Reverse Engineering Approach towards Indigenization of Refractory Brick Materials for 100 TPH Boiler used for Propulsion System

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Abstract: This document describes the process for identifying various refractory materials used in a 100 TPH propulsion boiler. The approach undertaken to identify key technical properties required for defining the strength and operational capability of the refractory materials. Sampling and testing carried out with rationalizing the test results to develop refractory materials within India. The paper defines the exact process undertaken by INS Shivaji CoE(ME) to indigenize refractory bricks required for 100 TPH propulsion boilers

1. Introduction

Refractory materials in nature have high temperature resistance and are capable to resist deformation and loose physical properties at elevated temperatures. Uses of refractory materials are mainly in the field of metal and ore processing, petrochemical industry and glassworks, where the refractory materials are constantly subjected to elevated temperature and corrosive environment. The major development in the field of ceramics has been due to iron and steel industries. An offset of this technology is widely used in power generation and propulsion systems, where the refractory materials are subjected to high temperatures but not to corrosive environments. One of such applications is in boilers used to generate pressurized steam in a closed environment which will be converted to mechanical and electrical energy using turbines.

The generation of steam inside the closed chamber is carried out by burning fuel directly. Temperatures inside the boiler can reach up to 2800^0C, to sustain this temperature and effectively utilize the energy, the inside walls are covered with refractory insulating materials.

Refractory insulating materials are often used in environments of elevated temperature and have a primary function to reduce heat losses and save fuel. The physical form of these insulating materials can be in the form of insulating brick, refractory fiber board or blanket, or special vacuum cast shapes. Advancement in coating technology has paved way for ceramic coatings. The thickness of these coatings varies from few microns to 100 mm, with capability to sustain 30000C for prolonged period of time. The coating technology is seldom used in refractory applications, since the refractory materials, typically are rapidly consumed or worn away in use. However, in certain applications, the life of a refractory metal or ceramic part may be extended by applying a high-density refractory material to the surface by flame or plasma spraying. Such coatings are typically limited to special applications and would not be used in conventional furnaces [1]. The most important aspects of a refractory material are that it must be able to provide necessary thermal properties without entering into any undesirable chemical reaction.

Present day scenario dictates use of energy in an efficient manner to avoid wastage and improve efficiency. In Military vessels steam is used widely for propulsion, power generation and run various auxiliary systems onboard. Generation of this steam is done by converting heat energy from nuclear reaction or by burning diesel fuel in the boilers. Indian Navy uses boilers of different capacity in various ships for propulsion; these boilers are fired using LSHSD fuel.

This paper focuses mainly on refractory bricks used in Russian make КВГ-3Д boiler of 100TPH capacity, operating at max 64 bar. The boiler is used in the premier ship of the IN for propulsion and power generation. The main challenges faced during the indigenized development of the insulating refractory material for boiler application were lack of any technical document or OEM support. This had a unique challenge to first identify different type of refractory materials used and the quantity required, classification of these materials and requisite properties of the material to sustain at operational regime of the boiler. Refractory supplies to these ships are tight and sometimes delivery promises are often extended well beyond twelve months from placement of orders. With the changing competitive structure of the import-export trade and quantitative restrictions on importation created by government policies, tight supplies of refractory materials hinder the operational capabilities of the vessel. Therefore, the development of refractory materials within India is justified under the programme of Make in India. The materials so developed are to meet the stringent technology requirements for military applications.

II Approach

The brickwork of refractory materials is expected to work in an environment, where outside temperature fluctuations will be from -400C to +500C with relative humidity of 0 to 100% and atmospheric pressure is expected to be of 1 bar. With experience gained on brickwork carried out in the boilers, initially the refractory materials were identified as solid state materials and liquid state materials. Further solid state materials were classified into powders and bricks. Based upon the literature survey of MIL, IS, ASTM and GOST standards the technical properties required for indigenous development of bricks were identified as Physical, Thermal properties and chemical composition. Key features of individual properties and its effect on the quality of the product were decided upon industrial consultancy and literature survey. Reverse engineering approaches with key tests for various properties were carried out. This paper only emphasis on the indigenization of bricks and the processes involved for the same.

III Test Procedure

A Physical Shape and Size

Total of nine bricks are used in the refractory brick works in КВГ-3Д boiler. Each brick has a different shape and are anchored using bolts at some place and cementing at other places. Initial observations revealed the colour of bricks are pinkish for five bricks and grey for other four bricks. The bricks without any contours or profiles were measured using Vernier caliper (LC 0.01mm), radius gauge and plug gauges. The bricks with contour were measured initially using height gauge and later on 3D CMM machine for profile contours and shapes. To check for dimensional tolerances, sample of 5 bricks of individual shape figure(1) were measured. The results attained as in Table.1 were checked for consistency and variations. On the similar ground, surface roughness of the bricks was checked using portable surface roughness finder, the results obtained from the test table 3 indicated the surface roughness varied from 1.2 Ra to 3.4 Ra.

B Chemical Composition.

Refractory materials are composed mainly of metal oxides or of silicon carbide. Other major elements in the refractory material will be carbon or graphite. Newer refractory materials which are developed for special applications consists of carbides, nitrides, borides and suicides. These are specifically built because of economic considerations. The most commonly used refractory oxides are Si02, $A1_20_3$, MgO, CaO, C r_20_3 and ZrO_2. Those refractories containing $Si0_2$ or $Zr0_2$ are referred to as acid, those with MgO or CaO as basic, and those withAl_20_3 or Cr_20_3 as neutral [2].

Study of test procedures as explained by Sani Aliyu.et.al [3] has concluded that sample test preparation plays a very important role in determining chemical composition, physical and thermal properties of refractory material. Using standard test procedures and sample preparation methodologies mentioned in IS 1528 Part 7 [4] the requisite test samples were created from different bricks. As per ISO 12677 [5] the sample testing was carried out using X-Ray fluorescence (XRF) fused cast bed method to determine the individual element in terms of percentage, also an EDS spectrum analysis using ZEISS machine was carried out at different laboratory Fig 2 and Fig 3. The element percentages obtained were comparable in both the test reports. Results obtained are discussed in section 4.2. A parallel process of determining the chemical composition was also carried out using chemical analysis, here the samples were prepared and tested for exact composition by mass for the bricks. The results obtained from this analysis are tabulated in table 3. Based upon the tests conducted it was determined that five (05) bricks had similar composition with alumina (commercial name Chamotte) as main ingredient and similarly other four (04) bricks were of Silicon carbide based.

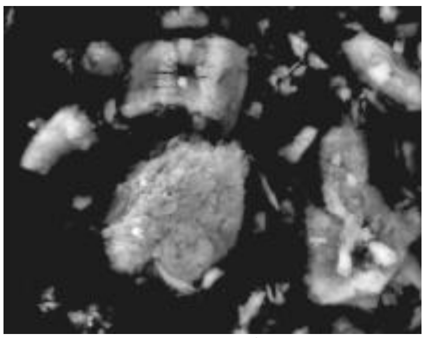

Fig1. EDS Images of Chamotte

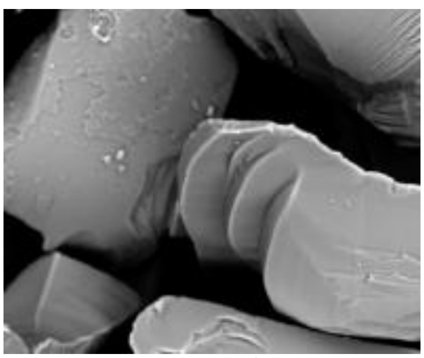

Fig3. EDS Images of Chamotte

C Physical Properties

The refractory materials ability to maintain its strength at high temperatures and other significant properties mainly depend upon the mineral makeup, the particle-size distribution of the minerals, and the way these materials react to high temperatures and working environments. Typically unfired particles have the size in the range of 6 mm or less than 74. These particles form finer particles and develop a ceramic bond under pressure and temperature, which gives these materials its characteristic ability to work at elevated temperatures. The fired refractory consists of bonded crystalline mineral particles and glass or smaller crystalline particles, depending largely on the composition of the refractories. In the case of fireclay and high-alumina refractories, elongated mullite crystals tend to interlace and form relatively strong bonds at temperatures approaching their melting point. When the bond in the refractory is glassy in nature, the brick has good strength at lower temperatures. If at furnace temperatures the glass has a low viscosity, however, it will soften and the refractory will deform under load. When choosing a refractory for a particular application, a variety of physical properties must be considered but, bulk density; apparent porosity, cold crushing strength and Modulus of rupture at ambient temperature are the main physical properties which are essential for performance of the refractories and play a key role in manufacturing of bricks.

All the test samples were prepared in accordance with IS 1528 Part 7 [4]. The sample pieces were extracted from five different batches of bricks collected from stores and those available onboard. The preparation of all these test samples was carried out in a certified lab with over 30 years experience in refractory industry.

1. Bulk density (BD): is the weight per unit volume of the refractory including the volume of open pore space. Density of all ceramic materials is an indirect ions measurement of their capacity to store heat – a particularly useful property in heat exchanger installations [7]. It determines the weight of the refractory brick at the foundation – one of the key element for boiler design which determines the size of the boiler. Strength of the bricks made of non-porous material is higher compared to that developed by porous material. Bulk density was determined by direct volume measurement method, test apparatus shown in fig 3. A test specimen was cut from the core of the refractory shape with the help of a cut-off wheel. Adhering particles were wiped off from test specimen. The dry weight and saturated weight of the test specimen was then determined using the relation

Bulk density (BD) = $\frac{D\ P}{(W-S)}$ g/cm3 …1

Where D = weight of dry test piece, W = weight of test piece soaked, S = Suspended Weight and P is density of water. The results obtained are tabulated in table 4.

Fig3 Bulk Density test apparatus

2. Apparent Porosity (AP): Porosity is a measure of the volumes of all pores present in a material. The material may contain open or closed pores. Generally open pores are interconnected to each other through channels; this makes the material permeable to liquids or gases. Closed pores form isolated spaces or may enclose within individual particles within the matrix of the body so that the material is permeable to liquid or gas. Apparent porosity is the ability to be impervious to gases and liquids. Clay samples with low apparent porosity have greater resistance to penetration by slags/ fluxes, resistance to corrosion/erosion and usually lower gas permeability than those with high porosity. There is an inverse relationship between thermal conductivity and porosity of refractory bricks [8]. True porosity represents the volume of both open and close pores in the volume of the volume of the body. Porous refractoriness has high permeability, poor heat conductivity, low strength and less sensitivity to temperature fluctuation. The experiment was conducted using test apparatus shown in fig 4. The apparent porosity is calculated using

Apparent porosity (AP) = $\frac{W-D}{W-S}$ x 100 …2

Where D = weight of dry test piece, W = weight of test piece soaked, S = Suspended weight. The results obtained are tabulated in table 4.

Fig4 Apparent porosity test apparatus

3 Cold Crushing Strength (CCS): The ability of the brick to resist abrasion and loading, without any cracking or crumbling to powder or lumps is known as Cold crushing strength. This property defines the strength of the material at ambient temperature and is the key property to define brick layup procedures. This property defines the ability of the bottom brick to sustain loads due to bricks placed above it [10]. The trials were conducted on 5 different specimens of 50 mm cube for strength under universal strength testing machine, the test apparatus is shown in fig 5; load was applied axially to the piece until crack was noticed. The load at which the specimen cracked was noted, which represents the load required for determining cold crushing strength of the test specimen. Cold crushing strength was then determined using equation

CCS = P/A…(3). Where 9 is the load (kg) and A is the area (cm2)

The strength values both in the directions and normal to the directions of forming of the bricks were recorded in table 4. This is the ability of clay to bear load. This is an important indicator of the ceramic materials to withstand handling or shipping and impact or abrasion at low temperature. It does not, however, give an indication of the clay's strength at a given temperature [11].

Fig5 CCS test apparatus

4 Modulus of Rupture (MOR): This defines the maximum bending load the refractory brick can bear before complete failure [12]. For this a specimen as Defined in IS 1528 (Part 5) is prepared and subjected to three point support system, a load is constantly applied till the failure occurs. The distance of the failure is measured from the support point and the MOR is calculated using $MOR = \frac{3}{2} X \frac{FL}{bh^2}$ …..4

Where F is the maximum load, L is the distance of failure from support; b is the breadth of the test piece, h is the height of the test piece. The results are tabulated in table 4.

D Thermal Properties

Fig6 Thermal Shock Test Apparatus

*1 Pyrometric Cone Equivalent (PCE)***:** PCE defines the temperature at which the refractory losses its ability to insulate and fail [13]. It is an indicative value of the temperature at which the ceramic softens [14]. For this test cones were prepared by mixing each clay sample aggregate with sufficient quantity of water to make the clay become plastic and molded by hand into a cone shape. The samples were dried and fired to a temperature of 900^0C in a vacuum induction furnace. Orton make standard Pyrometric cones[15] designed to deform at 1300^0C, 1400^0C, 1500^0C, 1800^0C and 2000^0C were placed round the samples and the temperature rose to above 1000^0C at 10^0C per minute. The heating was discontinued when the test cone bent over and leveled with the base of the disc, as shown in fig 6. The Pyrometric cone equivalent (P.C.E) of the samples was recorded to be the number of standard Pyrometric cone corresponding to the time of softening of the test cone.

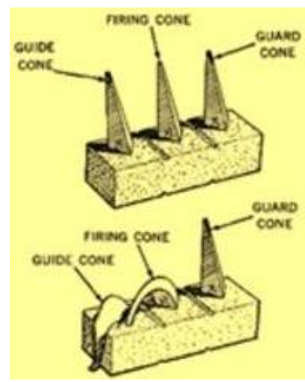

Fig5 PCE test procedure

2. Thermal Shock Resistance: The number of cycles of heating and cooling the test piece endures before cracking is termed as thermal shock resistance [14]. For this test specimen measuring 5cm X 5cm X 4cm was used. The prepared samples were inserted in a furnace which has been maintained at 1000^oC (test apparatus shown in fig 6). This temperature was maintained for 10 minutes. The specimens were removed with a pair of tongs from the furnace one after the other and then cooled for 10 minutes and observed for cracks. In the absence of cracks (or fracture),the specimen were put back into the furnace and reheated for a further period of 10 minutes and then cooled for another 10 minutes. The specimens were returned to the furnace for further 10 minutes. The process was continued until the test pieces were cracked. The test results are tabulated in table 5.

3. Linear Shrinkage: All refractory materials expand on heating. For boiler brickwork this is considered very important to achieve leak proof chambers. For refractory material it is imperative to have a very low thermal expansion in order to cool back effectively and maintain the structure integration. If refractories used as insulators shrink beyond the design limit during operational cycles, this will result in cracks on cementing leading to failures. To determine the shrinkage properties of the specimen, the specimen were pressed in a fabricated wooden box of size 5x5x4cm. The rectangular test pieces were marked along a line in order to maintain the same position after heat treatment. The distance between the two ends of the slab was measured with vernier caliper. The samples were air dried for 24 hours and oven dried at 110^{O}C for another 24 hours. They were then fired for 6 hours. The test pieces were cooled to room temperature and measurements taken. The linear shrinkage are calculated using. Linear

Shrinkage = $\frac{D-F}{D}$ X100, where D is dried length and F is Fired Length.

IV Results and Discussions.

A Results

1 Dimensional Tolerance: The total of five bricks of each type was checked for length, breadth and height. The contours and curvatures were later measured using 3D CMM and brought out in the drawings for production

Table.1 Dimensional Tolerances of the Bricks

Ser.	Specimens	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	Brick Type	Length (mm)					Breadth (mm)					Height (mm)				
1.	Chamotte Bricks (Big)	101	103	100	97	98	152	154	148	148	149	164	162	158	159	159
2.	Chamotte Bricks (Small)	44	41	36	39	39	152	152	148	148	150	163	161	157	159	159
3.	Chamotte Brick with Central Hole.	100	96	105	103	97	164	165	155	158	159	162	163	157	159	159
4.	Chamotte Brick with Off-Central Hole.	101	99	102	102	97	163	162	157	159	159	160	161	161	160	159
5.	Chamotte Rectangular Brick	115	116	111	112	113	66	65	60	63	64	232	233	227	229	230
6.	Silicon Carbide, For D180	176	177	173	172	175	162	162	160	159	159	189	188	187	186	185
7.	Silicon Carbide, For D280	122	122	118	117	119	223	224	218	219	221	161	60	157	159	159
8.	Silicon Carbide, Triangle 125x125 mm	98	98	104	101	100	180	182	174	175	178	161	162	160	160	160
9.	Silicon Carbide 160x160 mm	100	99	99	99	100	160	160	160	159	159	159	159	159	159	160

Table.2 Geometrical Tolerances off the Bricks

Sl. No.	Specimens	R_a									
		1	2	3	4	5	6	7	8	9	10
1.	Chamotte bricks	2.8	2.9	3.4	3.2	3.6	2.5	1.8	3.3	2.6	1.9
2.	Silicon Carbide	3.0	3.1	2.9	2.7	2.6	1.9	1.8	3.0	3.2	1.8

Table.3 Chemical Composition

Sl. No.	Brick Type	Specimens	Al_2O_3 (%)	SiC (%)	Fe_2O_3 (%)	CaO (%)	SiO_2 (%)	C (%)
1.	Chamotte Bricks	1	57.5	-	1	-	-	-
		2	57.8	-	1	-	-	-
		3	57.3	-	1	-	-	-
		4	57.2	-	1	-	-	-
		5	57.9	-	1	-	-	-
2.	SiC bricks	1	-	90	0.5	0.5	5	2
		2	-	90.8	0.6	0.55	5.2	2.1
		3	-	89.9	0.5	0.52	5.1	2
		4		90	0.52	0.54	5.2	2.2
		5		90	0.5	0.5	5.0	2

Table.4 Physical Properties of the Bricks

Sl. No.	Brick Type	Specimens	BD gm/cc	AP (%)	CCS kg/cm^2	MOR kg/cm^2
1.	Chamotte	1.	2.28	23.98	450.1	75.3
		2.	2.32	23.9	450.2	74
		3.	2.29	23.94	450.4	75.2
		4.	2.31	23.96	449.8	75.1
		5.	2.28	23.97	449.9	75.2
2.	Silicon Carbide	1	2.42	18.2	750.4	150.1
		2	2.43	18.4	750.1	150.5
		3	2.39	18.1	750.3	150.2
		4	2.40	18.15	750.25	150.15
		5	2.41	18.1	750	150.2

Table.5 Thermal Properties of the Bricks

Sl. No.	Brick Type	Specimens	PCE	TSR	LS (%)
1.	Chamotte	1.	+38	22	3.1
		2.	+38	23	3.2
		3.	+38	22	3.0
		4.	+38	23	3.1
		5.	+38	23	3.1
2.	Silicon Carbide	1	+38	23	3.0
		2	+38	23	3.0
		3	+38	22	3.1
		4	+38	22	3.1
		5	+38	22	3.1

2 Geometrical Tolerances: To ascertain the quality of the bricks and the ability to adhere to cements the surface roughness was tested. Total of 10 test samples were subjected to test, the samples were randomly picked from the slot.

3 Chemical Composition: The chemical analysis of the bricks was carried out in the lab with NABL accreditation. The results indicated that variations in the Chamotte bricks and silicon carbide bricks compositions respectively were negligible. Chemical compositions in terms of oxides for each clay sample are shown below. In general, three groups of oxides were of interest; silica, alumina and alkaline-containing oxides. The results show that the various components of the chemical analysis are in line and the lack of considerable content of other components is occasionally observed in Clays. The analysis shows a great similarity in the silica (SiO_2), Silicon carbide (SiC) and Alumina content - (Al_2O_3) in the clay samples.

4 Physical Properties: The physical properties of the clay samples were determined with respect to Apparent Porosity (AP), Bulk Density (BD), Cold Crushing Strength (CCS) and Modulus of Rupture (MOR). The results of these tests are as presented in Tables 4.

5 Thermal Properties: The thermal properties of the clay samples were determined with respect to Pyrometric Cone Equivalent (PCE), Thermal Shock Resistance (TSR) and Linear Shrinkage (LS). The results of these tests are as presented in Table 5.

B Discussions

1 Determination of Chemical Composition: The Alumina Content of all the clay samples indicated the core element to be Al2O3 with content varying from 57.5 to 57.9 %. It is evident that these bricks are used as heat insulating bricks and can sustain up to the temperature of 1600^0C. The SiC brick shows that it has 90% SiC as core element and lime is used as one of the binder. The impurities such as Fe_2O_3, and SiO_2 are added to increase the strength of the mold and help in developing stronger bonds. The free carbon observed is a by product and has minimal effect on the effectiveness of the refractory brick.

2 Physcial Properties of the Brick: The Bulk density of the Chamotte brick is observed to be 2.28 to 2.32, this indicates the refractory is prepared in a brick klin and are considerably heavy. The structure of the brick is open as evident from the AP and all the five samples gave apparent porosity value which is within the acceptable range (10-30%) suggested for refractory clays [19], This implies that the clay samples have common major compositions in terms of oxides, which constitutes the highest percentage of the clay mineral compositions. The CCS is in the range of 449.9 to 450.2 kg/cm^2. The implication of this is that the samples could have more tendencies to bear load at low temperatures. This is desirable in the productions of load bearing structures as boilers. The MOR indicates the brick has considerably good strength to sustain bending loads generated due to vibrations. The SiC brick is observed to be of comparatively closed structure type with higher strength to sustain static and bending loads. The weight of the brick is comparable to Chamotte brick.

3 Thermal Properties of the Brick: The Bricks both Chamotte and SiC had maintained their structural integrity for cone equivalent 38 (1800^0C). This indicates the brick can sustain its properties beyond 1800^0C which is more than the combustion temperature within the boiler. Both the bricks have considerable strength to sustain repeated thermal cycles in the range of 22-23, this is within the recommended range of 20-30 for fireclay refractories [20]. The linear shrinkage of both the bricks is less than 4% (by volume) and is well within the limit for fireclays. This indicates the bricks will have minimal thermal distortion over period of use and hence suitable for boiler applications.

V Conclusion.

The results obtained from the lab were discussed with industries for feasibility of manufacturing with the test data and concurrence was sought from industries to develop tailor refractory materials for onboard application. Further the test results were compared to relevant MIL [21][22][23][24] and GOST Standards. With the industrial discussions, referring to relevant MIL GOST standards and keeping in view of the stringent working environments onboard. Following conclusions were drawn:-

(a) The alumina content in the Chamotte content was decided to be of min 57% as the same will increase the refractoriness of the component and will meet the international quality as recommended in MIL and GOST.

(b) The SIC content was decided to be min 90% as the same bricks are used at zones subjected to comparatively higher temperature in the boiler. This will increase the refractoriness of the brick and increase thermal stability during operations.

(c) Impurites such as Fe_2O_3 will affect the strength of the brick and hence decided to be of max 1% for Chamotte bricks and 0.5 % for SiC bricks. CaO is the binding agent which helps in developing stronger bonds, but excessive CaO will lead to glass structure affecting the strength of the brick hence limited to max 0.5 %. SiO_2 is a natural occurring element which is mixed in the clay, max of 5% is allowed considering the raw material availability in India. C is a byproduct achieved after molding, this is an inevitable product in the SiC bricks and hence limited to max 2% based upon industrial consultations.

(d) The physical properties for the bricks were decided based upon the MIL, GOST standards in lieu with the test results as tabulated in table 6.

(e) The thermal properties for the bricks were decided based upon the MIL, GOST standards in lieu with the test results. The results obtained was checked with onboard data available and found to be suitable for the application. The results are tabulated in table 6.

Table.5 Physical Properties of the Indigenized Bricks

Sl. No.	Brick Type	BD gm/cc	AP (%)	CCS kg/cm^2	MOR kg/cm^2
1.	Chamotte	Min 2.3	Max 24	Min 450	Min 75
2.	SiC	Min 2.45	Max 18	Min 750	Min 150

Table.6 Thermal Properties of the Indigenized Bricks

Sl. No.	Brick Type	PCE	TSR	LS (%)
1.	Chamotte	+38	+22	Max 3
2.	Silicon Carbide	+38	+22	Max 3

Acknowledgement

The experiments for determining physical and chemical properties were conducted M/s refractory Shapes pvt. Ltd. Pune. The chemical compositions were determined at Carl Zeiss lab, Bangalore. It is imperative to mention the support extended by these firms in carrying out experiments and sharing their industrial insight towards indigenous development of refractory materials. At the same time we would like to extend our gratitude to M/s Air Seal, Hyderabad for their input on refractory developments, finally I would like to extend our gratitude to GTRE DRDO Materials Group in aiding for test specimen development and validation of results.

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