Clay-bonded Bauxite Refractories: Physical and Mechanical Properties

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The physical and mechanical properties of model refractory test pieces fabricated from Guyana refractory grade bauxite and the white-burning Valencia clay of Trinidad have been investigated. Specimen were fabricated by hydraulic compaction of compositions spanning the range 0 - 95% of the bauxite batched with the clay, followed by firing at processing temperatures of 1200°C and 1300°C. Compared with the control samples (100% clay), addition of up to 10% bauxite effected an initial enhancement in modulus of rupture, compressive strength and fracture toughness. Thereafter, all three parameters varied only slightly with increasing bauxite content up to 50 - 60%, followed by rapid decrease towards relatively low values for higher bauxite contents. Commensurately, apparent porosity increased rather sharply with increasing bauxite proportion above 60%. Inclusive of compressive stress-strain characteristics, the properties displayed correlated with the microstructures developed on firing as the clay/bauxite ratio is varied.

1. Introduction

Refractories are widely used essential materials in many industries incorporating high-temperature processes as part of production operation. For example, relevant to the Caribbean region, the processing of petroleum, bauxite, alumina, cement, steel and structural clay bricks all require the use of refractories. However, while the region has for many years been a major world exporter of refractory raw materials (e.g., alumina - Jamaica and Guyana; refractory grade bauxite - Guyana), the regional demand for finished products is satisfied exclusively by importation. Because of this, the question often arises as to the potential viability of home conversion of these raw materials into finished products. However, high capital expenditure, high operational cost and highly competitive world markets are often cited as mitigating factors. Further, depending on the nature of the production process, individual industrial operations often require highly specialised refractory products other than products based on clays, bauxite or alumina.

Nevertheless, from a materials point of view, a range of non-specialised, cost-effective products may be possible based on exploiting the versatility of clays as a binding agent for forming and, on firing, a bonding matrix for good strength and toughness. However, whatever the envisaged application of the product, the proportion of clay is important since it impacts on physical and mechanical properties and in-service dimensional integrity.

In view of these factors, the fired physical and mechanical properties of formulations based on the Guyana refractory grade bauxite and the Valencia clay of Trinidad have been studied. In choosing the Valencia clay as the binding component, thought was given to the fact that in its own right, it displays a number of desirable refractory features [1 - 3]. For example, it burns white, is of low iron content, exhibits low

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shrinkage and vitrifies significantly only at temperatures in excess of 1000ºC. This paper reports on the properties developed in formulations covering the range 0 - 95% bauxite fired at 1200ºC and 1300ºC.

2. Experimental

2.1 Materials and Fabrication

From previous work [3], X-ray diffraction established that the Valencia clay used in this study was kaolinitic and admixed with some quartz, mica and calcite.

After crushing and grinding, both the bauxite and the clay were sieved through a 500 μm mesh size sieve and the sub 500 μm fractions retained for the experiments. Particle size distribution in these fractions is shown in **Figure 1**.

Subsequent to dry-batching in the desired clay/bauxite ratios, damp granular mixes were prepared with suitable addition of water (8 - 16%, on a dry weight basis, depending on the clay/bauxite ratio). From the damp mixes, test bars of cross section 1.3cm x 1.3cm were fabricated by hydraulic pressing (at 2 MPa) in a metal mould. Following open-air drying, firing was done at hold temperatures of 1200ºC and 1300ºC for four hours in an electric furnace ramped at 10ºC/minute.

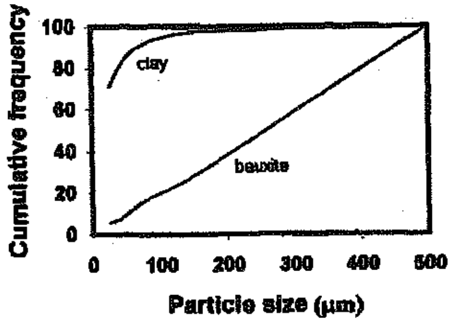

FIGURE 1: *Particle size distribution in the sub-500 µm fraction of the bauxite and the clay used in the study*

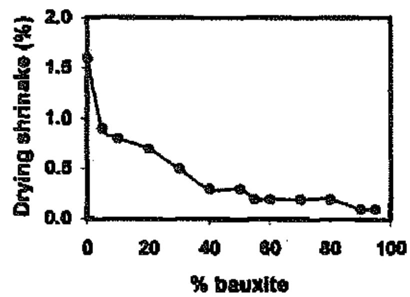

FIGURE 2: *Drying shrinkage as a function of body composition*

2.2 Mechanical and Physical Properties

Flexural strength or modulus of rupture, MOR, was determined in three-point bend loading configuration using a loading span of 2.5cm (specimen width and depth depended on the degree of shrinkage of each composition at each firing temperature). Similarly, fracture toughness (K_{IC}), based on the critical stress intensity factor concept [4], was measured in three-point bend using single-edge notched bars. The loading span used was 2.5cm while the notch depth, "a", was such that $0.45 < a/w < 0.55$, a requirement necessary for valid K_{IC} results, where w is the specimen depth. In compression, testing was done using specimens of aspect ratio 1.3. For each composition and firing temperature MOR, K_{IC} and compressive strength were averaged over values obtained from five or more specimens.

Before and after firing, linear drying and firing shrinkage of the test bars fabricated from the various compositions were determined using vernier calipers. Quantification of the apparent porosity, the water absorption and the bulk density of the fired bars was done by the water displacement method based on Archimedes principle.

3. Results and Discussion

3.1 Green Characteristics

As expected, **Figure 2** shows that drying shrinkage decreases with increasing bauxite content. However, for all the compositions studied except the control sample (100% clay), the magnitude of the shrinkage was less than 1%.

Due to sensitivity limitations of the measurement apparatus and the friable nature of the specimens in the green state, reliable determination of green strength was not possible. However, for all the compositions studied, green strength is expected to be less than the 0.3 MPa exhibited by the control (100% clay) samples. Nevertheless, except for compositions containing more than about 80% bauxite, this posed minimal difficulty in handling the unfired samples.

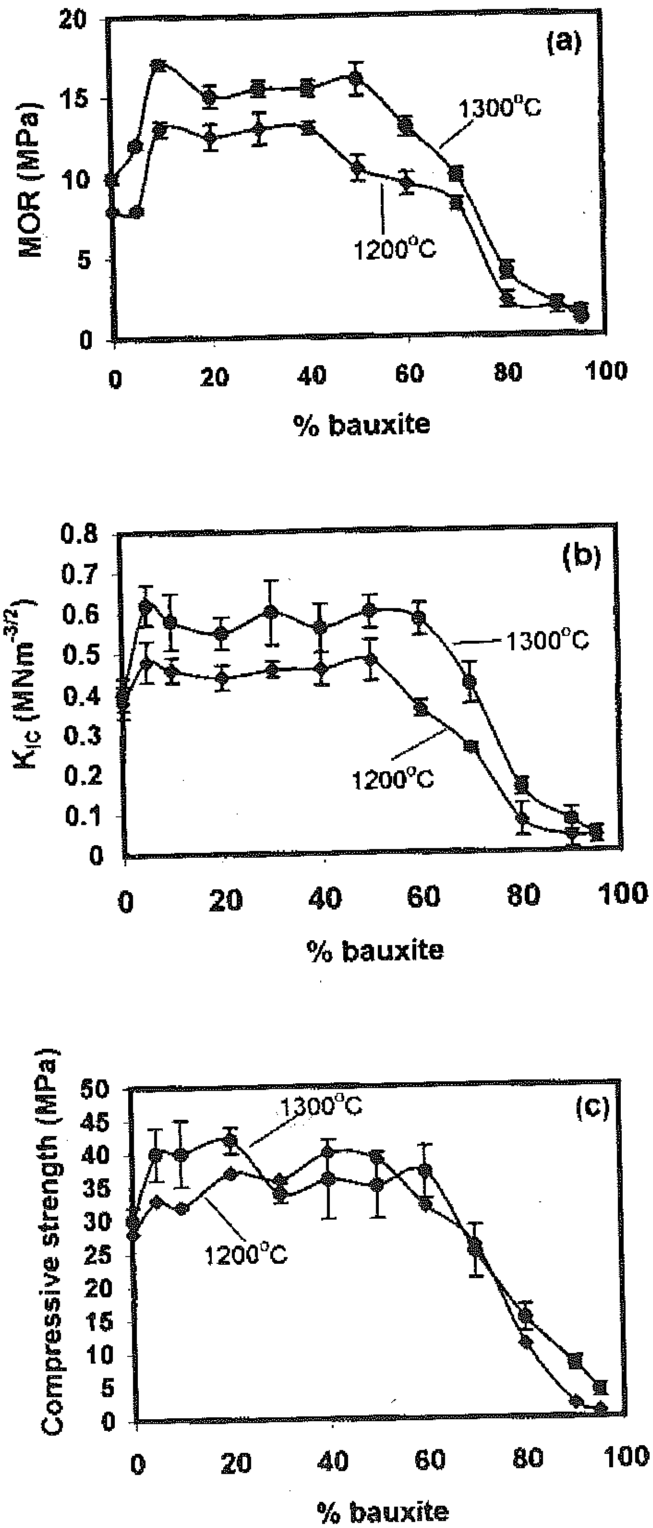

FIGURE 3: *(a) Modulus of rupture (MOR),*
(b) Fracture toughness (K_{IC}) and
(c) Compressive strength as functions of body composition after firing at 1200°C and 1300°C

3.2 *Fired Characteristics*

(a) *General*

Generally, the test bars fired creamish to grey with the colour deepening with increasing bauxite proportion. In addition, for all the compositions studied and for both firing temperatures, the test bars maintained shape integrity, displaying neither warping, nor bloating nor cracking.

(b) *Mechanical Properties*

Figure 3 shows modulus of rupture, fracture toughness and compressive strength as functions of body composition for the two firing temperatures studied. As can be seen, for corresponding compositions, the samples fired at 1300°C exhibit superior strength and toughness compared with those fired at 1200°C. However, for both firing temperatures, the trend in variation of all three parameters as a function of bauxite content is similar. In particular, compared with the control samples, all three parameters are enhanced by bauxite addition up to 10%. Further addition of bauxite up to 60% effects no further improvement. Above 60% bauxite, however, MOR fracture toughness and compressive strength decrease rapidly towards low values with increasing bauxite content.

(c) *Physical Properties*

Figure 4 shows that in general, firing shrinkage and bulk density decrease while apparent porosity and water absorption increase with increasing bauxite content for both firing temperatures. However, consistent with the mechanical properties (**Figure 3**) showing little variation with increasing bauxite content in the range 10 - 60%, the apparent porosity also varies only slightly within this range. Further, above ~ 60% bauxite where strength and toughness decreased towards low values, the porosity and water

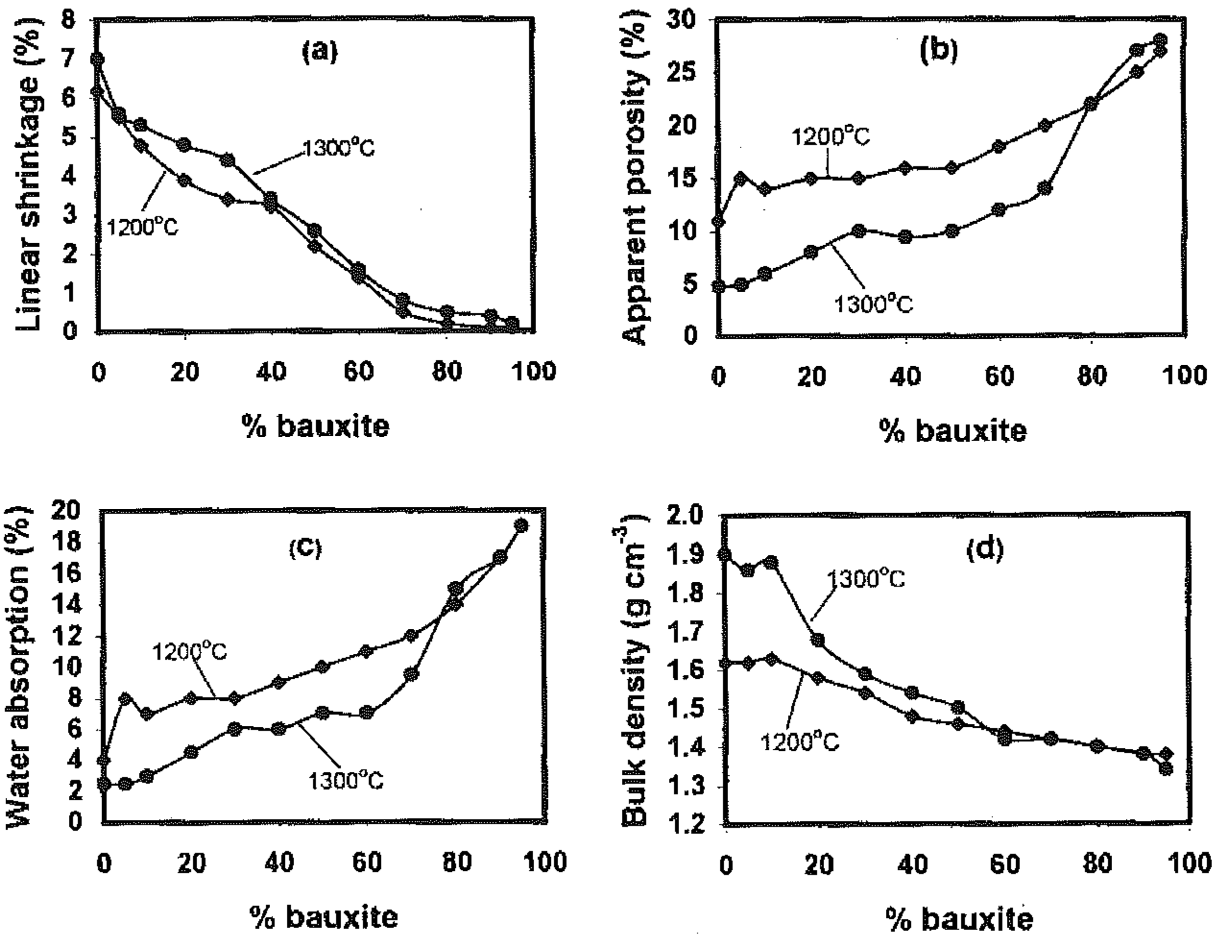

FIGURE 4: *(a) Firing shrinkage, (b) Apparent porosity, (c) Water absorption and (d) Bulk density*

absorption increase sharply while firing shrinkage and bulk density decrease.

(d) Microstructure/Property Relationship

As seen earlier, compared with the control samples, bauxite addition up to about 50 - 60% effected enhancement in strength and toughness for both firing temperatures. This, together with the significant decrease in strength and toughness above 60% bauxite is a consequence of the microstructures developed on firing. In particular, scanning electron microscopy study of fractured surfaces reveals that for compositions containing up to 50 - 60% bauxite, there is sufficient clay to form a continuous or near-continuous bonding matrix on vitrification. Dispersed in the matrix, the "inert" bauxite particles impede crack propagation by blunting and/or deflection, resulting in the observed enhancement in strength and toughness, similar to the behaviour previously reported for formulations of the same clay batched with alumina [5].

For compositions containing more than about 60% bauxite, there is insufficient clay to form a continuous cementing matrix on vitrification. Consequently, the microstructure is dominated by regions of only bauxite contact resulting in high porosity and weak inter-particle bonding, since at the firing temperatures studied, the bauxite particles do not sinter to any significant degree. Hence, as the bauxite content is incrementally increased above about 60%, strength and toughness progressively decrease and porosity increases.

From **Figure 5**, compression stress-strain responses seem consistent with the microstructures developed as the bauxite content is varied. In particular, **Figure 5(a)** shows that for low bauxite proportions where the bonding matrix is continuous and porosity is lowest, the stress-strain curves exhibit essentially linear behaviour up to fracture. This suggests predominantly elastic deformation and typical brittle fracture. However, for bauxite proportions within mid and high range (**Figures 5(b)** and **(c)**), the stress-strain relationship is no longer linear, with a decrease in slope preceding fracture. These features are consistent with significant compaction as opposed to elastic deformation, and crushing dominated failure instead of typical brittle fracture during compression loading of samples of relatively high porosity anbd/or comparatively weak bonding.

4. Conclusions

Drying shrinkage decreases with increasing bauxite proportion but is of the order of less than 1% for all the compositions studied. Similarly, firing shrinkage decreases with increasing bauxite proportion, with compositions containing above about 50% bauxite exhibiting values less than 2%.

Compared with the control samples, incremental increase in bauxite content up to about 50 - 60% results in enhanced mechanical properties on firing at both 1200^{0}C and 1300^{0}C. Thereafter, strength and toughness progressively decrease with increasing bauxite content. Nevertheless, even at as high a bauxite content as 80 - 85% modulus of rupture and compressive strength tend to be better than 1 MPa and 5 MPa respectively for both firing temperatures.

The variation in physical and mechanical properties is consistent with the variation of the observed microstructures.

Compositions containing high proportions of the bauxite are expected to be most suitable for refractory applications. These generally combine good strength and toughness with relatively low bulk density. Where high refractoriness is required, mixes will need to contain >60% bauxite and firing may have to be done above 1300^{0}C.

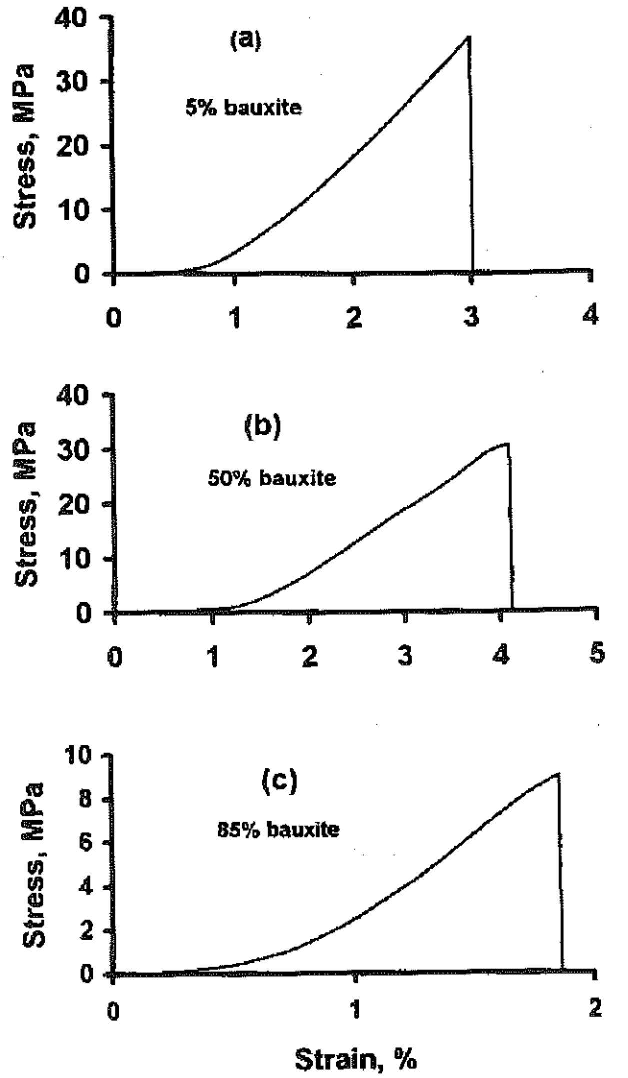

FIGURE 5: *Typical compressive stress-strain responses of fired samples formulated with low, medium and high bauxite proportions*

Acknowledgements

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