Property Optimization of Kaolin - Rice Husk Insulating Fire - Bricks

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Abstract

In this work, the suitability of using Kaolin - Rice husk - plastic clay to produce insulating firebrick was experimentally investigated and the optimal ratio of these constituents determined. Ten brick samples of different compositions were fired at a temperature of 1200ºC. Three of the samples (samples 6, 7, and 8) crumbled during firing. The surviving samples gave the following limits of results: - shrinkage: 9.7% - 13.6%; effective moisture content: 28.34% - 32.52%; modulus of rupture: 4.26kgf/cm^2 - 19.10kgf/cm^2; apparent porosity: 56% - 95.93%; water absorption: 42.27% - 92.12%; bulk density: 1.04g/cm^3 - 1.41g/cm^3; apparent density: 2.56g/cm^3 - 5.77g/cm^3; and thermal conductivity: 0.005W/mK - 0.134W/mK. The results showed that they all had good insulating characteristics. Samples 1 - 5 and 10 showed good level of refractoriness, while mixing ratio of 4:1:2 (representing weight in grams of Kaolin, plastic clay and rice husk respectively) for sample 4 gave the optimum performance values in terms of refractoriness, thermal conductivity, modulus of rupture, shrinkage and bulk density and the effective moisture content.

Keywords

Refractories, Firing, Shrinkage, Modulus of rupture

Introduction

The insulating firebrick is a class of brick, which consists of highly porous fireclay or kaolin. They are lightweight, low in thermal conductivity, and yet sufficiently resistant to temperature to be used successfully on the hot side of the furnace wall, thus permitting thin walls of low thermal conductivity and low heat content. The low heat content is particularly valuable in saving fuel and time on heating up, allows rapid changes in temperature to be made, and permits rapid cooling [1]. Over the years, insulating firebricks have been made in a variety of ways, such as mixing organic matter with clay and later burning it out to form pores; or a bubble structure incorporated in the clay-water mixture which is later preserved in the fired brick.

The term “Refractory” means “Hard to Fuse”. High temperature operations are involved in almost all the industries dealing with the treatment of ores and other materials for the manufacture of metallurgical, chemical, and ceramic products. Refractories are, therefore the class of materials, which withstand high temperatures, resist the action of corrosive liquids and dust-laden currents of hot gases, etc [2].

In technology, refractories are generally referred to as the materials employed for the construction of furnaces, flues, crucibles, etc, used in high temperature operations to ensure equipment resistant to the corrosive action of gases and slag present therein [2].

Thermal conductivity increases with the decrease of porosity. Porous refractories have air entrapped in their pores and this acts as a non-heat conducting material. The amount of the entrapped air increases with porosity of the refractory and hence its thermal conductivity decreases. Refractories used in melting furnaces, etc, should have low thermal conductivity to ensure least heat losses and maximum heat efficiencies, whereas in recuperators where maximum heat transfer is desired to take place, refractories with high thermal conductivities are used. Insulating refractories have low thermal conductivities.

It is stated [3] that heat insulating and building materials have thermal conductivity range of 0.023 to 2.9W/mºC. Kaolin has numerous industrial applications and new uses continue to be discovered. It is a unique industrial mineral due to its several properties, including chemical inertness over a wide range of acid/ alkaline conditions. Some uses of kaolin require very rigid specification including particle size distribution, color and brightness, and viscosity. Fireclays (or plastic clay) are also refractory in nature, but often more plastic than kaolin. The color of raw fireclays varies from white to yellow; brown or gray, and the sand content can be more than 50% [4]. An author [5] has reported that fireclay is located in commercial quantity at Ukpor, Ozubulu, Enugu, Kwi, and Otukpo (all in Nigeria), to mention but a few.

It has been hypothesised elsewhere [2] that rice husk being a good combustible material can be used to produce insulating firebrick since their complete combustion could create pores within the bulk of a clay composite material. Literature [2] shows that high alumina wool, which is used as insulating material, has a thermal conductivity of not more than 0.29 W/mk. What is not available in literature (to the authors' knowledge) is: what mixing ratio of rice husk to other constituents is required to produce insulating firebricks? This work therefore, had as its objective the evaluation of the refractory properties of insulating fire bricks produced from a fired mixture of kaolin-rice husk-plastic clay, and to determine the mixing ratio that gives the optimum refractory characteristics.

Materials and Methods

The materials used in this work are kaolin, rice husk, and plastic clay.

The equipment and tools include sieve, basin, containers, wooden moulds, mechanical dryer, electric furnace, measuring tape, Vernier calliper, measuring cylinder, weight balance, electric oven, pyrometric cone, and thermal conductivity apparatus.

The production of insulating firebrick

The production of insulating firebrick using local raw materials - kaolin, plastic clay and rice husk was carried out as discussed below.

Rice husk was screened/examined to be sure that there existed no rice grain. It was then ground and sieved through a mesh of size 30 to get a desired particle size, which was stored in a labeled dry container.

Refined kaolin and plastic clay were crushed and ground differently to desired particle size of 30 mesh, which were then stored in their respective labelled dry containers.

These materials were measured and wet-mixed (until a satisfactory even distribution of aggregates was achieved) in a basin/container (see tables 1 for detailed compositions of samples).

Wooden-brick moulds of internal dimensions (18.3·8.2·8.0) cm and (8.2·8.2·8.0) cm were made. A test specimen mould of internal dimensions (10.0·1.6·1.3) cm was also made. Moulding was carried out by hand (that is, hand moulding). A test specimen of the same composition accompanied each brick sample. The moulded bricks together with their test are specimens were left to dry atmospherically and then dried in a mechanical (controlled humidity) dryer at 110ºC.

Table 1. Composition of Brick Samples by weight (Total weight = 1500g)

Sample	Kaolin (g)	Plastic clay (g)	Rice husk (g)
1	600	375	525
2	675	300	525
3	750	225	525
4	825	225	450
5	900	150	450
6	500	250	750
7	300	300	900
8	480	120	900
9	600	150	750
10	720	180	600

This increased their green strength and made them safe for subsequent handling.

The dried bricks and test specimens were finally fired to a temperature of 1200ºC in a muffle furnace. This resulted in the burning out of the rice husk and leaving plenty of pores in the finished bricks. The initial/original length, dried length, fired length, wet weight, and dry weights were noted.

Shrinkage test

Test specimens from each composition were dried at 110ºC for 24 hours to ensure total water loss. The test specimens were then measured (in terms of dimension) and their values were noted as dry lengths.

The test specimens were also fired in an electric furnace to temperature of 1200ºC. They were allowed to cool. The specimens were weighed and measured. And the fired weight and fired length were recorded. For each sample, 10 different specimens were tested and the averages of the above parameters were calculated and recorded.

The drying shrinkage, firing shrinkage and the total shrinkage were calculated for each test specimen using the following formula [4]:

$$\% \text{ Avg Drying Shrinkage} = (OL-DL)/OL*100 \quad (1)$$

$$\% \text{ Avg Firing Shrinkage} = (DL-FL)/FL*100 \quad (2)$$

$$\% \text{ Total Shrinkage} = (OL-FL)/OL*100 \quad (3)$$

where: OL means original length; DL stands for dry length and FL is fired length.

The drying shrinkage indicates to some degree the plasticity of the mixture. A large drying shrinkage means that mixture could absorb much water, which in turn indicates fine mixture particles. The firing shrinkage indicates how fusible the mixture is. A high shrinkage normally means a lower melting point. The total shrinkage of refractory bodies tells how much bigger we should make our moulds [4].

Bulk density, apparent density, apparent porosity, and percentage water absorption tests

The test specimens were dried at 110ºC for 24 hours to ensure total water loss, and later fired up to 1200ºC in an electric furnace. Their fired weights were measured and recorded. They were allowed to cool and then immersed in a beaker of water. Bubbles were observed as the pores in the specimens were filled with water. Their soaked weights were measured and recorded. They were then suspended in a beaker one after the other using a sling and their respective suspended weights were measured and recorded.

Their respective bulk density, apparent density, apparent porosity, and percentage water absorption were calculated using the formulae [2]:

$$\text{Bulk Density} = D/(W-S) \ (g/cm^3) \quad (4)$$

$$\text{Apparent Density} = D/(D-S) \ (g/cm^3) \quad (5)$$

$$\text{Apparent Porosity} = (W-D)/(W-S)*100 \quad (6)$$

% Water Absorption

where: D = Weight of fired specimen, S =Weight of fired specimen suspended in water, and W = Weight of soaked specimen suspended in air

Effective moisture content test

The wet brick samples were weighed one after the other, and their weights were recorded. They were later dried at 110ºC for 24 hours so that all water evaporates. They were then weighed immediately one after the other and their dry weights were recorded.

Effective moisture content for the brick samples were calculated using the formula [4]:

$$\% \text{ Moisture content} = (A-B)/A*100 \quad (7)$$

where A =Wet weight of brick, and B = Dry weight of brick

Modulus of rupture test (M.O.R)

Moduli of rupture tests were performed on a standard mechanical machine. Test specimens, measuring (10.0·1.6·1.3) cm for each brick composition were dried and fired at 1200ºC along side with the bricks. Each of them was placed one after the other on the bearing edges of the compression machine positioned 7.0 cm apart. Loads were then applied at the middle of the specimens, uniformly at 1.25 kgf per minute. The loads at which the specimens failed were calculated from the relation given in [2]:

$$M.O.R. = 3WL/2bt^2 \ (kgf/cm^2) \quad (8)$$

where L = the distance between bearing edges (cm), b = width of the specimen (cm), t = thickness of the specimen, and W = load at which the specimen failed

Thermal Conductivity Test (using Ibrahim's [6] thermal conductivity apparatus; the steam method)

Test specimens of area $0.002m^2$ and thickness of 0.01m were cut from their respective mother bricks. The test specimens were tested one after the other. Each specimen was fixed in the provided space within the equipment. A conical flask containing 50ml of water was placed directly above and in contact with the specimen. A cork having a thermometer passing through it was used to cork the mouth of the conical flask. The thermometer reads the temperature changes of the water in the flask. The test section was then closed and the initial water temperature was noted. A second thermometer with the aid of a cork was inserted into the steam outlet pipe offset to monitor the steam temperature so as to ensure a constant base temperature of 100ºC.

The boiler water outlet valve was closed while 5 litres of water was measured and poured into the boiler. The steam inlet valve, outlet valve, and condensate outlet valve were all closed. With the boiler cover remaining opened, the boiler was switched on. Immediately the water started boiling, the boiler cover was closed, while the steam inlet valve was fully opened with all the remaining valves closed. Timing commenced with the aid of a stopwatch immediately the steam inlet valve was opened.

The testing was timed in each case for 10 minutes and final temperature of the water in the beaker was noted at the end of time. Each specimen was tested (experimented) twice and a mean temperature value was obtained. At the end of each experiment, the steam outlet

Issue 9, July-December 2006
p. 167-178

valve was opened to release steam. The water in the boiler was refilled to maintain 5 litres and the experiment was repeated as stated above for other specimens.

The value of the thermal conductivity, K for each of the specimen was determined using the formula [6]:

$$K = 2.303MCL/A\,[\log(\theta_1/\theta_2)]/\tau \quad (9)$$

where

- K = thermal conductivity of the specimen,
- T_1 = temperature of steam k,
- T_i = Initial temperature of water in conical flask,
- T_4 = Final temperature of water in conical flask,
- τ = Time (s), A = Specimen area, (m^2),
- M = mass of water in conical flask k (kg),
- C = specific heat capacity of water in conical flask (J/kgk),
- L = thickness of specimen (m),
- $\theta_1 = T_1 - T_i$,
- $\theta_2 = T_1 - T_4$.

Results

The results obtained for the different experiments carried out in this investigation are presented in tables 2-7 and the property trends are discussed below.

Table 2. Shrinkage Values

Sample code ifb	Original length (cm)	Dry length (cm)	Fired length (cm)	Dry shrinkage %	Fired shrinkage %	Total shrinkage %	Temperature (ºC)
1	5	4.775	4.32	4.5	9.52	13.6	1200
2	5	4.8	4.5	4.0	6.23	10.0	1200
3	5	4.8	4.5	4.5	6.00	10.2	1200
4	5	4.3	4.5	3.4	6.52	9.7	1200
5	5	4.8	4.5	3.2	6.80	9.8	1200
6	5	4.8	4.5	2.3	6.20	8.4	1200
7	5	4.9	4.5	1.6	7.52	9.0	1200
8	5	4.9	4.5	2.0	8.89	10.0	1200
9	5	4.8	4.5	4.0	6.25	10.0	1200
10	5	4.79	4.4	4.2	8.14	12.0	1200

Table 3. Percentage of Apparent Porosity, Water Absorption, Apparent Density and Bulk Density

Test specimen code	Fired weight (g)	Suspended weight (g)	Soaked weight (g)	% Apparent porosity	% Water absorption	Apparent density (g/cm^3)	Bulk density (g/cm^3)	Tempt. ºC
1	363	280	560	61.83	54.49	4.40	1.30	1200
2	385	305	610	73.75	58.43	4.82	1.27	1200
3	380	302.5	605	73.96	59.21	5.17	1.26	1200
4	405	310	620	69.35	53.08	4.27	1.31	1200
5	455	323.75	647.5	56.40	42.27	3.48	1.41	1200
6	-	-	-	-	-	-	-	1200
7	-	-	-	-	-	-	-	1200
8	-	-	-	-	-	-	-	1200
9	240	230.63	461.26	95.93	92.19	2.56	1.04	1200
10	265	219	438	79.03	65.33	5.77	1.21	1200

Table 4. Percentage Moisture content of Samples

Sample code ifb	Wet weight (g)	Dry weight (g)	% moisture content
1	830	560	32.52
2	847.5	590	30.39
3	870	595	31.61
4	855	600	29.82
5	900	645	28.34
6	750	530	29.33
7	665	445	33.09
8	1530	1030	32.68
9	1700	1180	30.59
10	1760	1200	31.82

Table 5. Values of Modulus of Rupture

Test specimen code	Breaking load (kg)	Distance between support (cm)	Width (cm)	Thickness (cm)	Modulus of rupture kgf//cm^2	Temperature ºC
1	2.46	7	1.13	1.36	12.39	1200
2	2.55	7	1.16	1.66	8.66	1200
3	3.19	7	1.22	1.65	10.04	1200
4	4.71	7	1.12	1.52	19.10	1200
5	4.76	7	1.23	1.67	15.46	1200
6	-	CRUMBLED			-	1200
7	-	CRUMBLED			-	1200
8	-	CRUMBLED			-	1200
9	0.88	7	1.24	1.32	4.26	1200
10	1.20	7	1.29	1.39	5.04	1200

Issue 9, July-December 2006
p. 167-178

Table 6. Thermal Conductivity (K) Values

Sample code ifb	Initial tempt. T_i(ºC)	Final tempt t_4(ºC)	Steam tempt t_1 (ºC)	$\theta_1 = t_1-t_i$ ºC	$\theta_2 = t_1-t_4$ ºC	Thickness l(m)	Thermal cond. K (w/mk)
1	34.5	38.75	100	65.5	61.25	0.10	0.117
2	36.0	38.0	100	64.0	62.0	0.10	0.055
3	37.0	38.8	100	63.0	61.2	0.10	0.050
4	31.0	34.8	100	69.0	65.2	0.10	0.099
5	32.5	37.5	100	67.5	62.5	0.10	0.134
9	31.2	31.4	100	68.8	68.6	0.10	0.005
10	31.0	31.6	100	69.0	68.4	0.10	0.015

Table 7.Summary of Results

	Shrinkage (%)	Effective moisture content (%)	Modulus of rupture (kgf/cm^2)	Apparent porosity (%)	Water absorption (%)	Bulk density (g/cm^3)	Apparent density (g/cm^3)	Thermal cond. K (w/mk)
1	13.6	32.52	12.39	61.83	54.49	1.30	4.40	0.117
2	10.0	30.39	8.66	73.75	58.43	1.27	4.82	0.055
3	10.2	31.61	10.04	73.96	56.21	1.26	5.17	0.050
4	9.7	29.82	19.10	69.35	53.08	1.31	4.27	0.099
5	9.8	28.34	15.46	56.40	42.27	1.41	3.48	0.134
9	16.51	30.59	4.26	95.93	92.19	1.04	2.56	0.005
10	20.69	31.82	5.04	79.03	65.33	1.21	5.77	0.015

Note: Firing Temperature for all samples is 1200ºC

Discussions

Compositions 6 - 8 crumbled during firing. This suggests poor plastic mixture, that is, rice husk content was too high for clay to bind. Compositions 1 - 5 and 10 showed a good level of refractoriness. Composition 9 showed a high level of rice husk and a very high degree of porosity, but with a low value of modulus of rupture.

Shrinkage

From the summary of results (Table 7) the percentage shrinkage values of the samples obtained at 1200ºC varied from 9.7% for sample 4 to 13.6% for sample 1. It does appear that kaolin inhibits shrinkage. This inference is clear from the values of samples 1-3, which have same weight percents of rice husk, but different kaolin content. The higher the kaolin content, the lower the shrinkage.

Effective Moisture Content

From Table 7, sample 1 showed the highest percentage moisture content, 32.52% while sample 5 showed the lowest, 28.34%. This is dependent on the cumulative weight percent of kaolin and clay treated as a whole within the firebrick structure. When this combined weight percent is about $^2/_3$ of the total weight of the firebrick, the effective moisture content is least. This is an indication of the optimal combination ratio.

Modulus of Rupture

From Table 7, sample 9 showed the lowest strength, 4.26 kgf/cm^3 while sample 4 showed the highest, 19.10 kgf/cm^3. It may be said that the higher the percentage of rice husks in a sample, the lower its strength, and vice versa. This is because, during firing in a furnace, the rice husk burns out leaving plenty of pores in the bricks. The presence of these pores in a brick induces poor transfer of load in the brick, and thus, lowers the modulus of rupture (strength) of the brick.

Apparent Porosity

From Table 7, sample 9 showed the highest porosity, 95.93% while sample 5 showed the lowest, 56.40%. This indicates that high percentage of rice husk in a sample leads to high porosity of that sample. This is as a result of the rice husk burning out during firing and leaving plenty of pores in a brick. These pores make a brick porous. The more the percentage of rice husks in a brick, the more porous would be the brick. Thus, the better heat insulator the brick would be because heat cannot pass through motionless air, which is trapped in the pores, [4]. This trapped air is what acts as insulator [3].

Porous refractories have poor heat conductivity and therefore, act as good insulators [2].

Water Absorption

From Table 7, sample 5 showed the lowest water absorption, 42.27% while sample 9 showed the highest, 92.19%. This indicates that high percentage of rice husk in a sample leads to high water absorption by that sample. This is possible because rice husk burns out and leaves plenty of pores, which leads to high absorption of water by that sample.

Bulk Density

From Table 7, sample 9 showed the lowest bulk density, 1.04g/cm^3 while sample 5 showed the highest, 1.41g/cm^3. The higher the percentage of rice husks in a sample, the lower the bulk density of that sample. Rice husk burns and leaves pores in a sample, which reduces its density. The lower the density of a sample, the lower its thermal conductivity.

Apparent Density

From Table 7; sample 9 showed the lowest apparent density, 2.56g/cm^3 while sample 10 had the highest, 5.77g/cm^3**.** For this trend, the explanation given above for bulk density holds good.

Thermal Conductivity

From Table 7; sample 9 showed the lowest thermal conductivity 0.005W/mk while sample 5 had the highest, 0.134W/mk. This shows that high percentage of rice husk, which burns out during firing and leaves plenty of pores in a brick induces low thermal conductivity of that brick. Thermal conductivity has a relation with density and porosity of a brick. It decreases with decrease in density and increase in porosity of a brick.

Conclusions

Based on the properties of the brick samples tested and analysed in this study, it can be concluded that:

1. The local raw materials - kaolin, rice husk, and plastic clay are suitable for the production of insulating firebricks.
2. Samples 1 - 5, 9, and 10 are all insulating firebricks that can withstand temperature up to 1200°C. Samples 1 - 5 and 10 are of acceptable standard for hot-face insulating firebricks

production. And sample 9, whose structure is very porous, is suitable for back up insulation. However, its composition can be varied to improve on its refractoriness.

3. The mixing ratio used for sample 4 gave the best combination of strength and thermal conductivity and would perform best when used for hot-face insulating firebricks. In fact, sample 4 can serve well as firebrick both for backup and hot-face insulation.
4. For minimal effective moisture content, the cumulative weight percent of kaolin and clay (treated as a whole) in the firebrick must be about $^2/_3$ of the total weight of the firebrick.

If the production of insulating firebricks is commercialized, it will not only create job opportunities for Nigerians, but will save Nigeria some foreign exchange.

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