Suitability of Nigerian Rocks as Refractory Materials for Monolithic Furnace Lining

Lawrence Opeyemi Osoba & Ayo Samuel Afolabi

A Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, University of Manitoba, Winnipeg, Manitoba, Canada
B Department of Civil and Chemical Engineering, University of South Africa, Johannesburg, South Africa

Available online: 21 Nov 2011

To cite this article: Lawrence Opeyemi Osoba & Ayo Samuel Afolabi (2012): Suitability of Nigerian Rocks as Refractory Materials for Monolithic Furnace Lining, Particulate Science and Technology: An International Journal, 30:3, 209-219

To link to this article: http://dx.doi.org/10.1080/02726351.2011.555936

Please scroll down for article

Full terms and conditions of use: http://www.tandfonline.com/page/terms-and-conditions

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae, and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand, or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.
Suitability of Nigerian Rocks as Refractory Materials for Monolithic Furnace Lining

LAWRENCE OPEYEMI OSOBA¹ AND AYO SAMUEL AFOLABI²

¹Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, University of Manitoba, Winnipeg, Manitoba, Canada
²Department of Civil and Chemical Engineering, University of South Africa, Johannesburg, South Africa

The physical, chemical composition and service properties of imported monolithic refractory and locally produced refractory lining materials were investigated and compared in this study. The samples were compacted in a standard rammer, cured in air for 24 h and oven dried for 24 h. They were then heated to temperature of 100°C and characterized to determine their refractory properties. These samples were tested for parameters, such as bulk density, porosity, thermal conductivity, electrical conductivity, refractoriness, permeability, and cold strength. The results obtained indicate that local acidic ramming mass was found to be a good substitute to imported ramming masses due to comparative properties of the former. A fusion temperature of 1620°C was obtained in the local sample which is equivalent to the value obtained for the imported ramming masses. The results of other properties show little or no variation between the locally produced ramming mass and the imported ones.

Keywords furnaces, lining, refractoriness, refractory

1. Introduction

The increase in demand for refractory materials is closely connected with metallurgical industries which consume up to 80% of all refractories produced (Hiavac 1983; Hasan 2001). The progress in metallurgical field in Nigeria has called for increase in demand for refractory materials in recent times. A large proportion of these materials are currently being imported to meet this demand (Borode et al. 2000). From estimates by the year 2015, Nigeria steel industries will be consuming about 80,000 tons of fired bricks and 50,000 tons of high alumina bricks per year (Chukwuogo 1984). The need has, therefore, arisen to develop good refractories using the locally available materials. This would result in tremendous saving in foreign exchange. Apart from metallurgical industries, refractory products are also required for various processes in chemical, ceramic, petrochemical, and oil...
industries. Unfortunately, there is no major specialized refractory industry in Nigeria despite the fact that there are abundant deposits of these rocks in the country.

In early days, furnaces were built of bricks whose properties were only sufficient for thermal insulation but technological advancement has led to replacement of connection bricks lining by monolithic lining that are either rammed or cast into positions. This has improved productivity of various furnaces and involved the use of special materials like refractory mortars, cements, castables, and ramming masses, which have demanded special methods for the production and processing of ceramics powders and their mixtures. Monolithic refractory linings used in induction furnaces are the neutral, basic, and acidic refractories. The acidic lining materials have the major constituents from the quartz, which is obtained from quartz rock, that is, igneous rocks known as ganister or quartzite which contains 93 to 98% silica (SiO$_2$).

Ramming masses as a class of refractory materials are used for obtaining monolithic working faces. Such refractory compounds have specific applications in the repair and construction of various furnace parts where the refractory lining should have high strength at the working temperature, high resistance to abrasion and slag attack, and high volume stability. The ramming masses set either chemically, by heat or by the use of ceramic materials. The setting methods used depend on the chemical composition of the ramming masses. The setting refractories are manufactured by processes in which mechanical strength is imparted by chemical bonding agents as against those by firing techniques. Air setting refractories develop a strong bond drying. Such include mortars, plastic refractories, and ramming mixes. The dry composition (ramming mixes) requires tempering with water to develop the necessary consistency. Heat setting refractories require relatively high temperatures for the development of an adequate bond, commonly called the ceramic bond. In ceramic setting refractories, the mechanical strength is developed by a heat treatment, which causes the cohesion of adjacent particles.

Therefore, the need to increase local content for industrial application has necessitated the desire to characterize some local rocks for use as monolithic furnace lining. This study will comparatively analyze locally prepared ramming mass with the imported monolithic refractory materials to assess the suitability of Nigerian rocks as a refractory material for monolithic lining furnace. This study is the first attempt to experimentally justify Nigerian rock for monolithic lining of induction and other high temperature melting furnaces.

2. Experimental

Imported monolithic lining materials were sourced from two local foundries in Lagos, Nigeria, while the locally made refractory was sourced from a local supplier. The imported ramming masses were premixed with sodium silicate binder and compacted in standard rammer of dimension 30 × 80 mm while the local sample was mixed in proportion of 20% big quartz, 50% medium quartz, 28–29% silica flour and 1–1.2% boric acid, and compacted in the same rammer. The materials were denoted thus:

A. corax neutral lining from England
B. patching-grade acidic lining from England
C. acidic lining from Indian
D. basic lining from Indian
E. local acidic lining from Nigeria.

**Permeability**

All the specimens were cured in air for 24 h before being oven dried at 100°C. The samples were completely sealed on the sides and the lower surface was exposed to an orifice. The test cylinder was filled with 2000 cm$^3$ of water, the orifice was opened and a bell jar was put in place. The orifice was opened and the time taken for the 2000 cm$^3$ of water to displace equal volume of air through the specimen was taken. The pressure difference between the surfaces was measured by manometer and the permeability was calculated from (1)

$$P_A = \frac{Vh}{Apt}$$  \hspace{1cm} (1)

where

- $P_A =$ permeability number,
- $V =$ volume of air,
- $h =$height of the specimen,
- $A =$ the cross-sectional area,
- $p =$ pressure of air, and
- $t =$ time taken for air to pass through.

**Bulk Density**

Samples A–E were cured in air for 24 h, oven dried at 100°C, and heated to a temperature of 1100°C. It was then cooled in a desiccator and weighed to the accuracy of 0.0018 after which they were transferred to a beaker and heated for 30 min to release the trapped air. They were cooled and the soaked weight (w) was measured. They were suspended in a beaker containing water placed on a balance. The suspended weight was taken and the bulk density was calculated from (2)

$$\text{Bulk density} = \frac{\rho w}{w - s}$$  \hspace{1cm} (2)

where

- $w =$ soaked weight,
- $s =$ suspended weight, and
- $\rho =$ density of water.

**Apparent Porosity**

Standard test samples A–E were prepared, cured in air 24 h and oven dried at 110°C for 24 h. They were fired to a temperature of 1100°C, cooled, and then transferred into a desiccator and weighed to the accuracy of 0.01 g. The samples were later transferred into a 250 ml beaker in an empty vacuum desiccators and water was poured into the heater until the test pieces were completely immersed. The samples were allowed to soak in the boiled water for 30 min and were being agitated from time to time to release trapped air bubbles. They were cooled in vacuum desiccators, the soaked weight (w) recorded and they were then weighed after being suspended
in water using a beaker placed on balance. The apparent porosity was calculated using (3):

\[
\text{Apparent porosity} = \frac{W - D}{W - S} \times 100\%
\]  

where

\(W\) = soaked weight,
\(D\) = dried weight, and
\(S\) = suspended weight.

**Refractoriness**

The test samples A–E were loaded in a furnace, heated, and had their temperatures monitored using calibrated digital optical pyrometer attached to the furnace. The heating continued until a glass form was obtained and the temperatures were recorded. The theoretical refractoriness values of the samples were calculated using (4):

\[
\text{Refractoriness} = \frac{(360 + \%Al_2O_3)}{0.228} - R_0,
\]  

where \(R_0\) is the sum of all other elements apart from alumina and silica in the composition.

**Chemical Analysis**

The chemical analyses of the samples were carried out using atomic absorption spectrophotometer (AAS).

**Grain Size Distribution**

An American Tyler Screen was used, 250 g of the samples were poured into screen of mesh 2.8, 1.0, and 0.6 mm of vibrating sieve and made the grains to pass through the mesh and the weights of the samples on the individual mesh were recorded.

**Electrical Conductivity**

The electrical resistance of the samples was conducted using a micro ohmmeter by passing a voltage of 220 V through the samples. The resistance was measured using attached measuring device and the current passing through was calculated from Ohm’s law (5)

\[
V = IR
\]  

and

\[
I = \frac{V}{R}.
\]  

Electrical resistance is the ratio of the degree to which an object opposes an electric current through it. The micro-ohmmeter was adjusted to zero resistance during
the measurement, so the resistivity of the material was calculated from (7)

\[ R = \frac{L \times \rho}{A}. \]  (7)

Therefore,

\[ \rho = \frac{RA}{L}, \]  (8)

where \( L \) is the length, that is, 90 mm, \( A \) is the cross sectional area, that is, 19.7 mm\(^2\), and \( \rho \) is the resistivity.

The electrical conductivity is an inverse of electrical resistivity which is given by the formula (9),

\[ K = \frac{1}{\rho}, \]  (9)

where \( K \) is the electrical conductivity in \( \Omega m^{-1} \)

**Thermal Conductivity**

Test sample bricks of dimension 200 \( \times \) 100 \( \times \) 50 mm were prepared, cured in air for 24h, and placed on an electric heater for 15 min. The other parts of the bricks were insulated with fiber glass to prevent heat loss to the atmosphere. The temperature between the fiber glass and the brick (\( T_1 \)) was measured using a thermocouple and the temperature at the surface on the hot plate and bricks (\( T_2 \)) was measured while the resistance of the heating element was also measured using the micro-ohmmeter.

From Fourier’s law;

\[ Q = -KA \frac{(T_1 - T_2)}{\Delta x} \]  (10)

where

\( Q \) is the quantity of heat flow,
\( K \) = the thermal conductivity (Wm\(^{-1}\)k\(^{-1}\)),
\( A \) = the Area (m\(^2\)),
\( T \) = the temperature (in Kelvin), and
\( x \) = the thickness (m);

\[ Q = I^2R \]  (11)

where

\( I \) = the current (A) and
\( R \) = the resistance of heating element.

From Ohm’s law,

\[ I = \frac{V}{R} \]

where \( V \) is voltage (220 V).
Combining Equations (10) and (11), the expression for thermal conductivity can be obtained, thus;

\[ K = (1^2 R) \frac{\Delta x}{A \Delta T}. \]  

(12)

**Cold Strength**

Test samples of standard dimension (200 × 100 × 50 mm) were prepared, cured in air for 24 h, and oven dried at 110°C for 24 h, before they were fired in to a temperature of 1100°C. The test samples were placed on a compressive tester and load was applied axially by turning the wheel at a uniform rate till failure occurred. The manometer readings were recorded and cold crushing strength (CCS) values were calculated from (13).

\[ CCS = \frac{\text{Maximum Load (KN)}}{\text{Cross sectional area (m}^2\text{)}}. \]

(13)

**Linear Shrinkage and Thermal Expansion**

Slabs of 100 × 200 × 50 mm were made from the samples and a line of 30 mm was drawn on them and were cured in air for 24 h before being oven dried at 100°C and the length \( L_1 \) was recorded. They were fired in furnace to temperature of 1100°C for 6 h and length \( L_2 \) was also measured.

\[ \text{Fire shrinkage} = \frac{(L_1 - L_2)}{L_1} \times 100\% \]

(14)

where \( L_1 \) is the dried length and \( L_2 \) is the fired length. Hence, the thermal expansion is

\[ \frac{(L_1 - L_2)}{L_1} \times \Delta T, \]

(15)

where \( \Delta T \) is the temperature difference.

**3. Results and Discussion**

The test samples used to carry out all the experimentation are:

A. corax neutral lining from England,
B. patching-grade acidic lining from England,
C. acidic lining from Indian,
D. basic lining from Indian, and
E. local acidic lining from Nigeria.

Table 1 shows the percentage composition of major constituents of the test samples as determined by AAS. The analysis shows that the principal oxides in these materials are \( \text{SiO}_2 \) and \( \text{Al}_2\text{O}_3 \), except sample D which has no silica. The percentage
compositions of these oxides place the samples in the refractory products range (8–20% $\text{Al}_2\text{O}_3$) with the exception of sample B, which has 2.12% $\text{Al}_2\text{O}_3$. Oxides such as CaO and $\text{Fe}_2\text{O}_3$ act as impurities which both lower and widen the fusion range but they also increase the plasticity of the refractory material which is a desirable ramming property while the chemical stability of these materials is enhanced as the CaO, MgO, and $\text{Al}_2\text{O}_3$ increase (Ohring 1995). It is observed that the local sample has a similar chemical composition as the patching-grade acidic lining from England (sample B). Both samples have the highest content of $\text{SiO}_2$ and lowest content of $\text{Fe}_2\text{O}_3$ impurities. It is, therefore, expected that the other properties of these samples should be very similar.

Table 2 shows the comparison of the grain size distribution of the five specimens of the refractory materials. It can be observed that the local refractory material has a similar grain size distribution as the corax neutral lining from England (sample A). The sizes of all the samples were highest at mesh size 1.00 mm and reduce from that point as the mesh sizes reduce in all the samples except in acidic lining from Indian (sample C).

Table 3 shows the comparison of the physical properties of the samples in terms of apparent porosity, permeability, electrical, and thermal conductivities. In selecting refractory lining materials, porosity is very important as it affects the permeability, heat conductivity, strength, and temperature fluctuations. The porosity depends on grain fineness and firing temperature (Alexander et al. 2002; Nah et al. 2002; Gao et al. 2008; Gu et al. 2009). The values of the local refractory fall within the range of 10 to 25% as compared to imported refractory lining which is good for induction furnace. The value may be increased by the addition of fine-grade silica.

The permeability of the local refractory falls within the range of imported acidic lining but lesser than other basic and neutral lining (Table 3). Permeability is a function of numbers of pores of gasses or liquid passing through the ramming mass.

### Table 1. Percentage chemical composition of the samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\text{SiO}_2$</th>
<th>$\text{Al}_2\text{O}_3$</th>
<th>MgO</th>
<th>CaO</th>
<th>$\text{Fe}_2\text{O}_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>54.05</td>
<td>9.08</td>
<td>23.23</td>
<td>0.35</td>
<td>13.17</td>
</tr>
<tr>
<td>B</td>
<td>97.05</td>
<td>2.12</td>
<td>—</td>
<td>0.48</td>
<td>0.13</td>
</tr>
<tr>
<td>C</td>
<td>61.13</td>
<td>36.27</td>
<td>—</td>
<td>0.11</td>
<td>1.08</td>
</tr>
<tr>
<td>D</td>
<td>—</td>
<td>10.18</td>
<td>87.19</td>
<td>2.15</td>
<td>0.45</td>
</tr>
<tr>
<td>E</td>
<td>91.32</td>
<td>8.19</td>
<td>—</td>
<td>0.24</td>
<td>0.35</td>
</tr>
</tbody>
</table>

### Table 2. Grain size distribution of the samples

<table>
<thead>
<tr>
<th>Samples</th>
<th>Mesh size</th>
<th>A (g)</th>
<th>B (g)</th>
<th>C (g)</th>
<th>D (g)</th>
<th>E (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.8 mm</td>
<td>54.24</td>
<td>—</td>
<td>49.5</td>
<td>51.20</td>
<td>42.54</td>
</tr>
<tr>
<td></td>
<td>1.0 mm</td>
<td>93.65</td>
<td>114.67</td>
<td>74.52</td>
<td>75.75</td>
<td>117.55</td>
</tr>
<tr>
<td></td>
<td>0.64 mm</td>
<td>60.74</td>
<td>80.53</td>
<td>75.24</td>
<td>73.15</td>
<td>62.87</td>
</tr>
<tr>
<td></td>
<td>&lt;0.6 mm</td>
<td>41.37</td>
<td>54.72</td>
<td>50.98</td>
<td>49.75</td>
<td>26.63</td>
</tr>
</tbody>
</table>
lining. The refractoriness under the influence of gasses and liquid should be imper-
brious to eliminate the leakages of gasses and penetration of liquid but through the
wall of the furnace while samples A and D have high permeability which can aid
the penetration of gasses.

The results shown in Table 3 also show that the electrical conductivities of the
local refractory conform to the imported ones and with the resistance adjusted to
zero (0 Ωm⁻¹), no current would be allowed to pass through refractory materials.
The thermal shock property helps in predicting the possible number of heat that
the materials can withstand when in use. The controlling factors of this property
include the coefficient of linear expansion, thermal conductivity and the chemical
composition of the material. Alumina is known to improve the devitrification of
the refractory material on cooling.

It can also be seen from Table 3 that the thermal conductivity of the local
material is within the range of the imported ones particularly the patching-grade
acidic lining from England and the acidic lining from Indian (samples B and C)
and is as low as possible, which means that the rate at which heat passes through
it is very low compared to others. This property makes this sample to be desirable
for use as external lining of furnace while the sample D, which has the highest ther-
mal conductivity is not recommended for external lining. Good refractory materials
should have low thermal and electrical conductivities to prevent them from reacting
with reactive elements in induction furnace.

Table 4 shows the service properties of the samples in terms of bulk density, cold
strength, refractoriness, fired shrinkage and thermal expansion. The bulk density is a
useful property of refractory material and the factors affecting this property include
particle size, nature of the materials in the refractory material and treatment during
manufacturing.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Apparent porosity (%)</th>
<th>Permeability</th>
<th>Electrical conductivity (Ωm⁻¹)</th>
<th>Thermal conductivity (Wm⁻¹k⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12.80</td>
<td>95</td>
<td>0</td>
<td>32</td>
</tr>
<tr>
<td>B</td>
<td>13.80</td>
<td>15</td>
<td>0</td>
<td>1.25</td>
</tr>
<tr>
<td>C</td>
<td>12.17</td>
<td>35</td>
<td>0</td>
<td>1.35</td>
</tr>
<tr>
<td>D</td>
<td>12.12</td>
<td>75</td>
<td>0</td>
<td>40.7</td>
</tr>
<tr>
<td>E</td>
<td>19.06</td>
<td>10</td>
<td>0</td>
<td>1.28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>Bulk density (kN/m²)</th>
<th>Cold strength (kN/m²)</th>
<th>Refractoriness (°C)</th>
<th>Fired shrinkage (%)</th>
<th>Thermal expansion (K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.27</td>
<td>0.53</td>
<td>1620</td>
<td>3</td>
<td>2.5 × 10⁻⁵</td>
</tr>
<tr>
<td>B</td>
<td>1.94</td>
<td>0.41</td>
<td>1650</td>
<td>1.6</td>
<td>1.45 × 10⁻⁵</td>
</tr>
<tr>
<td>C</td>
<td>3.40</td>
<td>0.43</td>
<td>1750</td>
<td>3</td>
<td>2.5 × 10⁻⁵</td>
</tr>
<tr>
<td>D</td>
<td>2.90</td>
<td>0.54</td>
<td>1600</td>
<td>3</td>
<td>1.45 × 10⁻⁵</td>
</tr>
<tr>
<td>E</td>
<td>2.02</td>
<td>0.422</td>
<td>1650</td>
<td>0.8</td>
<td>7.57 × 10⁻⁶</td>
</tr>
</tbody>
</table>
The result of the bulk density were found to be very close to that of fire clay between 1.9 and 2.05 (Chester 1973) and to those reported for local refractory in Nigeria (Borode et al. 2000; Hassan 2001). But these values are less in samples A and C (i.e., coral neutral lining from England and acidic lining from Indian) which are slightly higher than this value range. The bulk density of the local monolithic lining falls within the range of expected values to be used as a furnace lining refractory material and is comparable to the values obtained by Chester (1973), that is, 1.7–2.4 g/cm\(^3\) for fire bricks lining and 2.5–3.5 g/cm\(^3\) for high alumina lining. The refactoriness of refractory materials is affected mainly by their chemical composition, hence, increase in alumina and silica contents is known to increase refactoriness while increase in the fluxing agents such as iron oxide (Fe\(_2\)O\(_3\) and alkalis, Na\(_2\)O, and K\(_2\)O) reduces this property (Chester 1973).

From Table 4, the highest fusion temperature obtained in all the samples is 1750°C which is sample C (i.e., acidic lining from Indian) and next to this value is 1650°C, which corresponds to samples B (i.e., patching-grade acidic lining from England) and E (local acidic refractory) while the lowest temperature values obtained is 1600°C for sample D. It will be observed that sample C having the highest temperature also has an almost balanced combination of both silica and alumina content as shown in Table 1. The value of the refactoriness of the local ramming mass also falls within this range and confirms it as a good refractory material for furnace lining. A composition such as in sample A having 9.09% Al\(_2\)O\(_3\) and 54.04% SiO\(_2\) could have its melting point as high as 1700°C but for the high presence of alkali impurities (Fe\(_2\)O\(_3\) = 13.17%), the melting temperature of the sample is, therefore, 1620°C. Sample B has the lowest Al\(_2\)O\(_3\) content but this value is complimented by high silica content (97.05%) to make the refactoriness as high as 1650°C. This is contrary to sample D which has no silica with low alumina content (10.18%), hence has the lowest refactoriness of all the samples. The theoretical refactoriness values were compared with the experimental values and it was observed that the theoretical refactoriness values are slightly lesser than the experimental values for different samples but fall within 0 and 70°C. The theoretical method of calculating refactoriness can be used to determine the maximum operating temperature of the refractory materials without using experimental method.

The cold strength of refractory materials incorporates lots of factors such as chemical composition, firing temperature, amount of water, the manufacturing processes, the particle size, and the extent to which the particles are bonded together. The strength increases with the amount of moisture content in the material up to an optimum value of 13% of water and then decrease with further increase in the moisture content. This is as a result of the plastic nature of the material; the plasticity is lost when too much water is added (Gatos et al. 2005). The degree of vitrification depends on the composition of the refractory material which also affects the compressive strength of the sample. From the Table 4, we see that the strength of individual samples show the effect of firing on ceramic bond, and this may be achieved by firing, sintering characteristics, and pressing method with sample B from England having the lowest cold strength and local sample having the cold strength within the range. As the temperature increases, the rate at which the water is being removed from the sample increases. It can also be observed that the thermal expansion of all the samples is less than one.

The plot of volumetric contraction versus refactoriness of the samples (Figure 1) shows that samples A and C have equal response to contraction at various fusion
temperatures. A similar phenomenon is noticeable in samples B and D while sample E (i.e., local refractory) shows a slight difference from the imported samples. The volumetric contraction of all the samples increases with increase in fusion temperature, which is the characteristics of the refractory materials. Samples from England have the highest volume contraction, this is closely followed by the samples from Indian, and the local sample has the least volume contraction with increase in fusion temperature.

4. Conclusion

The studies conducted on the comparison between the local and imported refractories reveal that both the physical and service properties of the local materials are favorably comparable to the imported refractories. The acidic local refractory have silica content greater than 66% in its composition and refractoriness of up to 1650°C and can therefore be used as a monolithic acidic furnace lining. Other service properties such as bulk density, porosity, permeability are in the same range with the imported refractories.

References


