# Bauxite — a global review

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Bauxite is used principally as the raw material in the production of aluminium metal. Nonetheless, beyond this are a number of very significant non-metallurgical applications, mainly abrasives, cements, chemicals, and refractories. Bauxites used in producing end products for these special applications must meet much more stringent compositional and physical requirements than the crude ore commonly employed for aluminium production, and as such, are limited to a few specific sources, such as Guyana, China, and now Brazil. This article reviews the major sources, applications, and requirements of the global non-metallurgical bauxite industry.

## Bauxite in perspective

Bauxite is a naturally occurring, heterogeneous material composed primarily of one or more aluminium hydroxide minerals, plus various mixtures of silica ($SiO_2$), iron oxide ($Fe_2O_3$), titania ($TiO_2$), aluminosilicate (clay, etc.), and other impurities in minor or trace amounts. The principal aluminum hydroxide minerals found in varying proportions within bauxites are: gibbsite, $Al(OH)_3$; and the polymorphs boehmite and diaspore, both $AlO(OH)$.

Bauxites are typically classified according to their intended commercial application: abrasive, cement, chemical, metallurgical, refractory, etc. Of all bauxite mined, approximately 85% is converted ultimately into aluminium metal, an additional 10% goes to non-metal uses as various forms of alumina ($Al_2O_3$), the oxide of aluminium, and the remaining 5% goes to non-metallurgical grade bauxite applications (*Figure 1*). Therefore, the bulk of world bauxite production is currently used as feed for the manufacture of alumina via a wet chemical caustic leach method commonly known as the Bayer process. Subsequently, the majority of the resulting alumina produced from this refining process is in turn employed as the feedstock for the production of aluminium metal by the electrolytic reduction of alumina in a molten bath of natural or synthetic cryolite ($Na_3AlF_6$), the Hall-Héroult process.

Beyond this use of bauxite, to produce primary aluminium metal, lies the critical area of non-metallurgical or speciality

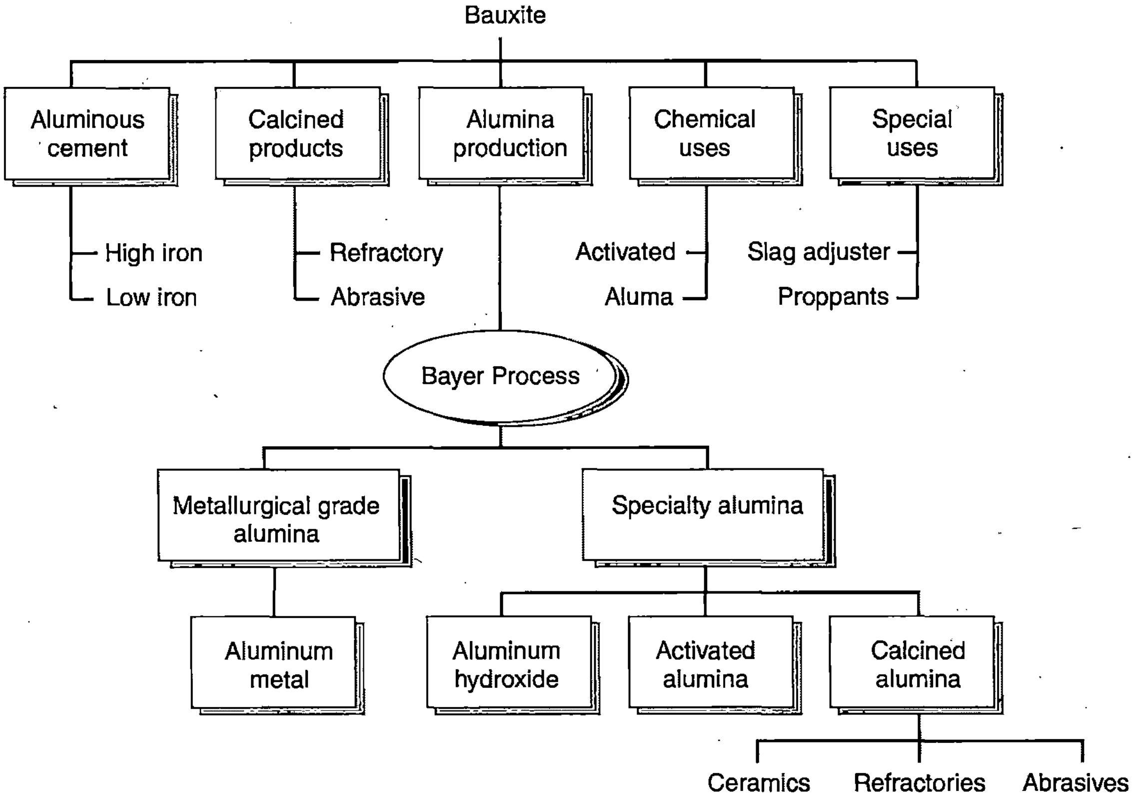

*Figure 1. The Bayer Process*

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*U.S. Bureau of Mines

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### Table 1. World Bauxite reserves ('000s tonnes)

| | *Reserves*[1] | *Reserve base*[1] |
|---|---|---|
| Australia | 5,600 | 7,900 |
| Brazil | 2,800 | 2,900 |
| Cameroon | 680 | 1,000 |
| China | 150 | 1,500 |
| Greece | 600 | 650 |
| Guinea | 5,600 | 5,900 |
| Guyana | 700 | 900 |
| Hungary | 300 | 300 |
| India | 1,000 | 1,200 |
| Jamaica | 2,000 | 2,000 |
| Surinam | 580 | 600 |
| USA | 20 | 40 |
| Venezuela | 320 | 350 |
| Other countries | 2,670 | 2,600 |
| World total[2] | 23,000 | 28,000 |

[1] Resource reserve definition, US Geological Survey circular 831, 1980.

[2] Data may not add to totals shown because of independent rounding

applications that quantitatively comprise 5% of total worldwide crude ore production. Precise figures on bauxite production and consumption levels within non-metallurgical markets are not commonly available on a systematic or routine basis for collection and analysis. It is currently accepted, however, that the principal industrial end uses for non-metallurgical grade bauxite, ranked in order of magnitude, are in the refractories and abrasives fields, followed by cement applications. In addition, the aluminium chemicals and steel industries also consume significant quantities of bauxite for other applications.

Furthermore, high quality abrasive, ceramic, chemical, and refractory products are also produced from the bauxite-derived, speciality-grade aluminas produced through the Bayer process (*Figure 1*).

In 1993, the most recent year for which complete annual production data are available, 27 countries reported bauxite mine production and total world production amounted to 108.5 million metric tons of bauxite . This was an increase of 4% over 1992 production.

The US Bureau of Mines (USBM) currently estimates the 1994 total world bauxite production, from a similar number of producing nations, at 107.5m. tonnes, approximately 1% below the production reported for 1993. Australia, Guinea, Jamaica, and Brazil, in order of volume, accounted for slightly more than 70% of the total bauxite mined during 1993, with a similar situation projected for 1994. In terms of non-metallurgical grade bauxite production, the principal sources of supply presently are very limited and comprise only a handful of nations; ie, abrasive grade - Australia, Guinea, China, and Guyana, and refractory grade - China, Guyana, and Brazil.

Total known world reserves for all types of bauxite are sufficient to meet cumulative world primary aluminium metal demand well into the 21st century. Although it may be noted that bauxite reserves are unevenly distributed throughout the world, with approximately 90% occurring in about a dozen countries, the sheer magnitude of these reserves (23,000m. tonnes) is sufficient to ensure a readily accessible supply for the future (*Table 1*).

In addition, considering the added probability of discovering further bauxite deposits, plus the likely possibility of employing lower grade bauxitic materials and other alternative sources of alumina, resources for the production of aluminium metal remain adequate to satisfy demand for well beyond the near term. The case is not quite as strong for non-metallurgical grades of bauxite, which normally must meet very stringent quality requirements and are supplied from a markedly smaller number of worldwide sources.

Even so, precluding any major disruptions within the very limited number of current producer nations, adequate reserves of non-metallurgical grade bauxite are available to satisfy worldwide industrial demand well into the next century (*Table 1*).

The world annual "in place" non-metallurgical grade bauxite mine production capacity at the end of 1994 was estimated by the USBM at approximately 6.8m. tonnes, about 5% of the estimated total crude bauxite production capacity. The principal non-metallurgical grade bauxite producers of the world are listed in *Table 3 (overleaf)*.

## General specifications

The bauxite used for producing abrasive, chemical, and refractory products must meet much more rigid compositional requirements than the crude ore that is commonly used for aluminium metal production, as shown in *Table 2*.

Specifications for the premier grades of bauxite are based on the processing requirements and special properties required of their final commercial products. The natural chemical impurities that exist within these speciality-grade raw materials are not chemically removed from the ore during a refining procedure, as in the case of metallurgical grade bauxite, where impurities are eliminated through the Bayer process. Non-metallurgical ores are utilised in an essentially unrefined chemical form, as direct feedstocks for the production of their ultimate end products.

The general chemical requirements for the principal speciality bauxites, as outlined in *Table 2* and listed in terms of their increasing total alumina content, are as follows:

### Table 2. Chemical analysis of typical raw bauxites (by grade)

| *Grade* | *Major oxides (%)*[1] | | | |
|---|---|---|---|---|
| | $Al_2O_3$[2] | $SiO_2$ | $Fe_2O_3$ | $TiO_2$ |
| Metallurgical | 50-55 | 0-15 | 5-30 | 0-6 |
| Cement | 45-55 | max. 6 | 20-30 | 3 |
| Abrasive | min. 55 | max. 5 | max. 6 | min. 2.5 |
| Chemical | min. 55-58 | max. 5-12[3] | max. 2 | 0-6 |
| Refractory | min. 59-61 | max. 1.5-5.5 | max. 2 | max. 2.5 |

1. Most of the remainder represents hydroxyl (OH) groups
2. Total alumina
3. A major portion of the bauxite used by the US chemical industry exceeds 15% $SiO_2$

### Table 3. Principal non-metallurgical grade bauxite mines (1994)

| *Region and country* | *Company* | *Mine location* | *Estimated total year end capacity (tpa)* | *Grades* |
|---|---|---|---|---|
| North America | | | | |
| USA | C-E Minerals | Eufaula, Alabama | 100,000 | Refractory/abrasive |
| | Harbison-Walker Refractories | Eufaula, Alabama | 100,000 | Refractory/abrasive |
| | C-E Minerals | Andersonville, Georgia | 20,000 | Refractory/abrasive |
| | CYTEC Industries Inc. | Andersonville, Georgia | 150,000 | Chemical |
| South America | | | | |
| Brazil | Cia Brasileira de Bauxite | Paragomines, Pará | 20,000 | Refractory |
| | Mineraçao Curimbaba Ltda | Poços de Caldas, Minas Gerais | 244,000 | Refractory/abrasive |
| | MSL Minerais SA | Caracuru, Parà | 200,000 | Refractory/chemical |
| Guyana | Berbice Mining Enterprise Ltd | Berbice | 400,000 | Refractory/abrasive chemical/cement |
| | Linden Mining Enterprise | Linden (Mackenzie) | 1,250,000 | Refractory/chemical |
| Europe | | | | |
| Albania | Mineralimpeks districts | Tiranë and Libazhd | 10,000 | Chemical/cement |
| Bosnia and Herzegovina | Energoinvest | Jajce and Bosanska Krupa | - | Cement |
| | Energoinvest | Mostar | - | Cement |
| Croatia | Istrian Bauxite Mines - Rovinj | Istrian Peninsula | - | Cement |
| France | Garrot-Chaillac | Bedarieux, Herault | 70,000 | Cement |
| | Sodicapei | Velleveyrac, Herault | 85,000 | Speciality |
| Greece | Bauxites Parnasse Mining Co. | Ghiona and Parnasse mountains | 300,000 | Cement/abrasives/ slag adjuster |
| | Eleusis Bauxite Mines | Ghiona and Oeti mountains | 75,000 | abrasive/slag adjuster |
| | | Itea | 75,000 | Chemical/slag adjuster |
| | Helicon Bauxite | Helicon mountains | 100,000 | Cement |
| Russia | Severnaya Onega Bauxite Mine | South of Archangelsk | 100,000 | Refractory |
| Africa | | | | |
| Guinea | Compagnie des Bauxites de Guineé | Sangaredia and Bidikoum | 210,000 | Abrasive |
| Mozambique Zimbabwe | E.C. Meikle plc of Morondo | Alumen and | 8,000 | Chemical |
| Asia | | | | |
| China | Ministry of Metallurgical Industry | Various provinces | 2,000,000 | Refractory/abrasive |
| India | Gujarat Minerals Development Corp. | Kutch and Saurashtra, Gujarat | 500,000 | Abrasive/chemical/ cement/refractory |
| Malaysia | Johore Mining & Stevedoring Co. | Pengerang, Johore | 200,000 | Cement/refractory/ chemical |
| Pakistan | Black Mountain Minerals | near Manshera | 5,000 | Speciality |
| Turkey | Etibank | Milâs, Mugla | 125,000 | Cement/slag adjuster |
| Oceania | | | | |
| Australia | Comalco | Weipa, Queensland | 300,000 | Abrasive |
| | Nabalco Proprietary Ltd | Gove, Northern Territory | 200,000 | Cement |

**Cement grade** moderate to moderately high alumina content, low silica. Iron oxide content may be high for production of some grades but should be low in grades requiring structural strength. Diaspore is preferred but not essential for this application.

**Abrasive grade** high alumina content, low silica, moderately low iron oxide, low titania. Iron is often added during the electric arc furnace fusion process to achieve correct iron oxide to silica ratio for formation of ferro-silicon slag.

**Chemical grade** high alumina content, should be gibbsitic ore,

### Mining and beneficiation

Non-metallurgical bauxite mines, as with most metallurgical grade mines, ordinarily employ large scale open pit mining techniques to recover their mined product. In recent years, at least 80% of total world bauxite production has been achieved by surface mining methods.

After the non-metallurgical grade bauxites are mined, they are crushed and screened to remove fines, and in some instances are washed to eliminate clay and silica contaminants. At a few special mining operations heavy media separation techniques are employed to reduce the iron content or remove calcareous contaminants from the ore. It is from this point that the non-metallurgical bauxites undergo very special processing procedures to insure that they meet the strict market specifications demanded of their individual end products.

very low iron oxide and other acid-soluble oxides, silica (and clays) preferably low but not critical. In some instances, this material is essentially equivalent to crude or green refractory grade bauxite that has not been calcined.

**Refractory grade** high alumina content, low silica, low iron oxide, and very low alkalis.

## Commercial applications/market sectors

### Refractory applications

In the modern economies of the world, alumina ($Al_2O_3$), is the primary ingredient for a significant portion of the products used in high-temperature industrial applications. Alumina-based refractories are crucial components in nearly all high-temperature metallurgical, cement, ceramic, glass, and petrochemical manufacturing processes of modern industry.

The alumina content of a particular refractory may range from 30% to 100%, depending on the exact nature of raw material from which it is made and its intended application. The total spectrum of alumina-silica ($Al_2O_3 + SiO_2$) refractory products is delineated in *Table 4*.

Aside from the lower alumina categories, which are based primarily on clay minerals, and those products composed of natural aluminium silicate minerals (andalusite, kyanite, or sillimanite), refractories containing more than 45% to 50% alumina rely heavily upon bauxite as the origin of their contained aluminium oxide. In general, the ability of an alumina-based material to resist high temperatures increases with increasing alumina content.

Refractory applications presently provide the largest non–metal market for bauxites. Some extra-high alumina content refractories are produced directly from the premium quality alumina derived through processing of metallurgical-grade bauxite ores (*Figure 1* and *Table 4*), but the majority of standard refractory products incorporate a calcined or fire treated form of bauxite for their raw material base. These natural bauxitic materials provide users of refractory products with a reasonably priced, high-alumina feedstock that is readily available and in relatively abundant supply.

Bauxites suitable for use in refractory applications must meet very stringent physicochemical requirements. To satisfy the high temperature operating demands of quality refractory products, a high alumina, low iron oxide content bauxite, generally with a 2.5% maximum $Fe_2O_3$ content after calcination, is required. The alumina content, on a calcined basis, should be at least 86.5%, although it is often closer to 90%.

In order to keep the formation of low melting temperature glasses to a minimum, only trace amounts of alkalis and alkaline earths should be present in the raw ore. Excessive titania has an adverse impact on the high temperature properties of fired shapes, and the $TiO_2$ content commonly must be limited to a 4% maximum in the calcined product. The silica content ought to be low, but levels exceeding 10% may be acceptable; however, it should be present principally within a natural clay mineral and not as free quartz. The typical range of chemical compositions and related physical properties that various producers cite for their calcined refractory bauxites are characterised in Table 7.

The final market acceptance of a bauxite for refractory use is contingent upon the physical and chemical qualities of the commercial end product into which it is to be included or combined. The dimensional stability of fired refractories relies principally on the conversion of the contained alumina and silica within refractory raw materials to the highly stable corundum ($Al_2O_3$) and mullite ($3Al_2O_3 . 2SiO_2$) mineral phases of these oxides. Strict control of the feedstock grade and calcination process to achieve these physicochemical conversions, and to maximise the density of the materials on a consistent and unvarying basis are crucial to the production of quality refractory products.

### Economic considerations

The principal cost factors associated with the processing and production of calcined refractory grade bauxite are: acquisition of crude ore, labour wage rates, fuel charges, and transportation rates for the movement of the finished product to market.

Due to the high energy requirements associated with the processing of these materials, the sensitivity of calcined materials to fuel costs is of primary concern in the development and continued viability of refractory operations. This is demonstrated by the fact that the calcination phase of processing for a quality high- alumina calcined bauxite (85-90% $Al_2O_3$) requires approximately $13x10^6$ BTU per metric ton of product produced at a 1,700° C to 1,800° C calcining temperature.

In addition, economy of scale plays an extremely crucial role in the cost of production for such bulk mining enterprises, and low costs are usually associated with the highly developed infrastructure and mechanisation of large scale metallurgical bauxite mining operations. This effectively imposes a limiting factor on the number of economically viable non-metallurgical grade deposits capable of potentially providing refractory grade raw materials for major international markets.

**Table 4. Alumina silica refractory products**

| *Refractory type* | *Raw materials* |
|---|---|
| Low-medium alumina (30-50% $Al_2O_3$) | Flint and semi-flint fire clays, plastic and semi-plastic fire clays, kaolin and pyrophyllite |
| Medium-high alumina (50-70% $Al_2O_3$) | The andalusite-kyanite-sillimanite family of minerals, synthetic mullite, kaolin and various bauxitic clays |
| High alumina (70-90% $Al_2O_3$) | Natural bauxite-based materials (calcined). |
| Extra-high alumina (90-100% $Al_2O_3$) | Calcined Bayer-process alumina, tabular alumina, and fused alumina |

**Table 5. Typical chemical compositions and physical properties of calcined refractory bauxite[1,2]**

| | *Guyanese* | | *Chinese* | | *Brazilian* | *US high alumina* | |
|---|---|---|---|---|---|---|---|
| | *RASC[3]* | *85* | *80* | *75* | *Caracuru* | *70* | *60* |
| Alumina | 89.1 | 87.5 | 84.5 | 78.6 | 85-86 | 70.5 | 60.5 |
| Silica | 6.5 | 6.0 | 6.5 | 14.5 | 9.6-10.2 | 25. | 35.8 |
| Iron oxide | 1.25 | 1.5 | 1.5 | 1.2 | 1.8-2.1 | 1.4 | 1.31 |
| Titania | 3.0 | 3.75 | 4.0 | 3.5 | 1.6-2.2 | 2.68 | 2.25 |
| LOI | 0.15 | 0.2 | 0.2 | 0.2 | <0.10 | - | - |
| Bulk density | 3.15 | 3.1 | 2.8 | 2.7 | 3.2-3.3 | 2.85 | 2.8 |
| PCE | 40+ | 38 | 38 | 37 | - | 39 | 37 |

1. Standard producer product specifications. Grade based on alumina content.
2. All values except bulk density (g/cm$^3$) and PCE are in wt%.
3. Refracotry A-grade super calcined (Linden).

For refractory grade bauxite, as with most industrial minerals, the basic commodity price is a crucial factor in the economics of development and continued maintenance of product markets. The trade-off between price and product performance is a primary determinant in the choice of refractory grade bauxite, as opposed to various substitute materials in a variety of refractory applications. Examples of this price versus market tension are provided by synthetic mullite, created from kyanite and sillimanite, and refractory grogs, produced principally from kaolinitic clay, which constitute feasible product substitutes for medium-alumina-content bauxite-based refractories.

## Sources of supply

*(A full review of refractory grade suppliers appeared in IM March '95, p.27).*

A limited number of naturally occurring bauxites have been found to meet the stringent physical and chemical specifications expected of refractory grade bauxite, particularly within the very high-temperature fields encountered in most industrial applications. The highest quality materials have historically been supplied from South America, and in particular from mines in Guyana. As a result, because of its high quality, the RASC (Refractory A-Grade Super-Calcined) grade product from Guyana has frequently been used as a reference standard for comparison with calcined refractory bauxites from alternative sources of supply (*Table 5*).

In fact, until the late 1970s, refractory grade bauxite from Guyana amounted to approximately 80% of the world's supply of this product. At that time, a combination of labour, technical, and mining difficulties within Guyana led to a severe market shortage that was only alleviated through the large-scale introduction of refractory raw materials from China into the North American and European markets. This substitution in source of supply was accomplished through some fundamental compromises and product adjustments by the world's refractory materials users.

Chinese bauxite is composed primarily of diaspore [AlO(OH)], which has a greater hardness and, as a result, is more difficult to process, than the Guyanese ore, which is composed principally of gibbsite [$Al(OH)_3$] with subordinate amounts of boehmite [AlO(OH)]. In addition, green Chinese refractory bauxite ores contain more alkalis and alkaline earths than most refractory bauxites, resulting in the development of high glass levels within the final calcined product.

In recent years, with initial market penetration achieved, China has continued to expand the level of its calcined refractory bauxite exports and strengthen its market position to the degree that it has become a primary supplier of these high-alumina refractory raw materials to the US. After Guyana and China, other current sources of refractory grade bauxite are relatively minor.

Greece produces some material that has been used largely for domestic and European markets, and a few other countries such as Malaysia and India have limited production capacities. Production from Suriname, the third largest supplier to the US market in the early 1980s, ceased in 1983. In terms of current producer developments, some diversification of this restricted supply structure is beginning to occur, with export oriented refractory bauxite production capacity being developed and expanded in Brazil. The new Brazilian producers are currently testing the international export markets with their refractory product and some of the material has been imported into the USA in recent years.

**Table 6. US Imports of calcined refractory grade bauxite ('000s tonnes)**

| *Year* | *Source China* | *Guyana* | *Surinam* | *Other* | *Total[1]* |
|---|---|---|---|---|---|
| 1981 | 122 | 101 | 28 | <0.5 | 251 |
| 1982 | 55 | 52 | 22 | 2 | 131 |
| 1983 | 51 | 66 | - | - | 117 |
| 1984 | 78 | 110 | 1 | <0.5 | 190 |
| 1985 | 94[2] | 102 | <0.5 | <0.5 | 196 |
| 1986 | 112 | 109 | - | - | 221 |
| 1987 | 163 | 107 | - | - | 270 |
| 1988 | 103 | 98 | 5 | <0.5 | 206 |
| 1989 | 176 | 74 | - | 5 | 254 |
| 1990 | 126 | 84 | - | <0.5 | 210 |
| 1991 | 104 | 69 | - | 7 | 180 |
| 1992 | 174 | 54 | - | 9 | 238 |
| 1993 | 66 | 53 | - | 16 | 135 |
| 1994 | 153 | 25 | - | 2 | 181 |

1. Data may not add to totals shown because of independent rounding.
2. Excludes 75,496 calcined metric tonnes purchased for the National Defence Stockpile.

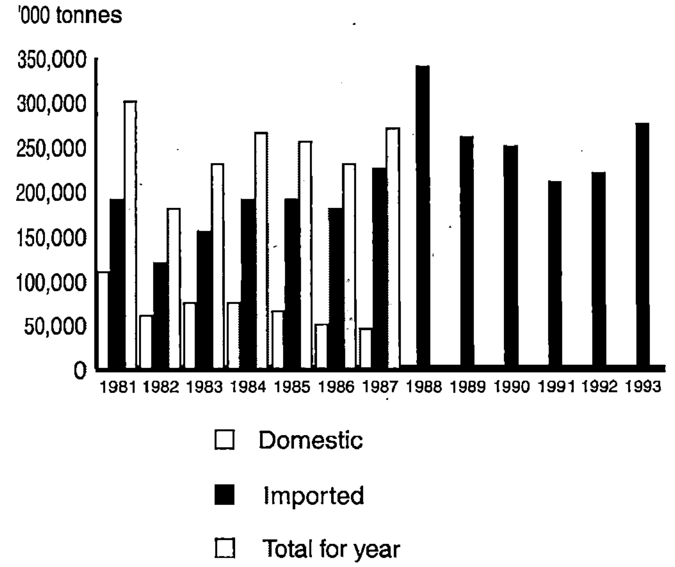

*Figure 2. Calcined bauxite consumption by US refractory industries*

However, Guyana has taken steps to regain a foothold in the world market (*see IM June '95 p.13*).

## Demand

Consumption of refractory grade bauxite in the market economies of the world is currently estimated to be between 700,000 and 800,000 tpa and, combined with demand from the former Soviet Union and China, total world consumption of bauxite for use in refractory applications is thought to be in excess of 1m. tpa.

Throughout the 1980s, the total annual consumption of calcined refractory grade bauxite in the USA by the refractories industry ranged from a low of 184,000 tonnes in 1982 to a high of 341,000 tonnes in 1988 (*Figure 2*).

Refractory grade bauxite has found wide application as a primary feedstock for the 60% to 90% alumina content category of refractory shapes and specialities (castables, plastics, and ramming mixes) largely in as much as it is the lowest cost, high alumina raw material that is readily available in abundant supply on the world's commodity markets. This usage by the refractories industry is closely tied to the production and consumption of primary metals, in particular iron and steel. On a worldwide basis, it is estimated that approximately 60% to 70% of all high alumina refractories are consumed by the iron and steel industry [8,14].

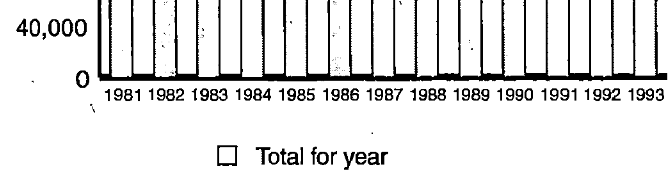

*Figure 3. Calcined bauxite consumption by US abrasive industries*

While the iron and steel industry remains the major market for refractory bauxite products, technological shifts over the last decade have resulted in the expanded use of higher performance speciality refractories, bringing about a marked decline in the consumption of refractories per ton of steel produced within the established steel producing countries of the world. These changes have occurred because of the transition away from traditional ingot casting methods of producing metal to the continuous casting means of steel making, with an accompanying increase in the employment of the basic oxygen furnace and the electric arc furnace within the ferrous metals industry.

Although overall demand for refractories in general has been projected to decline, as unit consumption continues to fall within the iron and steel industry, the outlook for alumina-based refractories remains somewhat more optimistic. A preference has developed for higher performance refractories, such as high alumina materials, and this has meant that these products have increased their market share over the more traditional lower alumina categories of refractories (fire clay, pyrophyllite, etc.).

**Table 7. Comparative analyses of calcined abrasive grade bauxite (%)**

| | *Australia* | *Guinea* | *China* | *Guyana* |
|---|---|---|---|---|
| Alumina | 82-85 | 88-90 | 86-90 | 85-88 |
| Silica | 4.5-5.5 | 1.2-3.0 | 6.0 | 6.5-9.0 |
| Iron oxide | 6-8 | 4-8 | 2 | 1.5-4.5 |
| Titania | 3.4-3.8 | 4-5 | 3-5 | 3.0-3.6 |

Source: Industrial Minerals, no. 252, pp. 67-83, Sept. 1988 Aluminium Verlag GmbH Roskill Information Services Ltd

## Prices

Prices of calcined refractory grade bauxite remained relatively stable during 1994, with only a slight decline in the prices of imported material. Domestic prices were estimated to be $195 to $200 per metric tonne in 1994.

The impact of the 1974 energy crisis, the initiation of a heavy assessment of bauxite levies by the International Bauxite Association (IBA) countries, such as Guyana, and the late 1970s and early 1980s refractory bauxite supply shortfall are readily evident in the progression of these reported commodity price fluctuations. During the supply shortfall, prices for Guyana RASC reached a peak of more than $235 per metric tonne in early 1981 and remained above $200 per metric tonne throughout most of the early 1980s. Although, after that time prices lingered at just below $165 per metric tonne from 1984 until late 1989, before rebounding to $175 per metric tonne in 1990, a market quotation that is still current, (as of July 1995). For a full review of refractory grade prices, refer to *IM March '95, p.27*.

## Abrasive applications

Fused aluminium oxide abrasive grain (artificial corundum) is produced by the electrofusion of either Bayer-process alumina or calcined bauxite (*Figure 1*). In both instances, fusion is accomplished in electric arc furnaces at temperatures in excess of 2,000°C, with the only difference being the resulting end product. Calcined, high-purity, Bayer-process alumina provides the feedstock for the production of white abrasive grain. White fused alumina contains 99.5% to 99.9% $Al_2O_3$. Fusion of calcined abrasive grade bauxite on the other hand produces brown fused alumina (*Figure 1*). Brown fused alumina normally contains between 94% and 97% $Al_2O_3$.

Abrasive grade bauxite, the feedstock for brown fused alumina, is prepared from low silica, low alkali material that is calcined at temperatures of approximately 1,100° C, lower than the firing temperature normally used for refractory grade bauxite but high enough to ensure that the calcined product does not readily reabsorb moisture to reform hydrated compounds.

The calcined bauxite is then electrofused in the presence of ground coke and iron borings that aid the electromelting process and facilitate the removal of impurities by electromagnetic separation. Fusion takes place at temperatures above 2000° C; 2,750 to 4,400 kWh of energy are required per tonne of brown fused alumina.

As indicated, the process requires the addition of special additives to the electric arc furnace in order to form a ferro-silicon slag that scavenges impurities. A source of carbon is needed to act as the reductant for the oxides of iron and silicon to form the slag, and coke is the preferred source. The iron content is adjusted by the addition of iron borings and the ferro-silicon usually contains about 16-18% silicon (Si). The magnetic susceptibility of ferro-silicon provides an efficient means of separating it and its associated impurities from the fused alumina product. This separation is achieved by passing the crushed artificial corundum through magnetic separators.

Both physical and chemical criteria are used to determine if a calcined bauxite meets the specifications required for the production of brown fused alumina. As in the case of refractory grade bauxite, the most critical chemical components are: alumina, silica, iron oxide, titania, alkalies, and moisture - as both free and chemically combined hydroxyl (OH) groups.

To maximise the efficiency of the electrofusion process, the alumina content of bauxites used for abrasive applications should be as high as possible and a minimum $Al_2O_3$ content of 80% on a calcined basis is normally required for this application. Even though the mineralogy of the bauxite itself is not of major significance, gibbsitic bauxites generally comprise the major portion of the feedstocks to this industry. Silica is the most significant impurity and very costly to remove. In general, the upper limit on the silica content in calcined abrasive grade material is 7%.

Unlike refractory grade bauxite, the iron oxide content is not as critical and it can even reduce the need for iron additives for ferro-silicon formation provided that the $Fe_2O_3$ to $SiO_2$ ratio does not exceed 3 to 1, although it is reported that the optimum ratio for this grade is closer to a value of 2 to 1. Titania, which is invariably present in bauxite, ideally needs to be in the range of 2-4%. If the $TiO_2$ content is too low, the corundum crystal structure is affected and the toughness of the fused alumina grain is impaired. Alternatively, if the titania content is above the 4% threshold level it must be eliminated in the ferro-silicon phase, which is exceptionally costly. As with refractory grade bauxites, low concentrations of alkalis are a requisite of abrasive grade material in order to minimise the formation of a glass phase.

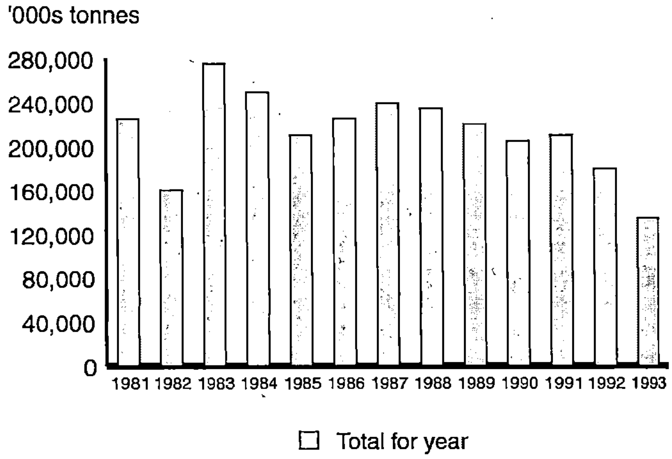

*Figure 4. Calcined bauxite consumption by US abrasives industries*

This phenomenon is of particular significance if the calcium oxide (CaO) content rises over 0.1%. The presence of moisture or chemically combined hydroxyl groups can be a potential hazard leading to the possible explosive generation of superheated steam. Therefore, the loss on ignition (LOI) of the calcined bauxite should not exceed 1%, and covered storage is commonly used for abrasive grade feedstocks. A comparison of the chemical composition of a variety of calcined abrasive grade bauxites is provided in *Table 8*.

Besides these strict chemical specifications, abrasive grade bauxite also must meet certain physical criteria. As previously mentioned, the calcined abrasive grade feedstock should have been fired at temperatures high enough to ensure that the calcine

**Table 8. US imports of calcined non-refractory grade bauxite ('000s tonnes)**

| *Year* | *Source*<br>*Australia* | *China* | *Guyana* | *Surinam* | *Other* | *Total*[1] |
|---|---|---|---|---|---|---|
| 1981 | 15 | 12 | 35 | 6 | <0.5 | 68 |
| 1982 | 10 | 18 | 17 | 14 | <0.5 | 59 |
| 1983 | 8 | 14 | 22 | 47 | 1 | 92 |
| 1984 | 24 | 18 | - | <0.5 | <0.5 | 42 |
| 1985 | 23 | 41 | 4 | <0.5 | <0.5 | 69 |
| 1986 | 14 | 48 | 9 | 11 | <0.5 | 83 |
| 1987 | 6 | 10 | 22 | 4 | <0.5 | 43 |
| 1988 | 20 | 152 | 15 | - | <0.5 | 188 |
| 1989 | 8 | 147 | 96 | - | 26 | 277 |
| 1990 | 14 | 173 | 52 | - | 108 | 348 |
| 1991 | 16 | 96 | <0.5 | - | 5 | 117 |
| 1992 | 8 | 88 | - | - | 13 | 108 |
| 1993 | 12 | 86 | - | - | 4 | 102 |
| 1994 | 7 | 137 | 12 | - | 25 | 180 |

1. Data may not add to totals shown because of independent rounding.

does not readily reabsorb moisture to reform hydrated compounds prior to its fusion in an electric arc furnace. Particle size is especially critical for abrasive production. The upper limit on particle size is 50mm with the lower threshold set at 100 mesh screen size. If the material is too coarse, complete calcination may not be achieved, and any material finer than 100 mesh is likely to create dusting problems, resulting in material losses during handling, transportation, and fusion.

### Sources of supply

The principal sources of abrasive grade bauxite are Australia, Guinea, China, Guyana, and Greece in relative order of importance.

Collectively these countries presently supply the majority of the world's abrasive grade bauxite. Until 1987, Surinam was also an important supplier of abrasive grade bauxite to the United States but has withdrawn from the market.

### Demand

Currently, worldwide demand for calcined abrasive grade bauxite is estimated at approximately 0.8m.—0.9m.tpa. Through the 1980s and into the 1990s the total annual consumption of calcined abrasive grade bauxite in the USA by the abrasives industry has ranged from a low of 88,000 tonnes in 1983 to a high of 213,000 tonnes in the following year (*Figure 4*).

## Cement applications

### High-alumina cement

Aluminous cement differs from standard Portland cement both in its chemical composition and its end uses. The raw materials employed to produce high-alumina cements are normally bauxite and limestone, whereas Portland cement uses aluminous clay or shale, rather than bauxite. As a consequence, high-alumina cement consists of calcium aluminates as opposed to aluminosilicates and it is often termed calcium aluminate cement. The typical range and associated differences in chemical compositions encountered within calcium aluminate and Portland cements are shown in *Table 9*.

Concretes made with high-alumina cements are characterised by their rapid setting times, as low as 2-4 hours, with structural strength developed within 24 hours as compared with conventional Portland cement based concretes that may require several days to harden.

Fundamentally, there are two principal types of high-alumina cement: low and high iron. Both varieties can be used in castable refractories with operating temperatures up to 1,200°C. The high-iron type, often termed *Ciment Fondu* when used in conjunction with a suitable aggregate such as a refractory grog, can be employed as a refractory cement and mortar that retains its integrity up to 1,300°C. These high-alumina cements are also resistant to chemical attack by corrosive agents (ie., salt water, etc.). In addition to the above mentioned cements there is also a variant of Portland cement known as blast furnace cement derived from the aluminous slag produced as a co-product of the iron industry.

The bauxites used in high-alumina or calcium aluminate cements range considerably in chemical composition. The primary chemical determinant affecting the selection of a bauxite for use in high- alumina cement is the silica content, or more precisely the alumina to silica ratio. A high silica content hampers the rapid hardening properties of the cement. This means the silica content must be controlled and a typical requirement is that the $Al_2O_3$ to $SiO_2$ ratio should be at least 10:1, which normally excludes bauxites containing more than 6% $SiO_2$ from use in high-alumina cements. For the low-iron compositions it is common to specify an iron oxide content of less than 2.5%, while for the high-iron grade (Ciment Fondu) contents of 25% may be acceptable in certain applications, although the norm lies in the 10-18% range. The iron contributes to the hardening properties and acts as a flux, but if present in excessive amounts it may have adverse effects on the cement's refractoriness and overall strength.

The methods employed to produce high-alumina cement dictate the physical requirements of the bauxites used as feedstocks to this industry. In some processes using rotary kilns, where the bauxite is ground and mixed with limestone before sintering, particle size of the bauxite is of minor importance. On the other hand, one method for manufacturing the high-iron Ciment Fondu involves charging a mixture of coarse, lumpy, monohydrate-type bauxite (boehmite or diaspore) with limestone and coke into a vertical shaft/reverberatory furnace where rising volatiles from the fusion hearth pre-heat the descending feed. The molten furnace discharge is cast into pigs that are subsequently ground and size classified.

This operation is dependent upon coarse feed (50-100mm) to prevent channelling of the hot gases in the shaft furnace. As indicated, boehmite or diaspore are normally selected because of their low loss on ignition (LOI), which results in lower levels of disintegration and thereby presents less interference with gas flow through the furnace feed. Economic concerns provide another impetus for selecting monohydrates because they customarily have free and chemically combined moisture contents of 15-17% compared with the normal 35-40% for gibbsitic bauxites. This has an obvious impact upon the materials handling and transportation costs incurred by cement manufacturers.

The alumina content of low-iron type, high-alumina cements, normally ranges from 50-57% $Al_2O_3$, which is slightly above the levels found in the high-iron, Ciment Fondu, types. Silica also can be tolerated in quantities similar to that permitted in the high-iron grade material, typically 4-6%. The most striking difference in chemical composition between the low- and high-iron grades is in their iron oxide content. The maximum acceptable amount of $Fe_2O_3$ allowed in the low-iron type may reach 3%, although it is actually more commonly maximised at 2.5%. This translates into a minimum $Al_2O_3$ to $Fe_2O_3$ ratio of 20:1.

The titania content is also of significance for this material with a minimum $Al_2O_3$ to $TiO_2$ requirement of 16:1. While the high-iron grade is usually produced in oil fired shaft/reverberatory hearth furnaces, the low-iron type is ordinarily produced by fusion in electric arc furnaces. Therefore, finer sized bauxite feed can be used to manufacture this product and it has been found that optimum results are obtained using calcined bauxite.

### Portland cement

The essential raw materials for Portland cement are limestone and high-alumina clay or shale. In some cases, the alumina content of the clay or shale feedstock is too low for the formation of the required mineral phases during sintering of the cement and, therefore, bauxite is used to upgrade the feed. The critical parameter applied to determine the suitability of a raw bauxite for this application is the $SiO_2$ to ($Al_2O_3$ + $Fe_2O_3$) ratio commonly known as the silica modulus, which in this case should ideally be about 2.6 to 2.8.

Beyond the use of bauxite to increase the alumina content within the raw materials employed to produce Portland cement, there are several other very compelling explanations for why the cement industry has turned to bauxite as an additive in the manufacture of this product. By using low-silica bauxite, the industry is able to utilise low-grade, high-silica limestone that has previously been classified as sub-grade material and in turn this has greatly increased the limestone reserves available for use as feedstocks to the Portland cement industry.

Additionally, a reduction in alkali content can be achieved by using a bauxite feed that in return allows a broader range of

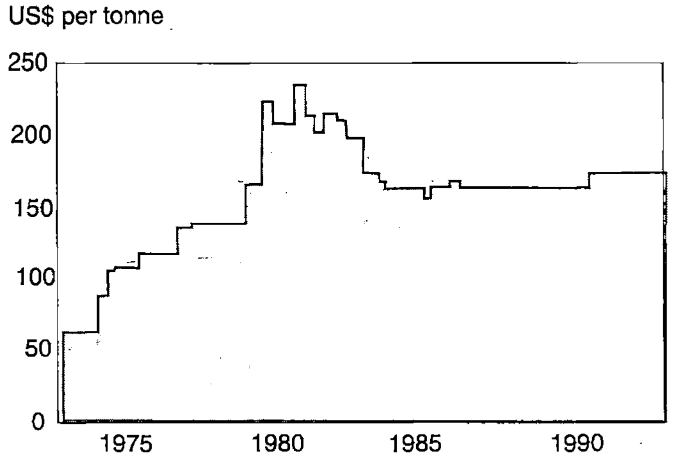

*Figure 5. Market quotations — US imports refractory grade bauxite (RASC) from Guyana*

reactive aggregates to be incorporated into the final concrete mix. Besides these factors, other advantages include improved kiln control and increased product uniformity, improved materials handling, and a reduction in freight costs.

## Chemical applications

The most direct use of bauxite in the chemicals industry is in the production of aluminium sulphate (alum), which is used principally as a flocculating agent in water and effluent treatment. This chemical application is derived from the fact that polyvalent ions such as $Al^{3+}$, and to a lesser degree $Fe^{3+}$, have the capacity to function as flocculating and coagulating agents. The trivalent aluminium ion is normally favoured over the ferric species due to its greater flocculating capability and absence of colour.

This compound is ordinarily produced by dissolving high-quality speciality grade bauxite in sulphuric acid ($H_2SO_4$) and only certain types of bauxite are amenable to this acid treatment. The solubility of gibbsite in $H_2SO_4$ is significantly higher than that of boehmite and, therefore, gibbsitic bauxites are commonly used for this application. Diaspore is relatively insoluble in sulphuric acid, except at temperatures around 300° C. The kaolin that is often present in bauxites also dissolves at a rate comparable with gibbsite; in fact, kaolin also can be used as a feedstock to produce aluminium sulphate. A much purer chemical form of aluminium sulphate, free from iron contamination, is often produced by direct acid treatment of Bayer-process aluminium hydroxide (*Figure 1*). This product is also utilised for water treatment purposes and, additionally, as a sizing agent in the paper industry.

Some of the other principal chemicals that theoretically can be manufactured from bauxite are aluminium chloride, aluminium fluoride, and sodium aluminate, although the preferred feedstock for the higher purity forms of these chemicals is, once again, aluminium hydroxide derived from the Bayer process (*Figure 1*).

The most significant requirement for a chemical grade bauxite is that its acid-soluble iron oxide content should be low. Chemical manufacturers customarily specify a maximum $Fe_2O_3$ content of 2-2.5%, or an $Al_2O_3$ to $Fe_2O_3$ ratio of about 23:1 or higher. Nonetheless, this is not an extremely stringent specification and it is totally dependent on the ultimate end use of the material, because much greater iron oxide levels may be tolerated in some water and effluent treatment applications. Even less crucial is the silica content because silica separates out as an insoluble residue during the acid digestion process. In practice, the chemical industry often utilises bauxites with silica contents exceeding 15% for this particular application.

Another special type of chemical grade material is prepared by low temperature roasting (400-800°C) of low-iron gibbsitic bauxite. The resultant product is a residue of coarse, abrasion-resistant particles that retain only 4-10% chemically combined moisture. As this is a reversible process, the "activated" bauxite readily recombines or adsorbs moisture. This makes activated bauxite an excellent drying agent for gases and organic liquids. In fact, this partially dehydrated material is also known for its high surface area that greatly contributes to its reactivity and enhances its use as an adsorbent for sulphur and fluorine based compounds.

Activated bauxites are commonly used as decolorising and moisture removal agents for the food and chemical processing industries. However, activated bauxite's use as a Claus catalyst for sulphur removal from sour gas in the petroleum industry has been mostly superseded by purer activated aluminas produced directly from Bayer-process aluminas.

## Demand

At present, worldwide demand for chemical grade bauxite is roughly estimated at about 500,000 to 600,000 tpa. Through the 1980s and into the 1990s the total annual consumption of chemical grade bauxite in the USA for direct use within the chemicals industry has ranged from a low of 169,000 metric tonnes in 1982 to a high of 281,000 metric tons in 1983 (*Figure 5*).

**Table 9. Comparative chemical analyses of high alumina & Portland cements**

| | *High alumina cement* | | *Portland cement* |
|---|---|---|---|
| | *low iron* | *high iron* | |
| Calcium oxide | 34-40 | 30-40 | 58-67 |
| Silica | 4-6 | 3-8 | 19-26 |
| Alumina | 50-57 | 38-56 | 4-11 |
| Iron oxide | 1-3 | 10-18 | 2-5 |
| Titania | 0.5-2.5 | 0.5-2.0 | 0.5-1.0 |
| Magnesia | 0-1 | 0-1 | 0-5 |
| Sulphur trioxide | 0-1 | 0-1 | 0-2.5 |

Source: SME, Bauxite (1984), W.H. Andrews

## Special applications

### Slag adjuster

The iron and steel industries commonly use additives to control the viscosity of slags. There are two principal areas in ferrous metallurgy where bauxite may be used as a slag adjuster. The primary use is in iron making, where bauxite is added to control the desulphurisation capacity and fluidity of the slag and at the same time provide feed for the manufacture of blast furnace cement. In addition, raw bauxite is also used to control the viscosity of slags during the production of steel. In general, monohydrates (boehmite or diaspore) are favoured for these applications. Western world consumption of bauxite in steelmaking is estimated to be in the region of 350,000 to 400,000 tpa.

Most bauxites used as a flux in iron and steel making must be high in alumina content, usually greater than 55%, and low in silica content. The maximum tolerable $SiO_2$ content commonly is 7%. Not surprisingly, for use in the iron and steel industry, sulphur and phosphorus should not be present in anything other than trace amounts. A low moisture content, both free and chemically combined, is also desirable.

### Proppants

Proppants, or propping agents, are associated with hydraulic fracturing, employed in the oil and gas industry to enable hydrocarbon recovery from deep petroleum reservoirs. In the hydraulic fracturing procedure, oil or gas held at great depths in tight rock formations is released by using high pressure fluids to crack open the host strata. Grains of sand or other materials, known as proppants, are usually introduced into the fractures to keep them open and provide permeable structures through which the gas or oil may migrate and be collected by a recovery well. For shallow reservoirs, selected quartz sands with high natural sphericity and roundness are sufficient to resist the loading pressure of the overlying rock. At greater depths, in excess of 3,000m, quartz proppants are unable to prevent fracture closure and sintered bauxite is chosen for these applications.

The general chemical specifications for bauxites used in the manufacture of proppants are as follows: high alumina content, low silica, low clays, and iron oxide content not critical. The bauxite is ground to a particle size of less than 12µ and then agglomerated into very small spheres prior to being sintered at around 2,000°C. The sintering process forms randomly oriented alpha alumina crystals that provide the material with its toughness and high bearing strength. In order to provide a product with maximum permeability, the proppant is screened into a restricted range of particle sizes, extending from 6 to 80 mesh screen size (3.35 to 0.8mm). The most frequently used size is the 20 to 40 mesh (0.85 to 0.425mm) range.

## Miscellaneous minor applications

In addition to the uses already described, there are some minor applications that require calcined bauxite feedstocks. While the principal applications of calcined bauxite remain in the refractory and abrasive industries, a few other very specialised commercial uses have been developed for this fired material, among which are welding flux materials and road surface aggregate. In total, these speciality end uses comprise a very small share of the entire non-metallurgical grade market.

Techniques for submerged arc welding require the use of a granular flux to shield the molten weld pool from the atmosphere during the weld's application or placement. Various proprietary compositions exist and in some cases calcined bauxite is incorporated into these formulations. Calcined bauxite may in some instances comprise up to 25% of the welding flux. In this special end use the most crucial specification involves the residual moisture content after calcination. It is mandatory that the moisture content should not exceed that allowed for calcined refractory grade material, ie., 0.5%. The reason for this rigorous requirement is the potential of any moisture present within the flux to reduce to hydrogen, if it is exposed to a welding arc. Should this occur and, if the hydrogen is absorbed by the molten weld pool, it will induce brittleness into the weld. Likewise, tight specifications also govern the presence of sulphur and phosphorus, which are detrimental to the weld. When present at high concentrations they induce porosity and cracking, and at lower concentrations they adversely affect the impact strength of the weld.

Another very special but, nevertheless, potentially significant market for calcined bauxite is as a special anti-skid road aggregate. This use was originally developed in the United Kingdom and has been researched for over two decades. As this anti-skid material is the most expensive form of road aggregate, the calcined bauxite-epoxy resin mix is just used at the most crucial locations to prevent accidents. This special application for calcined bauxite has seen only limited use in US markets.

## Outlook

The principal end uses of non-metallurgical grade bauxite are directly related to the production and consumption of raw materials for basic heavy industry, such as primary metals, cement, chemicals, ceramics, etc. This serves to make the demand for speciality bauxites cyclical, as they are directly tied to the basic movements of heavy industry, the "smokestack" component of the national economy, a trend that is expected to continue well into the future.

In the case of refractories, the largest market for non-metal bauxite, the outlook for possible future growth lies in the development of more advanced refractories with increased product longevity or greater endurance within very harsh high temperature environments. More sophisticated and demanding applications are being developed throughout the world for refractories via the modernisation of primary metal production processes (iron, copper, etc.) and this will be a major driving force to stimulate demand for high quality calcined bauxite products within the refractories industry in the future.

As with all industrial minerals, an intense competition for markets exists throughout the entire spectrum of non-metal applications for bauxite. This condition will continue and intensify over time as more sophisticated applications are developed for alumina-based materials. For the top end and high quality markets, bauxite will remain under sharp pressure from Bayer-process aluminas.

New major suppliers to the world market, such as Brazil, will help diversify the sources of world supply and insure the existence of a stable long term raw material resource base for the coming century.

While the long term outlook for growth in the more sophisticated and higher quality non-metallurgical grade bauxite uses appear to be promising, the major influence on future demand is envisioned to be the strength and vitality of the general economic structure of the world's industrialised countries and their heavy industries. Non-metallurgical grade bauxite use is closely tied to basic industry and it will remain so well into the future.

### References

A full list of references is available from the author on request.

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