold a crucial role in the future of high-temperature manufacturing. In a bid to develop a stable refractory brick, the study investigated the effect of the selected bonding material on the physical, mechanical, and thermal stability of the produced bricks. The microstructural examination of the bricks produced was carried out using scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM/EDS). This study is important to enable the selection of the bonding materials and the proportion that enhances overall efficiency in high-temperature industrial applications.

2. Materials and Methods

2.1 Materials

Quartz rock specimens were dug from the extraction sites using the appropriate crude instruments. Figure 1 (a) and (b) presented the as-collected quartz and the milled bentonite powder, respectively. Also, the functions and sources of the specimens utilized for manufacturing the refractories are presented in Table 1.

(a) (b)

Fig. 1. Image of materials used (a) quartz (b) bentonite

Table 1. Materials

S/N	Material	Source	Use
1	Quartzite	Ijero-Ekiti, Ekiti State, Nigeria	Production of refractory bricks
2	Bentonite	Sango, Ogun State, Nigeria	Binding material
3	Distilled Water	-	For mixing the refractory and binder

2.2 Methods

The collected rock samples were cleaned and sunbaked for 3 days to reduce humidity level for easy grinding of the rock samples [23]. The dried samples were then mechanically grinded into fine powders in a lab ball mill (Model 48-D0500/D and Serial No. 14002201). The fined particles were heated at 110 °C for 1 h in an oven to ensure that the unbounded moisture content had completely evaporated [23]. The pictorial illustration of the entire process followed while producing the refractory bricks is presented in Fig 2.

Table 2. Materials composition

	Materials and Percentage Composition	
S/N	Quartzite (wt. %)	Bentonite (wt %)
1	95	5
2	90	10
3	85	15

The process of turning the rock element's fine grains into a uniform mouldable mixture served as the first step in making refractory (insulating) bricks. This was accomplished by including 5, 10, and 15% bentonite as shown in Table 2 in succession as binder, and 8% water. The 8% water was adopted based on the study of [24], stating it to be the ideal amount required for best plasticity. The binder application is done to increase pre-fired or raw strength and serve as an addictive [25]. The slurry was then automatically homogenized by rapidly stirring in a clockwise manner with a ceramic blunger until a uniform plastic paste was achieved. The resulting paste was then put into the steel plate-made mould with dimensions 50 x 50 x 50 mm as shown in Figure 3. With the firing temperature reaching 1200 °C, the green samples were fired using an oven at 100 °C for 10 min. The refractory bricks were maintained at 1200 °C for 8 hr, after which a 24-hour cooling occurred within the furnace [23]. Diverse evaluations were carried out to establish insulating bricks' technical or mechanical characteristics and heat durability.

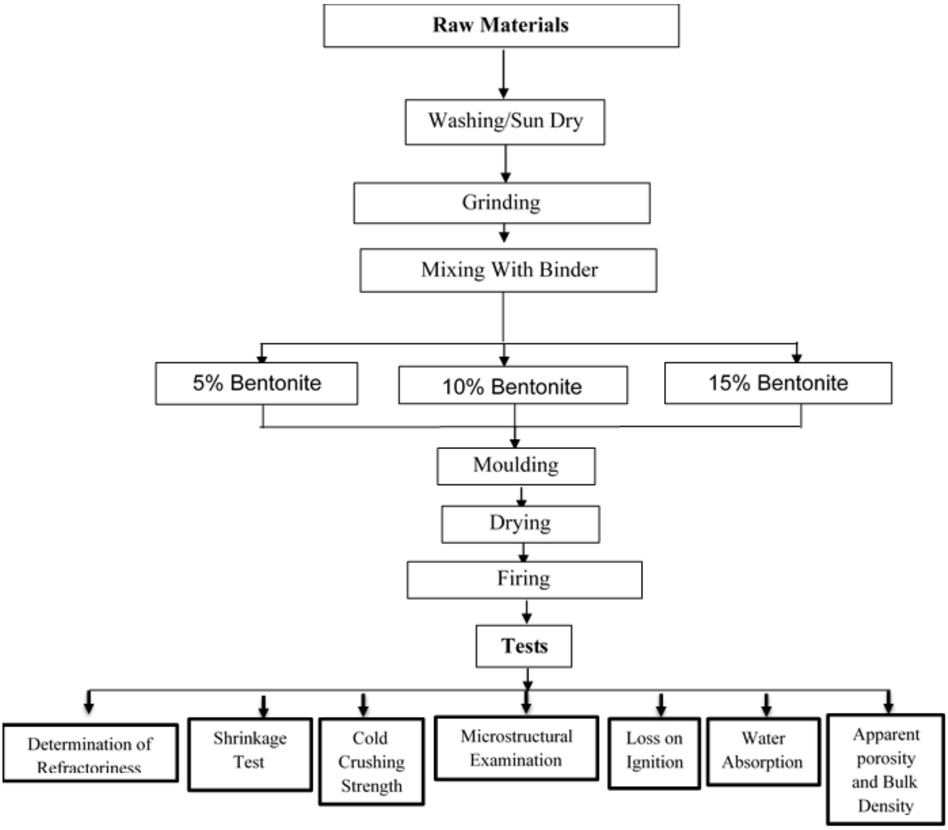


Fig. 2. Schematic representation of the method

Fig. 3. Produced refractory brick

2.2.1 Apparent Porosity of The Bricks

By immersing the brick in a water bath, the permeability of the refractory material produced was ascertained. The bath was kept at 100 °C and the immersion time was set to 24 h. Each brick sample's apparent porosity was assessed in accordance with [26] specification. Apparent porosity was therefore calculated using Eq. (1):

$$Apparent\ porosity\ (p_a) = \frac{w_{sww}-w_{da}}{w_{sww}-w_{sw}} \times 100 \tag{1}$$

where w_{sww}, w_{da}, and w_{sw} are saturated mass of the immersed sample in water, dry mass of the sample in ambient air, and mass of the sample immersed in water, respectively.

2.2.2 Brick Bulk Density Measurement

The bulk density of each refractory bricks was determined using the Eq. (2):

$$Bulk\ Density\ (B_d) = \frac{mass\ of\ material}{volume\ of\ material} \tag{2}$$

2.2.3 Shrinkage Test for the Bricks

The shrinkage analysis is essential for measuring the change in volume that occurs as the water content of refractory bricks fluctuates during manufacturing. To assess the shrinkage of the bricks, a diagonal line labeled as l_1 is drawn across each test sample. Sequentially, samples were exerted to a temperature of 1000 °C in the furnace. After firing, another line, designated as l_2, is depicted through the bias of the fired samples to establish their ultimate dimension. As a result, the material's linear shrinkage was calculated using Eq. (3) from the ASTM C596 - 18 specification [27].

$$Lineear\ Shrinkage = \frac{l_1 - l_2}{l_1} \times\ 100\% \tag{3}$$

2.2.4 Cold Crushing Strength (CCS) Test of the Bricks

The cold crushing strength test is a standard method utilized to establish the strength of bricks mechanically, refractory composites, and other similar products at room temperature varying two experiments per sample. It measures how materials endure a compression force excluding any deformation or failure experience. The CCS test is important for evaluating the quality and durability of bricks. It is the ultimate loading per unit area which a refractory material will exclude under specific conditions at ambient temperature before failing. Typically, cold crushing strength is utilized to assess the toughness of refractory materials mechanically using universal testing device (Testometric M500-50AT), the CCS of each brick was calculated in compliance with standard [28].

2.2.5 Loss on Ignition Test of the Bricks

Before subjecting a sample to heating, any residual moisture from drying needs to be eliminated. The Loss on Ignition (LOI) analysis is a common method employed to evaluate organic and inorganic composition content in bricks, refractory materials, and other similar products. It measures the percentage of weight loss experienced by a sample when subjected to high temperatures, typically in the range of 800-1000°C. The LOI test is essential for assessing the quality, purity, and composition of bricks. It signifies the variation in material mass before and in the aftermath of ignition.

In this study, LOI is the mass decrease using an overall mass of refractory bricks produced, represented in percentage. As a result, each brick's weight loss was estimated as the difference between their pre- and post-firing weights, and as a result, the LOI at 1200 °C was computed using Eq. (4) as per the [29] test standards.

$$LOI = \frac{W_1 - W_2}{W_1} \times 100 \tag{4}$$

where W_1 is the brick sample's initial mass before firing. Brick sample's ultimate mass W_2 following firing. Lost On Ignition of bricks produced was calculated utilizing the [29] test analyses.

2.2.6 Water Absorption Test of the Bricks

Water Absorption (WA) tests are frequently performed to assess the porosity and permeability characteristics of refractory materials. This test entails quantifying the quantity of water absorbed by a sample of the refractory material within a designated timeframe. Water absorption evaluation was executed by subjecting the ignited evaluation materials to boiling at 100 °C time interval of 24 h, then additional immersion into water was carried out in 4 h. Water absorption was determined by calculating the mass disparity of the produced material prior to and following immersion, utilizing Eq. (5) as outlined in ASTM C20-00-15 [26].

$$WA = \frac{W_s - W_d}{W_d} \times 100 \tag{5}$$

where soaked weight after boiling at 100 ^{o}C is W_S and dry weight is W_d

2.2.7 Determination of the Refractoriness of the Bricks

A sample's capacity to tolerate high heat exposure without significantly deforming is evaluated by its refractoriness. Moreover, the fusibility measurement of a refractory material reveals where the material starts to lose rigidity. Shuen's method was used in this study to assess the refractoriness of the sample bricks [30]. The amounts of alumina and other oxides in the refractory brick were measured engaging Shuen's formula to assess the thermal stability of the material. The brick materials were chemically evaluated via (XRF) X-ray fluorescence spectroscopy to achieve this. Eq. (6) was then used to determine the refractoriness of bricks:

$$K = \frac{360 + Al_2O_3 - RO}{0.2280} \tag{6}$$

where refractoriness (^{o}C) is represented by K, Al_2O_3 represents the refractory's alumina composition, and the total of the sample's other oxides except SiO_2 is represented by RO.

2.2.8 Microstructural Examination of the Bricks

Microstructural examination in bricks involves analysis of the internal structure, composition, and morphology of the brick material at a microscopic level. This examination provides valuable intuitions into the superiority, properties, and concert of the refractory bricks. Using scanning electron microscopy (SEM) coupled with energy dispersive spectroscopy (SEM-EDS) using model of Phenom Prox having a voltage of 15 kV, the framework morphology of refractory bricks produced was investigated. Before using SEM analysis, the evaluated materials were sputter-coated and placed on stubs made of aluminium. An energy dispersive detector that can distinguish between different X-ray energies was used to evaluate the X-ray emissions. After each element present was intensified using the EDS scan, the virtual representations were recorded, and the molar concentration in % was computed.

3. Results and Discussion

3.1 Apparent Porosity

The variation in the amount of bentonite used as a binder has an influence on the apparent porosity of refractory bricks. Highly porous brick does not crack because of the pores present. Because of this, depending on the specific service situation(s), Porosity level is a compromise. that are considered. Brick sample's APV, or apparent porosity values, are 43, 46, and 48% with respect to the 5%, 10%, and 15% of bentonite as a binder (Figure 4). From this outcome, it is observed that apparent porosity increases linearly with-respect to the upsurge in Bentonite Binder Content (BBC) for the quartz. A refractory Brick Sample (RBS) with a maximum apparent porosity parameter (APP) of 48% was noted in Q15 RBS and the lowest APP of 43% was observed for the Q5 RBS. The increase and decrease in APPs of RBSs via the addition of binders have been attributed to the particle packing factor of the binders. Binders with closely packed particles usually reduce the APPs of RBSs due to an equivalent elevation of the binding or bonding forces among the material elements, which lowers the number of voids inside of them. On the contrary, binders with loosely packed particles usually increase the APCs of RBSs due to poor adhesive strength between the particles thereby facilitating the presence of more [31].

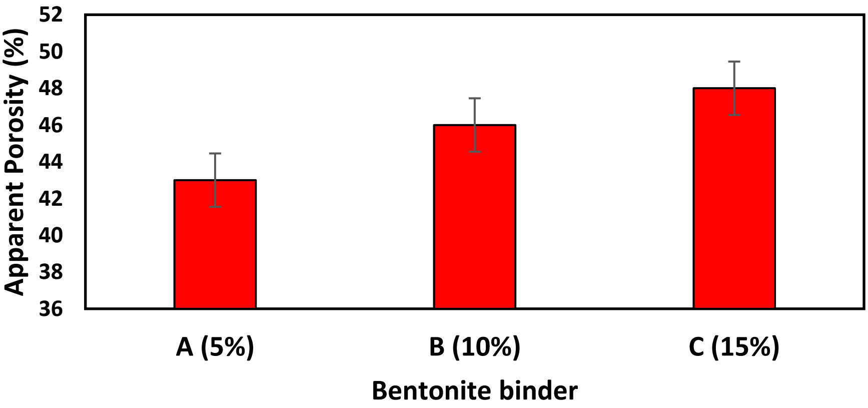


Fig. 4. Apparent porosity of refractory brick at diverse bentonite proportion

An equivalent observation was recorded when [32] studied the constancy of steel waste as heat-resistance material utilizing boric acid and bentonite as bonding agents. This is also comparable to what was reported by [31] in their study on the ceramics potential of Dabagi clay deposits. The experimental APPs in RBS are more complex than the suitable APPs (20-30%) when compared to standard siliceous fireclay. To address the problem, studies have suggested using bonding agents with densely packed particles in the refractory bricks samples hence applying the proper heat-time processing [33]. In a related investigation, sawdust was used as an addition, and the resulting apparent porosity parameters were 30.230, 39.50, 45.450, and 46.150%, correspondingly. Between 5 and 20% of the sawdust additive composition, comparing the control sample showed a development in apparent porosity parameters at an average of 200 percent. A direct relationship between porosity value and additive composition was established in the study. These outcomes reveal APPs of some burnt bricks solely depend on the amount of binders used, having a proportion enhancement in permeability vacillating from 104 to 199 percent in compositions of rice chaff additions of 5 to 20 percent [34].

3.2 Bulk Density

The bulk density provides a comprehensive indication of the produced bricks quality. Advanced bulk density with minimal porosity in refractories is generally considered to have a higher grade. A higher bulk density increases the volume's stability, thermal capacity, and slag resilience to infiltration [35]. As shown in Figure 5, the average sample's bulk density was determined to be 1644, 1516, and 1324 kg/m^3 with respect to the addition of bentonite as a binder of 5, 10, and 15%. From the result, it can be observed that an increase in the amount of BBC is unfavorable to the quartz sample. Meanwhile, [36] estimated that the bulk density of fireclay refractories should be 1910 kg/m^3. The bulk density parameters acquired in this research were minimal compared to the stipulated amount. The decrease in bulk density with increasing BBC may indicate a potential compromise in the quality of the quartz refractory bricks. However, the observed values are within the range reported for refractory clay, indicating that they still fall within acceptable limits for this type of material. Additional evaluation and deliberation in other properties might be introduced to wholly assess some quality and suitability of the refractory bricks. However, according to [37-39] the result is quite near to the range of 1700.0 to 2300.0 kg/m^3 for refractories mud. In the studies of [39, 40], Egbahieme clay with a comparable composition was reported to have a similar value of 1640 kg/m^3.

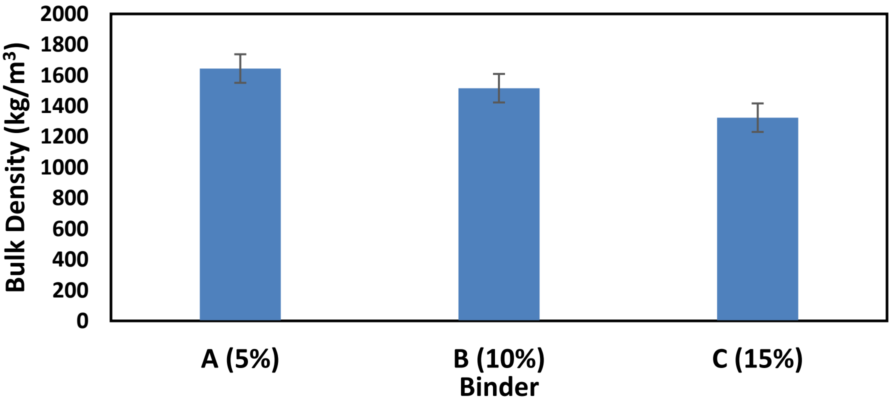


Fig. 5. Bulk density of the refractory brick at different bentonite percentage

3.3 Linear Firing Shrinkage

Linear firing shrinkage tends to modify the direct magnitude of the refractory brick samples during which it has undergone firing. In a thermal treatment furnace, a low shrinkage value is preferable for refractory bricks application [41]. The linear shrinkage values (LSV) obtained in this study were 1.71, 0.20, and 0.66% for 5, 10, and 15% of bentonite (binder), respectively. From the result, it can be observed that the effect of the BBC is significant for the quartz RBS. The highest LSV of 1.71% was observed for the Q5 RBS while the lowest LSV was observed for the Q10. As displayed in Figure 6, the overall RBSs exhibited LSVs between 0.2 and 1.71%, which were minimal compared to LSVs in the range of 4.0 – 10.0% in studies recommended for fireclays [42]. Nonetheless, other investigators claim that values less than 4% would be appropriate and that lower LSVs are preferable. [32, 44]. According to these studies, LSVs below 4% are tolerable, and lower LSVs are preferable. This suggests that the RBSs that are created would be less prone to volumetric shrinking. Furthermore, as the bentonite bonding agent confers proportional durability in Refractory Bricks Samples it does not contract as much as the specimens of rock do with temperature-time response, the minimal LSVs considering the RBSs can be linked to this property. [32] made a similar discovery. [44] additionally ascribed grog, which makes up 90% of their brick composition, having improved thermal stability and anti-shrinkage properties due to the low LSV (1.01%) ratio recorded for Ozanagogo clay.

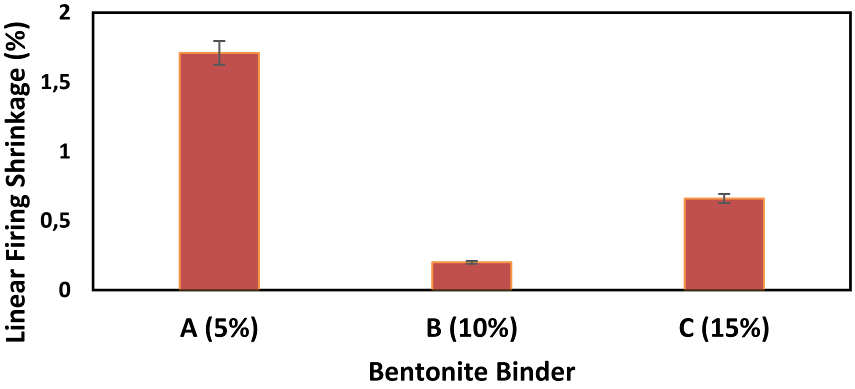


Fig. 6. Linear firing shrinkage of the refractory brick at different bentonite percentages

3.4 Cold Crushing Strength

From the result displayed in Figure 7, it can be deduced that the higher the proportion of the bonding agent, the lower the Cold Crushing Strength (CCS). The compressive stress at peak when 5%, 10%, and 15% binder was used on quarts sample is 2.165, 1.3805, and 1.0875 MPa, respectively. The highest stress that a brick can sustain before failing is 2.165 MPa for Q5 (i.e. 5% of binder to quartz sample), which is the CCS for the RBS. This number is within the range of 0.9810- 6.8670 MPa, for conventional compressive strength values as reported by [44]. The significant porosity of the brick sample can be attributed to the low strength of the bricks. Figure 8 is the image of the bricks that has undergone compression strength testing.

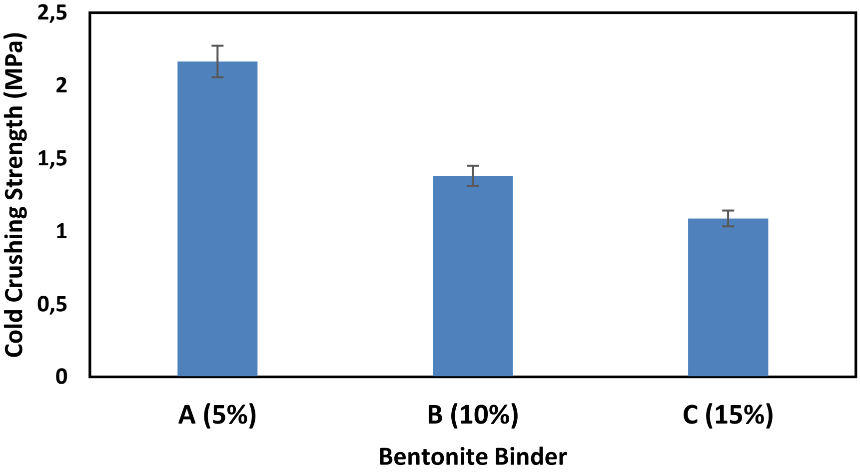


Fig. 7. Cold crushing strength of the refractory brick with different bentonite percentage

Fig. 8. Image of a failed Refractory Bricks under cold crushing strength test

3.5 Loss on Ignition Result

Shrinkage and porosity values are impacted by loss on ignition (LOI), which implies loss of organic solvent materials during firing. The results of the LOI in this study were comparable to research by [45]. The RBSs in this study had LOI values of 0.98, 1.70, and 1.86% for 5%, 10%, and 15% of bentonite (binder), respectively. This displays the maximum quantity of moisture that RBS can contain or the percentages of sample mass loss [23]. According to the minimal LOI ratio discovered during experimentation, RBS does not include much in the way of organic and/or hydrated components.

From the result (Table 3), observations showed that the highest LOI value was attained by the RBS with 15% bentonite while the lowest LOI value was attained by the RBS with 5% bentonite. However, with respect to bentonite wt. %; for the quartz-based RBS, the LOI values increased with an increase in bentonite wt. %.

3.6 Water Absorption (WA)

The quantity of water that a brick sample can absorb is determined by its water absorption (WA). The durability property of refractory bricks is ascertained via the water absorption test. According to Table 3, the RBS's WA on approximation is 2.43, 4.22, and 4.93% with respect to 5%, 10%, and 15% of the binding material, which is minimal when related to the research of [46]. The type of refractory and circumstances used to determine a precise effect of WA on refractory materials, though [47]. Refractories' WA is a crucial component since it has an impact on the material's toughness, longevity, and thermal shock resistance. A refractory becomes more porous and more vulnerable to mutilation in heat cycling and some stressors as its water intake increases. Lower water absorption, on the other hand, results in a refractory that is denser and stronger and can endure greater temperatures and harsher conditions. With less water penetration in refractory bricks, the durability of the bricks is enhanced as well as their capacity to resist the natural environment [41]. According to [48], WA lesser to 1 percent is regarded as having minimal absorption, whilst WA above 6% is regarded as having strong absorption. A clear correlation exists between perceived porosity and the absorption of water in the refractory bricks [41]. In this study, the increase in bentonite percentage tends to increase the WA value.

3.7 Refractoriness

Table 4 contains the refractory material's chemical compositions determined using the XRF. RMs with higher SiO_2 have content higher than 46.51 wt.% and can tolerate comparatively at high temperatures [49]. Also, Al_2O_3 content in refractories is reported to have a straight relationship with the refractoriness of the material in a way in which the higher the Al_2O_3 content, the higher the refractoriness [49].

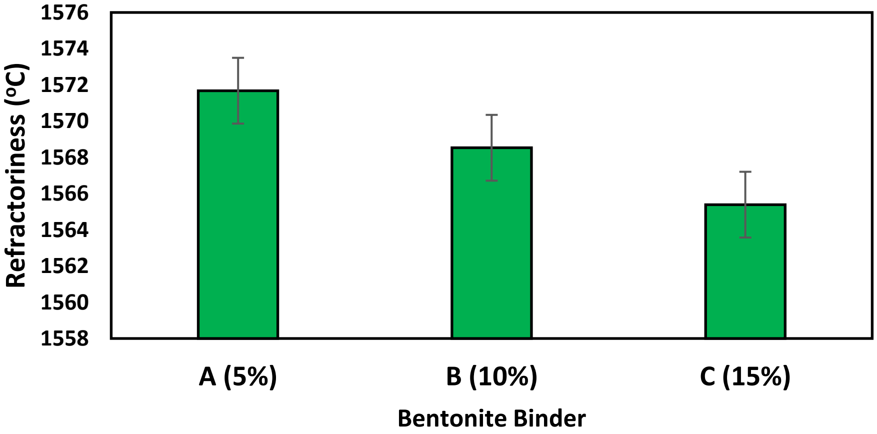


Fig. 9. Refractoriness of the refractory brick at different bentonite percentages

Refractory bricks must be able to tolerate high temperatures without melting, breaking, or degrading for these industrial applications to function well and last a long time. Refractoriness refers to a material's capacity to resist high temperatures without significantly altering its physical or chemical composition. As reflected in Figure 9 and Table 3, the RBS's refractoriness was determined to be 1571.68, 1568.53, and 1565.39 °C with the addition of bentonite at 5%, 10%, and 15% respectively, which is comparable to the 1550 °C that [50] determined for Egyptian magnesite. According to [51-53], the permissible range of refractoriness is often above 1,300 °C.

The summary of the properties obtained from the samples compared with an international standard (ASTM) is displayed in Table 3. Also, to determine the effect of the varied percentage of bentonite on the produced bricks, One-way Analysis of Variance (ANOVA) of the results at 5% significant level was calculated and presented in Table 4. Based on the p-values from the statistical analysis, the result statistically revealed that varying the composition of the binder has a significant effect on the refractoriness, cold crushing strength, water absorption, loss on ignition, and bulk density. Meanwhile, it is statistically insignificant in the apparent porosity and linear firing shrinkage. As presented in Table 5, adding bentonite to refractory bricks significantly affects their chemical composition. Table 4 indicates that bentonite is rich in SiO_2, which is one of the contents that gives the bentonite bonding strength [14].

Table 3. Refractory mechanical characteristic of refractory brick

Properties	Refractory Bricks Sample 5% Binder	 10% Binder	 15% Binder	International Standard (ASTM)
Apparent Porosity (%)	43	46	48	20–30
Bulk Density (kg/m^3)	1644	1516	1324	300 to 3200
Water Absorption (%)	2.43	4.22	4.93	1 to 10
Loss on Ignition (%)	0.980	1.70	1.86	0.5-3
Linear Firing Shrinkage (%)	1.710	0.20	0.66	0.3-2.5
Cold Crushing Strength (MPa)	2.165	1.3805	1.0875	0.981–6.867
Refractoriness (^{o}C)	1571.68	1568.53	1565.39	> 1300

Table 4. One-Way ANOVA of the Brick

(a) Apparent Porosity

Source	Degree of Freedom	Sum of Squares	Mean Square	F-Value	P-Value (0.05)
Samples	2	818.7	409.3	1.58	0.280

(b) Bulk Density at varied bentonite

Source	Degree of Freedom	Sum of Squares	Mean Square	F-Value	p-Value (0.05)
Samples	2	298443	149221	8.42	0.018

(c) Water Absorption

Source	Degree of Freedom	Sum of Squares	Mean Square	F-Value	p-Value (0.05)
Samples	2	934.8	467.42	22.86	0.002

(d) Loss on Ignition

Source	Degree of Freedom	Sum of Squares	Mean Square	F-Value	p-Value (0.05)
Samples	2	20.855	10.428	8.26	0.019

(e) Linear Firing Shrinkage

Source	Degree of Freedom	Sum of Squares	Mean Square	F-Value	p-Value (0.05)
Samples	2	0.7040	0.3520	1.74	0.253

(f) Compressive stress

Source	Degree of Freedom	Sum of Squares	Mean Square	F-Value	p-Value (0.05)
Samples	2	20.855	10.428	8.26	0.019

(g) Refractoriness

Source	Degree of Freedom	Sum of Squares	Mean Square	F-Value	p-Value (0.05)
Samples	2	24756.5	12378.3	294.11	0.000

However, it can be observed that higher bentonite content decreases SiO_2 content while it increases Al_2O_3, Fe_2O_3, and other oxides, enhancing the mechanical strength, thermal stability, and chemical resistance of the bricks. The increased Al_2O_3 content enhances refractory performance at high temperatures by improving mechanical strength and thermal stability while higher fluxing agents like Fe_2O_3 and K_2O tend to influence the melting behaviour and thermal expansion properties of the bricks which in turn enhances the brick's toughness. Also, increased Fe_2O_3 as well as increased CaO, TiO_2, and V_2O_5 influence the resistance to chemical attacks and abrasion. Meanwhile, lowered SO_3 and Cr_2O_3 lower the risk of chemical attack and corrosion attack, respectively. The chemical changes suggest that bricks with higher bentonite content may perform better in harsh thermal and mechanical environments, making them more suitable for high-stress applications.

Table 5. Chemical composition of refractory bricks samples gotten from XRF

Element Type	Conc (wt.%) at 5% Bentonite	Conc (wt.%) at 10% Bentonite	Conc (wt.%) at 15% Bentonite
SiO_2	92.16	90.01	87.86
Al_2O_3	3.09	3.81	4.52
Fe_2O_3	2.53	3.73	4.93
CaO	0.31	0.31	0.31
K_2O	0.22	0.29	0.36
SO_3	0.53	0.50	0.49
TiO_2	0.15	0.31	0.46
V_2O_5	0.02	0.03	0.04
Cr_2O_3	0.09	0.08	0.08
ZrO_2	0.01	0.02	0.03
MnO	0.03	0.03	0.04
Others	0.86	0.88	0.88

3.8 Morphological Analysis of the Samples using SEM/EDS

Figure 10 shows the SEM images of the quartz bricks and Figures 11 – 13 show the EDS analysis of the samples based on the 5, 10, and 15% bonding agents, respectively. The RBS's microtextural organization is made up of numerous ring layers (rims), which are signs of reactions taking place. The brick's inner portion, which is a holdover from initial brick production, which encircled by two rims, one on each that is made up of various complicated matrixes with needle-like silicon crystallization. Elements such as silicon have the highest weight concentrations of 88.38, 78.49, and 80.45% in the EDS analysis for the 5, 10, and 15% bentonite concentrations respectively which is comparable to concentrations of the chemical element in the refractory brick. The high concentration of silicon indicates a predominant presence of SiO_2 with the inclusion of other minor oxides such as Al_2O_3, PbO, P_2O_5, Fe_2O_3, and so on. Based on this analysis, high silica concentrations indicate enhanced thermal stability in all three binding proportions. Alumina on the other hand increases the overall strength of the refractory brick produced and it also constitutes heat retention and dissipation during the heating process. Alumina traces are found in all the binding proportions but have higher concentrations as the bentonite binding proportion increases. Iron, carbon, oxygen, and titanium, reduced the melting point of the bricks and improved the overall stability and durability of the refractory bricks as appropriate with the same ratio with percentages of binders used. The overall strength of the refractory bricks is influenced due to silicon's concentration and dispersion inside the bricks [54].

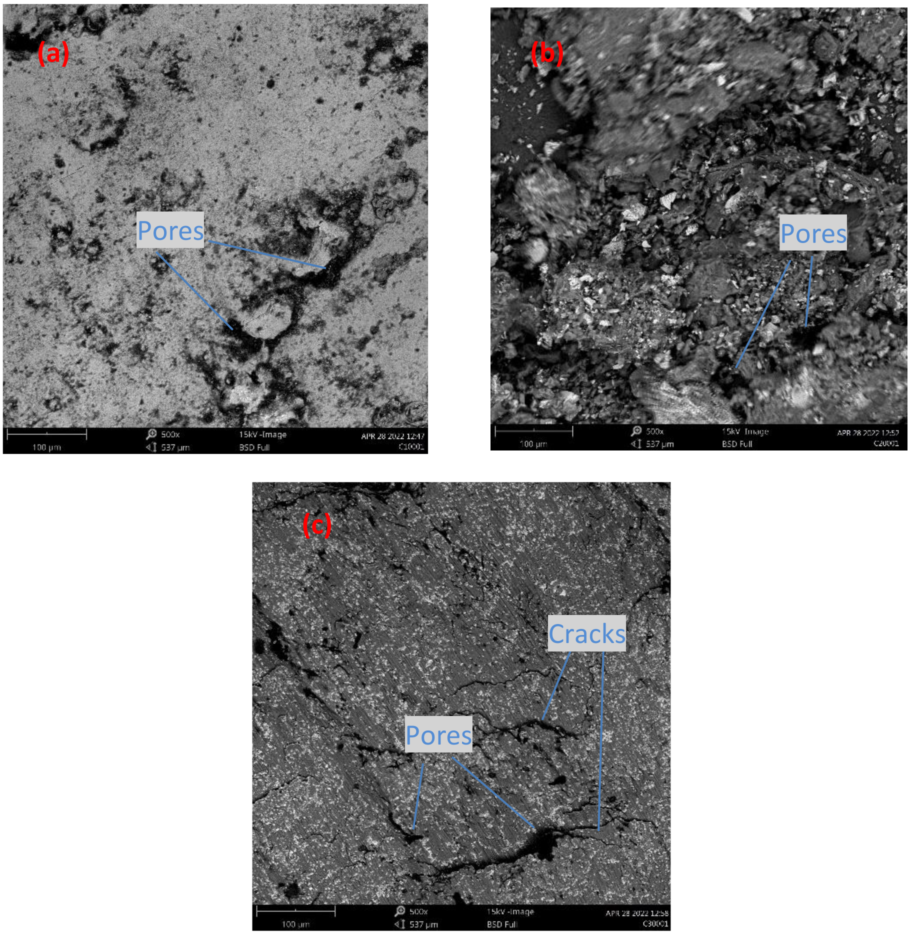
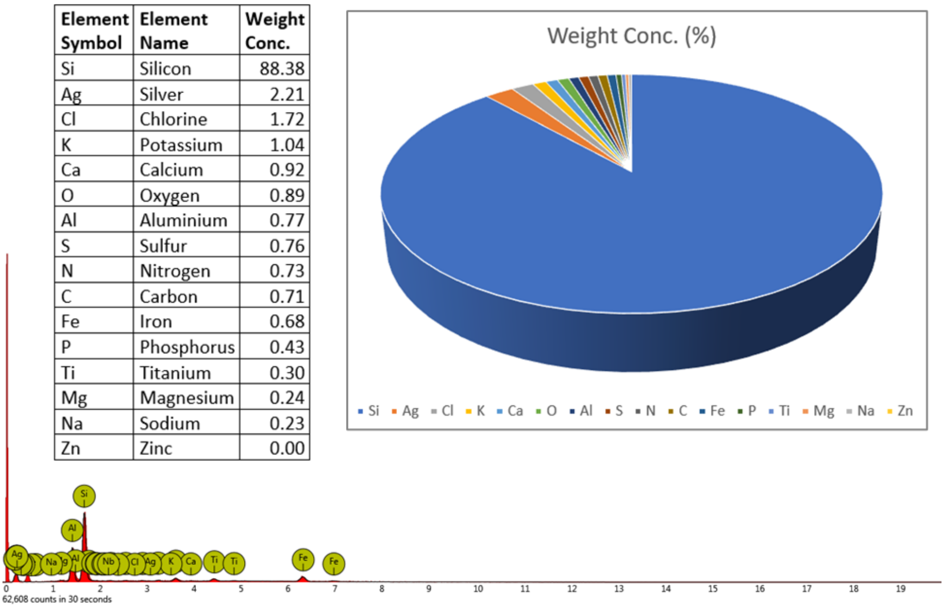


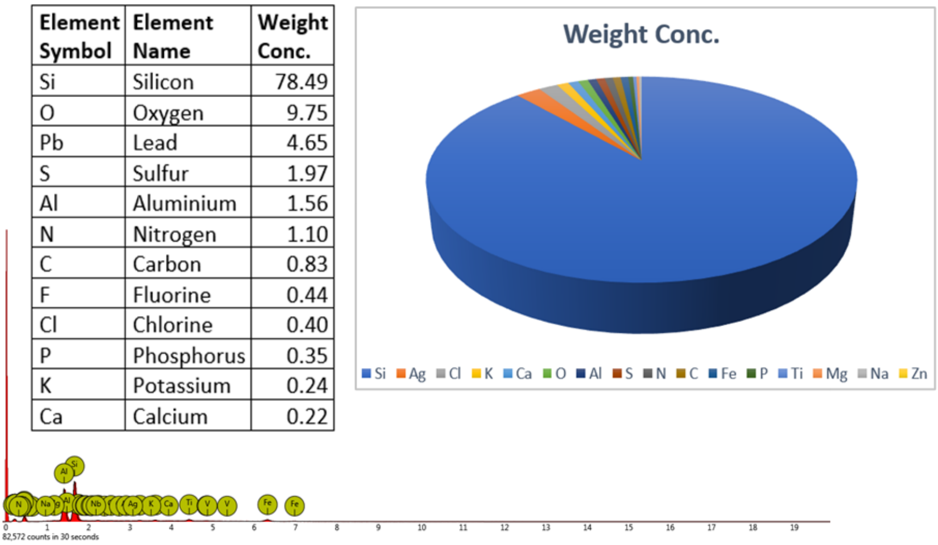
Fig. 9. SEM images of quartz brick at (a) 5% (b) 10% and (c) 15% binding proportion

The morphological analysis and other analyzed results have proved that the produced refractories are mechanically and thermally stable and suitable for applications in high-temperature industrial processes. Meanwhile, the materials utilized are relatively available and inexpensive, particularly bentonite compared to other materials used for bonding in the refractory industry [55, 56]. Additionally, bentonite has been reported to be non-toxic and biodegradable, making it an eco-friendly option for the refractory industry [56-58]. This is in tandem with the outcome of the chemical and morphological analysis of all the produced bricks as they proved to be chemically inert under natural and thermal conditions. Furthermore, the durability of the produced refractories suggests longer lifespan and reusability moreover, used refractory materials containing bentonite are often recycled [59]. Overall, in addition to the good thermal stability of the refractories, cost-effectiveness, good environmental impact and waste management are other favourable properties provided for utilization in high-temperature industrial processes.



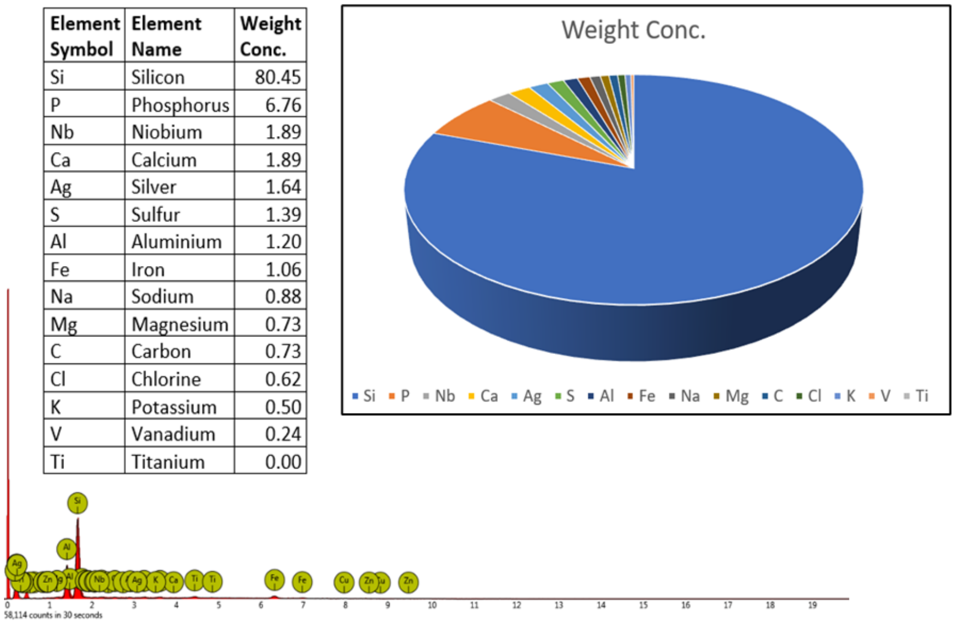
Element Symbol	Element Name	Weight Conc.
Si	Silicon	88.38
Ag	Silver	2.21
Cl	Chlorine	1.72
K	Potassium	1.04
Ca	Calcium	0.92
O	Oxygen	0.89
Al	Aluminium	0.77
S	Sulfur	0.76
N	Nitrogen	0.73
C	Carbon	0.71
Fe	Iron	0.68
P	Phosphorus	0.43
Ti	Titanium	0.30
Mg	Magnesium	0.24
Na	Sodium	0.23
Zn	Zinc	0.00

Fig. 10. EDS analysis of quartz brick at 5% binding proportion



Element Symbol	Element Name	Weight Conc.
Si	Silicon	78.49
O	Oxygen	9.75
Pb	Lead	4.65
S	Sulfur	1.97
Al	Aluminium	1.56
N	Nitrogen	1.10
C	Carbon	0.83
F	Fluorine	0.44
Cl	Chlorine	0.40
P	Phosphorus	0.35
K	Potassium	0.24
Ca	Calcium	0.22

Fig. 11. EDS evaluation of quartz brick at 10% binding proportion



Element Symbol	Element Name	Weight Conc.
Si	Silicon	80.45
P	Phosphorus	6.76
Nb	Niobium	1.89
Ca	Calcium	1.89
Ag	Silver	1.64
S	Sulfur	1.39
Al	Aluminium	1.20
Fe	Iron	1.06
Na	Sodium	0.88
Mg	Magnesium	0.73
C	Carbon	0.73
Cl	Chlorine	0.62
K	Potassium	0.50
V	Vanadium	0.24
Ti	Titanium	0.00

Fig. 12. EDS analysis of quartz brick at 15% binding proportion

4. Conclusions

The effect of developing refractory bricks using three different percentages of bentonite as binder has been examined. The study's measurements of bulk density (1644, 1516, and 1324 kg/m^3) and porosity (43, 46, and 48%) reveal crucial details regarding the sample's packing and compactness as refractory materials. The bricks produced were within the permitted range for refractory materials, according to both results. This shows that using bentonite as a binder enhances the mechanical durability of the produced bricks. The dimensional stability encompassed with the thermal expansion behaviour of quartz brick was significantly improved by the linear firing shrinkage and loss on ignition measurement. According to the findings, these refractory materials' linear firing shrinkage was within an acceptable range of the required percentage. According to the study, high cold crushing strengths are necessary to guarantee the mechanical veracity of refractory materials underneath pressure and it shows that the materials may show potential in being an elevated temperatures option for industrial refractory material furnaces. Additionally, the study's findings regarding water absorption indicated that the refractory bricks have a low water absorption rate. The brick's refractoriness supported this assertion since the uniformity of the significant silicon content and the brick structure content presented in micrographs indicate that they have a high potential to resist thermal shock. The outcome of the study showed that the material combination could be a viable choice for high-temperature industrial applications. Statistically, increasing the binding proportion of bentonite has significant effects on the refractory bricks. The mechanical strengths and thermal strength of the bricks were slightly reduced with increased concentration of bentonite some of which were proved significant by the statistical analysis even though the values are still within the acceptable ranges of good refractory materials. However, improved chemical composition was noticed with increased percentage of bentonite which indicates chemical durability and resistance to slag attack. The study affirmed that the refractory bricks produced in the range of bentonite percentages utilized are suitable where high thermal stability is required. However, while the thermal and chemical properties of the bricks improved with an increasing percentage of bentonite, some properties such as bulk density, water absorption, crushing strength, and refractoriness are unfavourable. Though their values are still within the accepted range for standard refractories, there is a need to look into optimizing the optimum percentage that will balance both the properties that are affected positively and the ones affected negatively.

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