

SUCCESSSES AND CHALLENGES IN THE MANAGEMENT AND USE OF BAUXITE RESIDUE

Ken EVANS [*Keynote Speaker*]

Consultant International Aluminium Institute, c/o 10 King Charles II Street, London, SW1Y 4AA, United Kingdom

ken.evans111@btinternet.com

Abstract

In spite of over century of effort looking for uses, over 1200 patents and hundreds of technically successful trials, less than 4 million tonnes of the 140 million tonnes of bauxite residue produced annually is used in a productive way. A large proportion of material that is used, is in China and driven by government pressure. This paper reviews the barriers and why the technical successes do not always translate into large scale uses. The most successful large scale uses are then discussed and include cement production, raw material for iron and steel manufacture, manufacture of building materials, landfill capping, road construction and soil amelioration.

Introduction

The paper serves as a brief overview of the developments in the management and use of bauxite residue, outlining: the dimensions of the problem; how methods of storage and disposal have changed over time and the implications for bauxite residue use; characteristics of bauxite residue; the technically successful uses; the challenges to implementation – real and perceived; a review of large scale/industrial scale successes; some hopes for the future.

Scope and Description of the Challenge

Annual production of smelter grade and chemical grade alumina in 2014 was some 108 million tonnes equating to some 140 million tonnes of bauxite residue/red mud. This is generated by some 60 active Bayer plants and there are at least another 50 closed legacy sites; together the active and legacy sites contain an estimated three thousand million tonnes of bauxite residue. Note that bauxite residue or red mud has been called a variety of names by various companies, sometimes after additional treatment and some of the names are registered trademarks: “Bauxaline®”, “Alkaloam™”, “Red Oxide Sand”, “Red Sand™”, “Ferraloks”, “Bauxsol®”, “ReadyGrit™”, “BPR – Bayer Process Residue”, “ARR – Alumina Refinery Residue”,

and “RMG”. Bauxite residue is arguably a more inclusive name as some alumina refineries separate the coarse high silica sandy fraction from the fine muds; some of the muds are brown rather than red; and some diasporic derived residues are almost black in colour. However, the name “red mud” tends to be more commonly used in North America and Europe.

Management of the disposal of bauxite residue has evolved progressively over the decades. In the early Bayer alumina plants, the residue generated was often merely piled up on site or immediately adjoining to the alumina plant. Occasionally nearby depleted mine sites, sometimes bauxite or coal mines, and quarries were used; in other situations nearby estuaries or sea lagoons were used and then later as the closest convenient areas were filled, valleys were dammed to contain the ever growing volume of residue.

This was especially true of the early European sites such as Bergheim (Germany), Burntisland (UK), Gardanne (France), La Barasse (France), Larne (UK), Ludwigshafen (Germany), Newport (UK), Salindres (France), and Schwandorf (Germany).

Prior to 1980, most of the inventory of bauxite residue was stored in lagoon-type impoundments and the practice is still carried out at some facilities. In this method, the bauxite residue slurry from the mud washing circuit is pumped, with a solids content of 20 to 30 %, into storage areas created by dams and other earthworks for secure containment. In many instances valleys were dammed (Ewarton (Jamaica), Gardanne, Ouro Preto (Brazil), Saint Cyr (France), Salindres) or former lignite mines (Bergheim), bauxite mines (Kirkvine (Jamaica), Bauxite (USA)), or oil shale quarries (Burntisland) were used. In the past three or four decades the storage areas have normally been sealed to minimise leakage to the underlying ground and groundwater. This, however, tended not to be the practice in the earlier years when no attempt to seal them was undertaken. Sealing approaches cover a range of materials including compacted clay and/or the use of plastic and other membrane materials.

The supernatant liquor was normally returned to the plant for reuse, thereby recovering some of the caustic soda value and avoiding contaminating the environment. Various drainage and seepage collection systems have been incorporated into the design and construction of the facilities. The construction of the storage area was often dictated by the type of bauxite residue and differed for clay like muds compared to more sandy residues. At Gramercy (USA), sand-bed filtration was used and “French Drains” were used with drainage pipes and covering layers of sand of different size and gravel to give permeability through the base of the lake. This was termed the DREW (Decantation, Drainage and Evaporation of Water) system. In some cases low dykes or levees were built to create areas for

storage, the impoundment was filled and the height of the dyke/levee walls were then increased. In other cases, the levees were built to the final expected height at the start and a new area constructed when more volume was required. The area of suitable land readily available dictated the approach.

If the residue material is not neutralised before discharge to the storage lagoon, it becomes a highly alkaline, poorly compacted mud area covered by a highly alkaline lake. This creates safety and environmental hazards including the potential for contact of humans and wildlife with alkaline liquor and mud, and contamination of surface and ground waters by leaching of caustic liquor and other contaminants. Regrettably, in many cases these early ponds have proved of limited efficacy and caustic liquor, plus other contaminants, has subsequently seeped into the surrounding environment. Ongoing remediation of these situations is proving to be a costly exercise.

Addressing the risk and to eliminate the potential for catastrophic failure of the dam/impoundment and consequent environmental hazard to the surrounding area/communities introduces high monitoring, maintenance, and remediation costs. Under some circumstances, this has created the prospect of an indefinite legacy.

Another disposal technique adopted by some plants was sea or river disposal particularly in the 1940s to 1960s. In at least six plants, two located in France, one in Greece and three in Japan, bauxite residue was discharged into the sea either via pipelines or from ocean going vessels. Other alumina plants disposed of the residue into rivers or estuaries, for example into the Mississippi River, and Severn Estuary. In other cases in Ireland, Wales and Scotland, land was reclaimed from the sea by disposing of the residue in tidal lagoons or behind sea walls. River discharge is no longer undertaken at any alumina refining facilities and of sea discharge will be completely phased out by the end of 2015.

As land for disposal became scarce for many plants, “Dry stacking” methods were used. They were adopted to a limited degree nearly 75 years ago in the UK but since the 1980s the trend has been towards dry stacking to reduce the potential for leakage of caustic liquor to the surrounding environment, reduce the land area required, and maximise the recoveries of soda and alumina. Additionally, improved methods for thickening and washing of the residues prior to storage, and recovery of decant water during storage, have been developed to increase the recovery of valuable soda and alumina to the Bayer process plants and to minimise the potential for leakage to the surrounding environment.

The current trend in residue storage practice is towards increasing use of dry stacking as the preferred technology, and further research to optimise this technology is appropriate. Partial neutralisation using seawater is practiced at a number of Australian plants close to the sea (Yarwun and QAL); carbonation by using waste carbon dioxide from ammonia production has been used (Kwinana (Australia)); and accelerated carbonation using intensive farming methods (Aughinish (Ireland), Kwinana, Worsley (Australia)) is showing considerable benefits.

Filtration using drum filters and plate and frame filter presses to recover caustic soda, produce a lower moisture and more handleable bauxite residue have been employed since at least 1941 but is now growing in usage. This trend opens up considerable benefits in terms of reuse as the material is normally produced as a friable cake, with typically less than 28 % moisture, and lower soda thereby dramatically reducing transport costs. Alunorte (Brazil), Distomon (Greece), Gardanne, Kwinana, Seydisehir (Turkey) and many plants in China have already adopted or plan to adopt plate and frame filter presses.

The appalling and tragic incident at the bauxite residue ponds adjacent to the Ajka alumina refinery in Hungary in October 2010 when some 600,000 to 800,000 m³ of caustic red mud slurry inundated the village of Kolontar and flowed into the Torna Creek, Marcal and Raba rivers had a significant effect on the alumina industry. The producers, via organisations such as the European Aluminium Association and International Aluminium Institute (IAI), have since worked collaboratively to look for improved solutions and propose best practice guidelines which were published in a guideline document.¹ The IAI continues to encourage collaborative effort on improving storage, monitoring, safety standards, looking at improved remediation techniques and reuse opportunities. In 2011 the International Aluminium Institute issued a set of objectives for IAI members to meet.² Key messages coming out of the best practice reviews have been the drive to dispose of bauxite residue in a safer way with lower caustic and higher solids content. These moves will encourage the utilisation of residue as the material produced will be in a more acceptable form for transport, handling and reuse.

Reuse of bauxite residue has for long featured in the thinking of Bayer plant operators but in spite of over a century of endeavour and trials, only some 2 to 3 % of the 140 million tonnes of bauxite residue produced annually is used in a productive way. Thousands of trials have been successfully completed and dozens of uses have been identified as being technically feasible but the challenge remains to find good economically viable uses for the amount generated every year let alone eat into the material already stockpiled.

The bauxite residue disposal costs for a plant are obviously very dependent on the availability of a suitable disposal site, the distance from the plant to the disposal area and the method of conveying used (by pumping, conveyor or truck). It should be noted that pumping over long distances can be achieved, even in excess of 50 km. Residues from different bauxite also behave quite differently in terms of composition, mineralogy and particle size. They will have different handling and pumping characteristics; display widely different settling and particle packing characteristics thereby influencing moisture contents after treatment and handling costs. The variation in composition naturally has an overriding effect on potential applications so any practical work looking at applications must take into account the specific chemical composition, mineralogy, pH, particle size distribution, morphology and nature of the residue emanating from a particular plant.

There is little published on the cost of disposal of bauxite residue but it is generally estimated to be between 1 and 3 % of the total production cost, perhaps 4 to 12 USD. This is lower than often expected and must be borne in mind when potential uses are considered. In the absence of landfill taxes, which for example were introduced on bauxite residue in the UK in 1996, most companies have been reluctant to spend more than is required to comply with the law and ensure storage is undertaken safely in a manner that does not pollute the surrounding environment and the area can subsequently be restored. Whilst there will be enthusiasm to reflect the desire of the company to present a 'green' and 'sustainable' corporate image, the utilisation opportunity must make economic sense, or at least close to, for resources to be committed. Corporate attitudes have changed dramatically over the past 10 years, reflecting growing community awareness and to meet the demands of concerned shareholders and NGOs, and producers now have a more holistic attitude to resolving the problem and reducing the area given over to residual disposal areas. It should be noted that funding research in reuse projects is rarely the problem but implementing the activity industrially is the issue.

Despite the increasing trend to higher solids contents and lower soda contents, one retrograde factor with respect to generation of bauxite residue is the current shortage of high quality, easily extractable, high alumina bauxite sources – this has the effect of driving up the amount of residue produced per tonne of alumina produced.

Bauxite Residue Characteristics

The key first steps in considering uses is a review of the chemical compounds present in the bauxite residue, the levels present and the physical characteristics of the material. As discussed, the variation in composition is extremely wide as shown in

Table 1; these are for commonly used bauxites and the complete range can be even wider for some unusual bauxites.

Table 1: Chemical composition, expressed as oxides, commonly found in bauxite residue

Component	Typical range (wt%)
Fe ₂ O ₃	5 - 60
Al ₂ O ₃	5 - 30
TiO ₂	0.3 -15
CaO	2 - 14
SiO ₂	3 - 50
Na ₂ O	1 - 10

A wide range of other components may also be present at low levels; these will invariably be as metallic oxides, e.g. arsenic, beryllium, cadmium, chromium, copper, gallium, lead, manganese, mercury, nickel, potassium, scandium, thorium, uranium, vanadium, zinc, zirconium, and rare earth elements. Non-metallic elements that may occur in the bauxite residue are phosphorus, carbon, and sulphur.

Sodium is the only element not found in the bauxite itself; some of the elements are soluble in the Bayer process and either build up in the Bayer liquor, or precipitate along with the aluminium hydroxide. Depending on the temperature used in the extraction process, some elements will increase in concentration in the bauxite residue relative to the bauxite, whilst others will be lower in the bauxite residue. Other than caustic soda, lime is normally the only other inorganic compound introduced during the Bayer process.

The minerals present are complex and comprise some which are present in the bauxite and others that are produced during the autoclaving and the desilication processes. The range of minerals typically found for bauxite residues is shown in Table 2.

In addition there are various other minerals sometimes found at low levels including Brookite, Calcite, Carnegieite, Chantalite, Dolomite, Hydrogarnet, Hydroxycancrinite, Katoite–Si, Lawsonite, Nepheline, Nosean, Portlandite, Schaeferite, sodium titanate, and zircon.

A wide variety of organic compounds can also be present, these are derived from vegetable and organic matter in the bauxite/overburden or the use of crystal growth modifiers or flocculants and includes carbohydrates, alcohols, phenols, and the

sodium salts of polybasic and hydroxyacids such as humic, fulvic, succinic, acetic, or oxalic acids.

Table 2: Typical range of components found in bauxite residues

Component	Typical range (wt%)
Sodalite ($3\text{Na}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{Na}_2\text{SO}_4$)	4 - 40
Goethite (FeOOH)	10 - 30
Haematite (Fe_2O_3)	10 - 30
Magnetite (Fe_3O_4)	0 - 8
Silica (SiO_2) crystalline and amorphous	3 - 20
Calcium aluminate ($3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{H}_2\text{O}$)	2 - 20
Boehmite (AlOOH)	0 - 20
Titanium Dioxide (TiO_2) anatase and rutile	2 - 15
Muscovite ($\text{K}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot 2\text{H}_2\text{O}$)	0 - 15
Calcite (CaCO_3)	2 - 20
Kaolinite ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$)	0 - 5
Gibbsite ($\text{Al}(\text{OH})_3$)	0 - 5
Perovskite (CaTiO_3)	0 - 12
Cancrinite ($\text{Na}_6[\text{Al}_6\text{Si}_6\text{O}_{24}] \cdot 2\text{CaCO}_3$)	0 - 50
Diaspore (AlOOH)	0 - 5

In addition, the bauxite residue will contain small quantities of some of the soluble sodium compounds resulting from the sodium hydroxide used in the extraction process, depending on the dewatering and washing systems used. All alumina refineries try to maximise the recovery of the valuable caustic soda from the residues in order to reuse it during the extraction process. The residual soluble sodium species, predominantly a mixture of sodium aluminate and sodium carbonate, give rise to an elevated pH for bauxite residue slurries. Over time the residual sodium species are partially neutralised by carbon dioxide from the air to form sodium carbonate and other metal carbonate species; these species will result in a lower pH for the bauxite residue which renders them less hazardous.

The other factors that are important when considering uses are the physical characteristics such as particle size distribution and some variable parameters such as moisture content. The breadth of particles is both very broad and very different between bauxite residues produced from different alumina plants and different bauxites; coarse sandy grains about 1 mm in size down to sub-micron particles. Some alumina refineries separate the different size fractions during processing whilst others do not; the coarse sandy fraction has been given various names, for example “Red SandTM” or “Red Oxide Sand”.

Technical Successes

Many potential applications have been considered and explored for decades focusing on the elements present in the bauxite residue. Even Bayer himself in his 1892 patent describing the Bayer Process proposed the potential for iron recovery.

Possible applications can broadly be broken down into various categories: recovery of specific components present in the bauxite residue, e.g. iron, titanium, rare earths; use as a major component in manufacture of another product, e.g. cement; use of the bauxite residue as a component in a building or construction material, e.g. concrete, tiles, bricks; soil amelioration or capping; conversion of the bauxite residue to a useful compound, e.g. Virotec process.

The list of areas where bauxite residue can be applied, covers almost all of inorganic material science and a full review would extend to pages, some of the most attractive have been: cement manufacture, use in concrete, iron recovery, titanium recovery, use in building panels, bricks, foamed insulating bricks, tiles, gravel/railway ballast, soil amelioration, calcium and silicon fertiliser, refuse tip capping/site restoration, lanthanides (rare earths) recovery, scandium recovery, gallium recovery, yttrium recovery, treatment of acid mine drainage, adsorbent of heavy metals, dyes, phosphates, fluoride, water treatment, chemicals, glass ceramics, ceramics, foamed glass, pigments, oil drilling or gas extraction proppants, filler for PVC, wood substitute, geopolymers, catalysts, plasma spray coating of aluminium and copper, manufacture of aluminium titanate-Mullite composites for high temperature resistant coatings, desulphurisation of flue gas, arsenic removal, chromium removal, soil amelioration.^{3,4}

The question so often asked is why some of these potentially exciting applications have failed to be implemented when on a small scale they look so attractive. It is certainly not the desire of producers to harbour their bauxite residue!

Major Barriers to Reuse

When considering the commercial/industrial implementation of uses that have been found to be technically successful, it is important to consider the barriers that have prevented the implementation of apparently sound and economic solutions. The materials that bauxite residue would be replacing in any application are very often readily and cheaply available so any negative feature or minor impediment is potential barrier to change. Assessing both the actual risk, and the perceived risk to the stakeholders for any particular application is crucial. Some important risk factors to consider are discussed below.

Leaching of heavy metals

The leaching of metals, especially heavy metals, into the environment is a particular issue for any material that is used in building products, bricks, roads, in construction, soil capping, or soil amelioration. Soluble chromium is normally the element of most concern though arsenic can also be a problem for some specific residues. This is generally only a particular issue when the materials are exposed to high or low pH values. Solubility/extraction tests of components or aggregates (for example EN 12457 – Waste Acceptance Criteria Testing) or metal uptake studies in vegetation may all be necessary depending on the application in order to show that the bauxite residue will not be a problem in use.

Possible concerns over liability of contaminating surrounding land may be a particular concern if the product is used in some way where the leachate from the structure etc. could leach into a water course.

Radioactivity

Most bauxites will contain low levels of radioactive elements, termed NORM (naturally occurring radioactivity material) in particular ^{238}U and ^{232}Th , and this is normally doubled in the bauxite residue. The radioactivity in the bauxite residue is sometimes referred to as TENORM (technologically enhanced naturally occurring radioactivity material).

In general two approaches are used to assess the risk from radioactivity: measurement of the elements that could lead to radioactivity, namely analysing for Ac, At, Bi, Pa, Pb, Po, Ra, Th, Tl, U, and then calculating a radioactivity value; or by direct measurement. The EU Radiation Protection Guideline 112 has a recommended range of 0.3 – 1 mSv/y for building materials; the particular limit being determined by the expected exposure.

There is limited data published but some information that has been reported on a range of bauxite residue shows that thorium was only present in significant levels in bauxite residue from Venezuelan bauxite but still remains below acceptable limits. The uranium content is over 10 mg/kg in Jamaican and Venezuelan bauxites but the total radioactivity calculated will still remain below legislative limits in bauxite residue. Some of the uranium does dissolve in the Bayer process but it subsequently re-precipitates and is associated with the coarser bauxite residue fraction. Meanwhile thorium is not affected by the extraction process and is most often associated with the fine bauxite residue fraction. Data for Australian derived bauxite residue shows a level of 0.005 – 0.2 Bq/g for the sand fraction and 0.15 – 0.6 Bq/g for the mud fraction due to ^{238}U and 0.3 – 0.8 Bq/g for the sand fraction and 1– 1.9 Bq/g for the mud fraction due to ^{232}Th and 0.07 – 0.23 Bq/g due to K^{40} in mud fraction.⁵

The IAEA (International Atomic Energy Authority) Basic Safety Guide for marketable materials sets a limit of 1 Bq/g per radionuclide; for uranium this is equivalent to 81 mg/kg. From the published data for bauxite residue, this level does not represent a problem for bauxite residues although it should be noted that the level measured for ^{238}U and ^{232}Th on bauxite residue from the closed Jamaican alumina plant at Moggetty was 0.97 and 0.32 Bq/g.⁶ The values generally present in local soil for ^{238}U and ^{232}Th were 0.22 and 0.037 Bq/g respectively.

A thorough understanding of the radioactivity issues are most important when any application is considered. Public perception and concerns must be addressed as despite the data shown above, the radioactivity levels measured have stopped a number of interesting applications proceeding. Examples include the manufacture of bricks for domestic buildings in Jamaica, the use of construction materials in applications other than roof tiles in Hungary and the manufacture of ceramic insulating fibre for domestic situations. An “Activity Index” assessment has been proposed to consider each application on its merits looking at the level of radioactivity in the bauxite residue, the amount of bauxite residue in the product and the time and degree of expected exposure.⁷

Alkalinity/high sodium

The high pH is a problem from both a health and safety aspect and potentially adverse effects in the particular application. This ranges from poor weathering resistance in construction materials to high sodicity when used in soil amelioration. Both high sodium levels and high pH will be reduced when press filters are used. Accelerating carbonation by the use of carbon dioxide, intensive farming or acid neutralisation as a first stage could also be considered to reduce the pH.

Hazardous rating of bauxite residue in some jurisdictions

There have been many discussions, particularly in the EU, concerning the hazardous nature of bauxite residue in particular in respect of its pH. If classified as a hazardous waste, this will add considerably to the cost of all aspects of handling, storage and transport. Based on a number of standard test criteria, material with a pH value above 12.5 is often considered hazardous. Implementation of an improved filtering operation, may reduce the pH to a level that avoids skin and eye irritation.

Moisture level

A high moisture level will add to transport costs and will be an issue if energy has to be expended in driving it off in drying or firing (calcination), so it is advantageous for the bauxite residue to have as high a solids content as possible. Additives such as starch have been used for dewatering for very many decades but from the 1980s there was growing use of synthetic flocculants. The use of plate and frame press

filters goes back a very long period and was certainly being used in the 1940s. It then seems to have fallen out of favour and rotary drum filters became more common. Now there is a trend back to the use plate and frame press filters being adopted to reduce water content which can yield a moisture level of 26/27 % or lower.

Transport costs

The logistics cost is very substantially increased if the material is classified as hazardous since special procedures must be implemented during transportation. Whilst the high alkalinity does not impose a problem with corrosion of steel, it does cause pitting of aluminium which is a part of the UN transport code. If the conversion or use is not carried out at the alumina refinery, the bauxite residue will almost certainly be competing with some other low cost ore, mineral or waste - reducing the transport costs to as low as possible is therefore essential. All mitigating operations should be considered, e.g. pumping the bauxite residue to some other area and processing it, dewatering methods/aids, solar drying.

A major trend since the 1980s has been the closure of small and medium size alumina plants, perhaps 100,000 to 300,000 t/y, in Europe and the growth of much larger plants in Brazil and Australia. The larger ones can be up to 6 million tonnes per year. These larger plants are very often remote from large centres of population which is likely to mean there is less industrial activity which might use the bauxite residue. This makes the transport cost issue even more critical when considering uses.

Industrial Scale Successes

It is generally estimated that some 2 to 3.5 million tonnes of the bauxite residue produced annually is used in some way although reliable data is difficult to obtain as it does fluctuate markedly from year to year as the economics change, this is especially the case for usage in China.

Current estimates from various sources are:

Cement – 500,000 to 1,500,000 tonnes;

Raw material in iron and steel production – 400,000 to 1,500,000 tonnes;

Landfill capping/roads/soil amelioration – 200,000 to 500,000 tonnes;

Construction materials (bricks, tiles, ceramics etc.) – 100,000 to 300,000 tonnes;

Other (refractory, adsorbent, acid mine drainage (Virotec), catalyst etc.) – 100,000 tonnes.

Bauxite residue can provide valuable iron and alumina values in the production of Ordinary Portland cement. Excluding China, the use of bauxite residue in the cement industry in the manufacture of clinker is estimated at approximately 260,000 t/y almost all of which is from the Nikolayev alumina plant in the Ukraine. The bauxite residue from Nikolayev is used in cement plants in Ukraine, Russia, Georgia, Moldova and Belarus. The Nikolayev refinery blends the residue produced to give the cement plant a consistent feed and the climate allows a reasonably low moisture product to be produced. There is modest usage of bauxite residue from AdG's plant in Distomon in cement production at a plant in Patras; further usage is restricted by the lack of dry storage. Much larger usage, up to 180,000 t/y was anticipated at a cement plant in Milaki, but changing economic circumstances have put increased usage on hold. The use of bauxite residue in cement in China was formerly several million tonnes a year but this has fallen because of the changes in construction industry standards and also a reduction in the number of plants operating a sinter or Bayer-sinter extraction route. It should be noted that the bauxite residue produced from the sinter or Bayer-sinter extraction route is very different chemically from that produced in a conventional Bayer alumina plant.

The usage of bauxite residue in steel manufacture is of the order of 70,000 to 100,000 tonne/year, excluding China. The iron ores that are normally used in iron and steel manufacture have an iron content of typically 55 to 70 % with 66 % being available from many good quality sources. Meanwhile for comparison, bauxite residues have a typical range of iron of 3 to 42 %. It is important to consider these contents and realise the difficulty in even closely matching the economics against using virgin iron ore, especially at the current price of iron ore. Some success has been achieved in China, particularly in plants in Southern China where the bauxite residue can have an iron content of up to 42 %. Notable success has also been achieved using magnetic separation techniques as a first stage of processing to concentrate the iron fraction. The bauxite residue material is also wet and has a high sodium content which is a disadvantage in steel production.

The simultaneous recovery of other metals, for example titanium and aluminium, would improve the economics of using bauxite residue for iron recovery in steel production. The only non-Chinese plant using bauxite residue for making steel is based in the Urals. The work on iron extraction from bauxite residue in the Southern Chinese alumina plants is discussed later. Several Indian sources of bauxite residue are relatively high in iron, between 30 to 39 %, and a considerable amount of work has been done to recover the iron values in the bauxite residue from the NALCO plant using the Romelt process, but whilst technically feasible, it was uneconomic because of the high energy costs involved in the process.

China is worth discussing separately as it is devoting a very considerable effort into searching for and implementing reuse of bauxite residue, much of it being driven by Chinese Government initiatives.⁴ China has shown the most dramatic change in the last 10 years with alumina production increasing from about 2.5 million tonnes in 2000 to over 50 million tonnes by 2014. The generation of bauxite residue has grown to over 50 million tonnes a year, the alumina manufacturing routes have traditionally been very different because of the nature of the indigenous bauxite. Sinter routes or combined Bayer-sinter routes were widespread but are now declining sharply and the industry has become more dependent on imported bauxites. This change in route has significantly changed the characteristics and composition of the bauxite residues being produced. Hitherto much of the imported bauxite was from Indonesia and Australia but curtailment of bauxite exports from Indonesia is changing the nature of the bauxite residue yet again. Traditionally, the alumina plants in the Northern part of China produced a residue very high in calcium and silicon oxides but low in iron oxide making them suitable for cement production whilst those in the south of China have a residue high in iron which makes the recovery of iron the most likely option for them to pursue. A very strong driving force in China has been government imposed legislation requiring that bauxite residue is reused.

The manufacture of bricks, tiles and other building materials has been shown to be technically possible by many groups of workers from a wide variety of sources of bauxite residue using both fired and chemically bonded methods. Outside China, however, whilst plants have started up, production has not continued.

Use of bauxite residue for capping municipal landfills is carried out in France; the amount varies considerably from year to year but is estimated at 40,000 to 100,000 tonne/year. It can only be undertaken within a relatively small radius of each refinery depending on local transport costs and the availability of other covering/capping materials; the maximum distance that the residue can effectively be transported for this application is estimated to be about 75 km. Municipalities will normally wait until an entire site is full before remediating/capping it, hence the wide variation in usage between years. The bauxite residue must be in form that can readily be carried in trucks on public roads. Possible concerns are dust from the bauxite residue when dry, and heavy metal leaching characteristics.

Somewhat related, has been the use as a soil amendment/conditioner for acidic/sandy soils; on large scale trials this has been shown to be safe and beneficial, especially in controlling high levels of phosphorous. Controversy over two decades has prevented its implementation until now.

Usage for road building and dyke/levee construction is estimated at 20,000 tonne/year, however, some is used internally within each alumina site complex, often for roads within the bauxite disposal area. A considerable amount of work has been done in Western Australia by Alcoa in conjunction with Curtin University on using Red Sand™ in the construction of roads.⁸ In this process, the coarse sandy fraction of the bauxite residue is neutralised with carbon dioxide to create the Red Sand™.

Soil amelioration of acidic and sandy soils offers considerable opportunities although current usage is limited and spasmodic.

Conclusions

In many ways it is discouraging that despite so much work over the last century only some 2 % to 3 % of the 140 million tonnes of bauxite residue produced annually is used in a productive way. Some of the applications have been economically beneficial for a number of years and then factors have changed which renders them no longer economically viable. Conversely, it is vital to consider how changes in process technology or demand requirements over time means that ideas previously considered not worth exploiting can become viable and commercially attractive. From the process side, improvements include: the increasing use of press filters will give residues with lower moisture levels, lower soda levels, lower contaminants, lower pH levels; the higher efficiency electro-magnets that are now available allows for more effective iron recovery from bauxite residue. Meanwhile the growing demand for scandium in aluminium alloys or the demand for particular rare earth elements also present new opportunities. In addition, public, corporate and government attitudes have never presented such an encouraging environment for developing and implementing bauxite residue uses.

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