

# Management and use of bauxite residue

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This paper serves as a brief overview of the history and trends in the management and use of bauxite residue, outlining: The dimensions of the problem; how methods of storage and disposal have developed 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; and some hopes for the future.

Annual production of smelter grade and chemical grade alumina in 2015 was some 115 million tonnes<sup>1</sup> which, with the exception of some plants in Russia, Iran and China, is all produced using the Bayer process. The global average for the production of bauxite residue per tonne of alumina is between 1 and 1.5 tonnes, though the range is much broader, so it is estimated that some of the 150 million tonnes of bauxite residue is produced annually. This is generated at some 60 active Bayer plants. In addition there are at least another 50 closed legacy sites, so the combined stockpile of bauxite residue at active and legacy sites is estimated at three thousand million tonnes.

## History and trends in disposal and storage methods

Management of and the methods of the storage of bauxite residue has evolved progressively over the decades<sup>2</sup>. In the early Bayer alumina plants, the residue generated was often merely piled up on site or an area adjoining the alumina plant. Occasionally nearby depleted mine or quarry sites, 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. These methods of storage were

especially true of the early European sites including: Bergheim (Germany) - on site storage then in a former lignite mines; Burntisland (UK) - disposal into an estuary, then behind a sea wall, see Figure 1, then an old shale mine; see Figure 2, Gardanne (France) - storage in a dammed valley then disposal by pipeline to the sea; La Barasse (France) - storage on site then nearby dammed valley then disposal to



Fig 1 - Bauxite disposal into an estuary to recover land

sea via a pipeline; Larne (UK) - disposal into sea water lagoons; Ludwigshafen (Germany) - storage on site; Newport (UK) – disposal into estuary from barges then sea water lagoons; Salindres (France) – on site storage then in a dammed valley and Schwandorf (Germany) – on site storage..

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 for example, Ewarton (Jamaica), see Figures 3 and 4, Gardanne, Salindres, Saint Cyr (France), Ouro Preto (Brazil). Examples of old mine storage were: bauxite mines (Kirkvine (Jamaica), Bauxite (USA)), lignite mines (Bergheim), and oil shale quarries (Burntisland).

In the case with sites constructed in the past three or four decades, the storage areas have normally been sealed to minimise leakage to the underlying ground and ground-water, however, this tended not to be the practice in earlier years. Sealing approaches cover a range of materials including compacted clay and/or the use of plastic and other membrane materials.

The supernatant liquor above the residue 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 Decantation, Drainage and Evaporation of Water (DREW) system.

There are many examples of this storage method but they include Stade (Germany), Burnside (USA) and Vaudreuil (Canada). In some cases, low dykes or levees were built

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Fig 2. Bauxite residue disposal into a former oil shale mine

to the final expected height at the start and a new area constructed when more volume was required whilst in others the dam walls were successively increased when the space was filled. 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, see for example the lake in Figure 4 which had a pH >12 and a soda level in excess of 2,000 mg/L many years after pumping had stopped.

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 (Gardanne and La Barasse), one in Greece (Distomon) and three in Japan (Shimizu, Ehime, Yokohama), 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 (Gramercy), and Severn Estuary (Newport). In other cases in Ireland (Larne), Wales (Newport) and Scotland (Burntisland), 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 all sea discharge will be completely phased out by the end of 2015.

As land for lagoon storage became scarce for many plants, "Dry stacking" methods were used. A dry stacking regime was adopted nearly 75 years ago in the UK<sup>3</sup> and about 50 years ago in Germany<sup>4</sup> and since the 1980s the trend has been increasingly towards dry stacking to reduce



Fig 3. Bauxite residue disposal into a dammed valley to create a lagoon, early stages

the potential for leakage of caustic liquor to the surrounding environment, reduce the land area required, and maximise the recoveries of soda and alumina. Considerable work was undertaken in Jamaica on the Robinsky<sup>5</sup> sloped thickened tailing disposal system and Ewerton adopted the practice in the mid-1980s<sup>6</sup>. See Figure 5. 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. Very many plants now use equipment such as Amphiroils to aid dewatering of the mud in order to compact and consolidate the residue. See Figure 6. 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 for some 80 years but is now growing in usage. Plate and frame filter presses were adopted in Vaudreuil in 1936 when the plant was constructed and in Burntisland in 1941 as the lagoons adjacent to the site were full. In the case of Burntisland the bauxite residue needed to be transported on public roads through the town to a nearby old oil shale mine so a high solids content mud was a key requirement. In the mid 1960s at Ludwigshafen, vacuum drum filters were adopted. Figure 7 shows a press filter.

In addition to helping recover more caustic, 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 issues and 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. Hyper Baric filters are reported to achieve particularly low moisture content material with the performance of the



Fig 4. Bauxite residue disposal into dammed valley, later stages

press being enhanced when steam is used; moisture contents lower than 25% have been reported.

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 800,000m<sup>3</sup> 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 European Aluminium and the International Aluminium Institute, have since worked collaboratively to look for improved solutions and propose best practice guidelines, which were published in a guideline document<sup>1</sup>. 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



Fig 5. Dry mud stacking

Aluminium Institute issued a set of targets for IAI members to work towards<sup>2</sup>. Key messages coming out of the best practice reviews have been the drive to dispose of and store bauxite residue in a safer way with lower caustic and higher solids content.

The changes within the industry over the last 20 years has meant that many of the relatively small Bayer plants have ceased operation and there has been an inexorable shift to much larger alumina refineries in countries such as Australia, Brazil and India. In a number of cases, the former alumina plant has been converted to a speciality alumina plant, which uses aluminium hydroxide as feed instead of bauxite; this trend has been particularly apparent in Europe and includes Ajka, Bergheim, Ludwigshafen, Salindres and Schwandorf. In the USA the two former Bayer plants at Bauxite have closed but the speciality alumina operation at the former Alcoa plant continues in operation.

Reuse of bauxite residue has long featured in the thinking of Bayer plant

| Component                      | Typical range (%) |
|--------------------------------|-------------------|
| Fe <sub>2</sub> O <sub>3</sub> | 5 - 60            |
| Al <sub>2</sub> O <sub>3</sub> | 5 - 30            |
| TiO <sub>2</sub>               | 0.3 - 15          |
| CaO                            | 2 - 14            |
| SiO <sub>2</sub>               | 3 - 50            |
| Na <sub>2</sub> O              | 1 - 10            |
| LOM                            | 5 - 20            |

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

operators but in spite of over a century of endeavour and trials, only some 2 to 3% of the nearly 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 on conveying used (by pumping, conveyor or truck). It should be noted that pumping over long distances can be achieved, even in excess of 50km. Residues from different bauxites also behave quite differently in terms of composition, mineralogy and particle size. They will have different handling and pumping characteristics and 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,

| Component  | Typical range (%) |
|--|-------------------|
| Sodalite (3Na <sub>2</sub> O.3Al <sub>2</sub> O <sub>3</sub> .6SiO <sub>2</sub> .Na <sub>2</sub> SO <sub>4</sub> ) | 4 - 40            |
| Al-goethite ((Fe,Al) <sub>2</sub> O <sub>3</sub> .nH <sub>2</sub> O)   | 1 - 55            |
| Haematite (Fe <sub>2</sub> O <sub>3</sub> )  | 10 - 30           |
| Magnetite (Fe <sub>3</sub> O <sub>4</sub> )  | 0 - 8             |
| Silica (SiO <sub>2</sub> ) crystalline and amorphous   | 3 - 20            |
| Calcium aluminate (3CaO.Al <sub>2</sub> O <sub>3</sub> .6H <sub>2</sub> O)   | 2 - 20            |
| Boehmite (AlOOH)   | 0 - 20            |
| Titanium Dioxide (TiO <sub>2</sub> ) anatase and rutile  | 2 - 15            |
| Muscovite (K <sub>2</sub> O.3Al <sub>2</sub> O <sub>3</sub> .6SiO <sub>2</sub> .2H <sub>2</sub> O)                 | 0 - 15            |
| Calcite (CaCO <sub>3</sub> )   | 2 - 20            |
| Kaolinite (Al <sub>2</sub> O <sub>3</sub> .2SiO <sub>2</sub> .2H <sub>2</sub> O)                                   | 0 - 5             |
| Gibbsite (Al(OH) <sub>3</sub> )  | 0 - 5             |
| Perovskite (CaTiO <sub>3</sub> )   | 0 - 12            |
| Cancrinite (Na <sub>4</sub> [Al <sub>5</sub> Si <sub>6</sub> O <sub>24</sub> ].2CaCO <sub>3</sub> )                | 0 - 50            |
| Diaspore (AlOOH)   | 0 - 5             |

Table 2. Typical range of components found in bauxite residues

particle size distribution, morphology and nature of the residue emanating from a particular plant.

There is relatively little published data 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 US\$4 to 12. 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. Despite the strong desire and enthusiasm of companies to present a 'green' and 'sustainable' corporate image, the utilisation opportunity must make economic sense, or at least close to, for



Fig 6. Mud dewatering and compaction

projects to be implemented. 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.

Despite the increasing trend to higher solids contents and lower soda values, one retrograde factor with respect to generation of bauxite residue is the current diminishing stocks 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 discussing uses is a consideration 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 range can be even broader for some unusual bauxites.

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.

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

and hydroxyacids such as humic, fulvic, succinic, acetic or oxalic acids.

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 will remain 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

Bauxsol®, ReadyGrit™, BPR – Bayer Process Residue, ARR – Alumina Refinery Residue, Bauxite tailings, Ferroalumina, Ferraloks, ART – Alumina refinery tailings, Redmedite, TerraB™, ViroMine™, ViroSoils™, ViroSewage™, Cajunite™ 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.

### Technical successes in the use of bauxite residue

Many potential applications have been considered and explored for decades with particular focus on the recovery of 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, aluminium, lanthanides, yttrium and scandium;
- 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;
- Use for soil amelioration or capping;
- Use for some specific property, which might include conversion of the bauxite residue to a useful material by modifying the compounds present, e.g. Virotec process.



Fig 7. Plate and filter press

minerals sometimes found at low levels including Brookite, Calcite, Carnegieite, Chantallite, Dolomite, Hydrogarnet, Hydroxycancrinite, Katoite-Si, Lawsonite, Nepheline, Nosean, Portlandite, Schaeferite, sodium titanate, and zircon.

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.

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

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 median particle size is normally in the range of 5 to 10  $\mu\text{m}$ , however, the breadth of particles is both very broad ranging from coarse sandy grains about 1mm in size down to sub-micron particles for bauxite residues produced from different alumina plants and different bauxites. 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 Sand™” or “Red Oxide Sand”.

It should be noted that bauxite residue or red mud has been called a variety of names by different companies, sometimes after additional treatment and some of the names are registered trademarks. These names include: Bauxaline®, Alkaloam™, Red Oxide Sand, Red Sand™, Ferraloks,

The list of areas where bauxite residue 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, refuse tip capping/site restoration, treatment of acid mine drainage, soil amelioration, road construction, dam/levee construction, pigments, glass ceramics. Meanwhile some other uses which have been shown to be technically feasible but not yet exploited to any significant degree are: Lanthanides (rare earth elements) recovery, scandium recovery, gallium recovery, vanadium recovery, cobalt recovery, yttrium recovery, adsorbent of heavy metals, dyes, phosphates, fluoride, water treatment chemical, ceramics, foamed glass, oil drilling or gas extraction proppants, gravel/railway ballast, calcium

and silicon fertiliser, 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, composites with epoxides, composites with poly aniline, manufacture of radiopaque materials for the construction of X-Ray diagnostic and CT scanner rooms, desulfurisation of flue gas, arsenic removal, chromium removal<sup>7,8</sup>. Some applications, such as use in pigments have been successful but use very small tonnages.

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 a 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 <sup>238</sup>U and <sup>232</sup>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.

The data published on radioactivity levels has historically been limited 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 more than 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 low temperature 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 <sup>238</sup>U and 0.3 – 0.8 Bq/g for the sand fraction and 1– 1.9 Bq/g for the mud fraction due to <sup>232</sup>Th and 0.07 – 0.23 Bq/g due to <sup>40</sup>K in mud fraction<sup>9</sup>.

The International Atomic Energy Authority (IAEA) 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 <sup>238</sup>U and <sup>232</sup>Th on bauxite residue from the closed Jamaican alumina plant at Moggetty was 0.97 and 0.32 Bq/g<sup>10</sup>. The values generally present in local soil for <sup>238</sup>U and <sup>232</sup>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<sup>11</sup>.

### 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

Fig 8. Use of Red Sand™ for road construction  
(Photo courtesy of Alcoa)



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, any waste material with a pH value above 11.5 is often considered hazardous. Implementation of an improved filtering operation, may reduce the pH of bauxite residue 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



Fig 9. Use of Bauxalite in landfill capping in Provence

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 annual production, in Europe and the growth of much larger plants, this is especially true in Brazil and Australia. The largest ones can produce more than 6 million tonnes per year of alumina. These larger plants are very often remote from large centres of population, which is likely to mean there is a lower level of industrial activity and consequently limit

some opportunities for the use of 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.

Current estimates from various sources are:

- Cement – 500,000 to 1,500,000 tonnes;
- Raw material/additive in iron and steel production – 400,000 to 1,500,000 tonnes;
- Roads (see Figure 8)/landfill capping (see Figure 9)/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 the 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. There has also been some historical usage of bauxite residue from the refinery in Tulcea in a local Romanian cement plant and also reportedly small-scale usage of bauxite residue from the Gandja alumina refinery in Azerbaijan in cement. 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%. Notably 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 devoting a very considerable effort into searching for and implementing reuse of bauxite residue, much of it being driven by Chinese Government initiatives<sup>8</sup>. 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 59 million tonnes by 2015. 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 a 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<sup>12</sup>. 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.

### Summary

The early history of bauxite residue storage involved using estuaries or land impoundment areas adjacent to the factory as a low solids slurry. Disposal into rivers, estuaries or the sea was common for a number of years but this has now ceased. Storage of bauxite residue as a dilute slurry in old mines, impounded areas or dammed valleys was widely practised until the mid-1980s but since then there has been a growing trend to higher solids storage method. More recently, filter presses to produce an even higher solids residue have become increasing common. 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. However, 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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### Acknowledgements

Thanks are due to Katy Tsesmelis of World Aluminium and George Banvolgyi for very helpful comments on the manuscript.