BAUXITE RESIDUE VALORISATION AND BEST PRACTICES CONFERENCE
Leuven 5-7 October 2015
Successes and challenges in the management and use of bauxite residue

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IAI consultant
October 2015
Contents

- IAI
- Dimensions of the problem/opportunity
- Overview of historic management methods
- Applications
- Challenges to implementation
- Lowering the barriers
- Industrial success stories
- New driving forces for (re)use
- Where next?
Red mud to Bauxite residue

- Red mud
- Bauxite residue
- Red oxide sand
- Red Sand™
- ReadyGrit™
- Alkaloam™
- Bauxaline®
- Ferraloks
- Ferroalumina
- Cajunite™
- BPR – Bayer Process Residue
- ARR – Alumina Refinery Residue
- ART - Alumina Refinery Tailings
- DBR - Dried Bauxite Residue
- RMG
- Redmedite
- Bauxsol®
- ViroMine™
- ViroSewage™
- ViroSoils™
- Terra B™
International Aluminium Institute

• The International Aluminium Institute (IAI) have a standing committee dealing with bauxite, alumina, aluminium and bauxite residue issues
• Represents 60% of the bauxite and alumina producers
• Have been involved in bauxite residue issues for many years, however, heighten interest after Ajka incident in October 2010
• IAI/European Aluminium “Bauxite Residue Management: Best Practice” – issued April 2013 – now available in Mandarin and Bahasa
• Supports various projects relating to improved management and uses of bauxite residue including conferences
Amount of bauxite residue generated

• Bauxites used range from just over 30% to 63% alumina content
• Very large range generated depending on bauxite, extraction conditions – 0.5 to 4 t/t alumina
• High alumina content bauxite using high temperature/pressure conditions
  – Often used when transport distances are large
• Low grade bauxites with low alumina and high sand contents
  – Often used when bauxite adjacent to the plant
• World average (2014) - 1.35 t/t alumina
• European average (2014) - 0.67 t/t alumina
Scale of the problem – or should we say opportunity?

- Annual alumina production in 2014: 108 million t/y - 95% via Bayer process
- Range of Bauxite residue produced per tonne of alumina: 0.5 to 4 t/t alumina
- Annual arising: 130 to 140 million tonnes
- Number of active alumina refineries: over 60
- Number of closed residue disposal sites: over 50
- Virtually all now disposed of: on land – all disposal in estuaries, and at sea to end by December 2015
- Only about 2 to 3% is used
- Amount stockpiled: 3,000 million tonnes (3 giga tonnes) – an enormous deposit to mine as a future resource!
Historic driving forces for dealing with bauxite residue

- Recovery of caustic soda for reuse in the process
- Lowest cost compatible with minimum effect on the environment
- A limited desire for (re)use but needed to be a cost effective solution
- Occasional attempts to (re)use – for example in times of war – iron and steel production
- Disposal cost – US$ 4 to 10/t
- Closure costs often ignored – “not present local management’s problem”
Possible consequence if not properly stored
Ajka Alumina Plant – October 2010
Ajka Alumina Plant – October 2010
Ajka Alumina Plant – October 2010
Ajka Disaster – October 2010
Impact of Ajka, Hungary incident
October 2010

• 700,000 m² of caustic bauxite residue slurry released as a result of a dam failure
• 10 people killed
• 150 people hospitalised
• Three settlements overwhelmed
• 300 houses destroyed or severely damaged
• 14 km² of agricultural land along Torna and Marcal waterways inundated with caustic liquor/BAuxite residue
• Extensive contamination of the River Danube
• Negative publicity – radioactivity, arsenic etc
Reactions following Ajka incident

- Immediate offers of support from IAI and EA
- Heightened interest and activities following Ajka incident in October 2010
- Preparation of European Aluminium/IAI documentation reviewing current methods of handling, treatment and uses (actual and potential) - IAI/EAA Best practice document issued
- Heightened concern of EU and national regulators
- EU looking at possible changes in waste directives and classification
- Important to make all sites as safe as possible and regular internal inspections
- Need to take into account natural disasters eg earthquakes, storms, in planning
- Increased motivation to find uses
Management approaches

• Lagooning
• Disposal to quarries, depressions, dammed valleys, captured by sea walls
• River, estuarine, sea disposal (pipeline and ship)
• Mud farming
• Dry mud stacking
• Filtration – drum filters, plate and frame etc
• Seawater neutralisation/pH reduction
• Acid neutralisation
• Carbon dioxide neutralisation
• Sulfur dioxide neutralisation
• (Re)use
Lagooning – early stages
Lagooning – later stages
Disposal in old quarries
Sea disposal
Sea/estuarine disposal - land reclamation
Mud farming
Mud farming
Dry mud stacking

- DILUTE MUD/SAND SLURRY FROM PLANT
- SAND SEPARATION PLANT
- CYCLONES
- SAND TOWERS
- DILUTE MUD SLURRY
- MUD THICKENER
- OVERFLOW RECYCLE
- SAND SLURRY TO AREA 2
- SAND SLURRY TO AREA 2
- RECYCLE TO PROCESS
- DECANT
- RUNOFF
- DECANT
- UNDER DRAINAGE
- SPRINKLERS
- EVAPORATION
- OVERFLOW HIGH DENSITY MUD
- UNDER DRAINAGE
- SUN
- TO MUD DROPPERS VIA MUD LINE
- HIGH PRESSURE MUD PUMPING
- DRY DISPOSAL AREA
Dry stacking
Filtration – plate and frame press
Applications
## Chemical composition – range (%)

<table>
<thead>
<tr>
<th>Element</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe$_2$O$_3$</td>
<td>5 – 60</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>5 – 30</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.3 – 15</td>
</tr>
<tr>
<td>CaO</td>
<td>2 – 14</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>3 – 15</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>1 – 10</td>
</tr>
<tr>
<td>As, Ba, Be, C, Cd, Cr, Cu, Ga, Hg, K, P, Pb, Mg, Mn, Mo, Ni, S, Sc, Se, Th, U, V, Zn, Zr + lanthanides</td>
<td></td>
</tr>
</tbody>
</table>

A rich source of elements
Mineralogical components – range (%)

• Sodalite (3Na₂O·3Al₂O₃·6SiO₃·Na₂SO₄) 4 - 40
• Goethite (FeOOH) 10 - 30
• Haematite (Fe₂O₃) 10 – 30
• Magnetite (Fe₃O₄) 0 - 8
• Silica (SiO₂) crystalline and amorphous 3 - 20
• Calcium aluminate (3CaO·Al₂O₃·6H₂O) 2 - 20
• Boehmite (AlOOH) 0 - 20
• Titanium Dioxide (TiO₂) anatase and rutile 2 - 15
• Muscovite (K₂O·3Al₂O₃·6SiO₂·2H₂O) 0 -15
• Calcite (CaCO₃) 2 - 20
• Kaolinite (Al₂O₃·2SiO₂·2H₂O) 0 - 5
• Gibbsite (Al(OH)₃) 0 - 5
• Perovskite (CaTiO₃) 0 -12
• Cancrinite (Na₆[Al₆Si₆O₂₄]·2CaCO₃) 0 - 5
• Diaspore (AlOOH) 0 -5
Bauxite residue possible applications

Hundreds of thousands of ideas, thousands of trials, many hundreds of patents, a few tens of industrial applications

• Use as a bulk material
  - Bricks, tiles, roads, dam/levee construction, landfill capping, soil amelioration

• Use for its chemical components
  - Cement, pigment, geopolymers, catalysts, refractories, phosphate removal, acid mine drainage treatment, heavy metal removal

• Extraction of chemical constituents
  - Iron, titanium, gallium, rare-earths (scandium, yttrium, lanthanum of particular interest)
Some proposed applications

Bricks, tiles, roads, dam/levee construction, landfill capping, soil amelioration, wood substitution, mineral wool manufacture, plastic (PVC) filler, railway ballast, treatment of acid soil, drainage pipe filler, glass ceramics, light weight aggregates, foamed aggregates, filling former mine shafts, land reclamation

Cement (OPC clinker), Sulfo-aluminate cements, pozzolanic material for mortar, supplementary cementitious additives, concrete additive, paint pigment, pigment for plastics, dye, geopolymers, catalysts, refractory lining to replace ilmenite, refractory bricks, gravel

Phosphate removal, water treatment chemical, arsenic removal, chromium and other heavy metal removal, acid mine drainage, sulphide oxidation, fertiliser, titanate-Mullite composites, plasma spray coatings

Extraction of iron, titanium, gallium, scandium, vanadium, yttrium, lanthanides and other rare earths
Bauxite residue applications - history

- 1880s – iron recovery by Bayer
- 1910s – internal roads and dykes in refineries and residue disposal areas
- 1930s - cement
- 1940s – iron and steel production
- 1950s – pigments
- 1980s - bricks
- 1990s – cement, brick colouration, sulfo aluminate cements, capping, soil amelioration
The red, iron containing residue after digestion settles well and, with sufficient practice, can be filtered and washed. Due to its high iron and aluminium oxide content, it can be, in an appropriate manner, treated or with other iron ores, be smelted to iron.
Levee construction
Building at JBI, unfired bricks
Building in Kingston
Radiological properties Jamaican buildings

- Pinnock UWI – 1991
- Gamma radiation measured by thermo-luminescence detector
- Radon using strips of CR 39 plastic to register tracks
- Building Research Institute 50% bauxite residue
Radiological properties Jamaican buildings

- Pinnock UWI – 1991
- Gamma radiation measured by thermo-luminescence detector

<table>
<thead>
<tr>
<th>Type of house</th>
<th>Gamma component (msv)</th>
<th>Radon component (msv/y)</th>
<th>Total (msv/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRI 50% BR</td>
<td>0.80</td>
<td>0.66</td>
<td>1.44</td>
</tr>
<tr>
<td>100% Bauxite residue</td>
<td>1.25</td>
<td>0.82</td>
<td>2.07</td>
</tr>
<tr>
<td>Typical concrete</td>
<td>0.51</td>
<td>0.35</td>
<td>0.86</td>
</tr>
</tbody>
</table>
Bauxite residue (re)use targets/goals

• Chinese Government target of 25% (re)use by 2015
• Shandong Province target of 40% (re)use by 2015
• Note, however, > 10% re(use) achieved in China
• IAI Alumina Technology Roadmap strategic goal of 20% by 2025
Bauxite residue uses – large tonnage estimates

- Clinker – Ukraine, Greece, Russia, Georgia, Moldova, Belorussia, Romania, ~250,000 t/y + China
- Global estimate for clinker/cement additive 1 to 1.5 million t/y
- Use in iron and steel production 0.2 to 1.2 million t/y especially China
- Road construction, sometimes in conjunction with fly ash – widely used for internal roads on residue disposal sites – Australia, France ~ 50,000 tonnes
- Capping landfill sites – France 70,000 to 100,000 t/y
- Building materials 0.5 to 1 million t/y
- Miscellaneous 300,000 t/y
- TOTAL 2.4 to 4.4 million t/y
Beneficial attributes of bauxite residue in clinker

- Ordinary Portland cement composition – 5% $\text{Al}_2\text{O}_3$, 3% $\text{Fe}_2\text{O}_3$, 21% $\text{SiO}_2$, 62% CaO
- Provides iron – driving force at some plants
- Provides alumina – driving force at some plants
- Optimum ratio iron oxide to alumina from some studies - 0.8:1.2
- Silica and calcia useful although less critical
Use in clinker, mortar and concrete

- As a raw material in the production of the Ordinary Portland Cement clinker
  - Mainly as a source of iron and alumina
  - Reduced carbon dioxide emissions
- As a supplementary cementitious material which is used in mortar or concrete mixes
  - Can provide better mechanical properties
  - More efficient use of resources
  - Lower carbon dioxide emissions
- In certain types of ‘special’ cement for example calcium sulfo-aluminate (belite type cement)
  - Substantially lower carbon dioxide emissions during production
Industrial uses in clinker

- Nikolayev alumina plant in the Ukraine
  - Up to 250,000 t/y in 10 cement plants in Ukraine, Russia, Georgia, Moldova and Belarus
    - Transported up 950 km
    - Used predominantly for iron but also alumina value

- AdG, Distomon, Greece
  - 9,000 t/y TITAN, Patras
    - Driven by alumina value
    - Limits
      - Storage (~30,000 t/y if overcome)
      - Chromium (partly due to chromium level of other constituents)
      - Soda 2.8% acceptable

- Lafarge, Milaki (300,000 t/y still a possibility)
  - Driven by iron content
  - Concerns
    - Soda – 2.5% target
    - Moisture
    - Chromium
Other work involving Bauxite residue in clinker

- Historically large use in India 2.5 million tonnes in the 1990s
- Proposal for 160,000 t/y in Jamaica in a new cement plant
- Significant scale trials in Japan
Possible usage rates in clinker, supplementary cementitious materials, special cements

• In Ordinary Portland Cement clinker
  – Up to 5%
  – Global production of cement 5,000 million tonnes so large potential

• As a pozzolanic/supplementary cementitious material
  – Up to 40%

• In special cements
  – Difficult to quantify but 10% in one study
Situation in China

• Alumina production in China in 2014 > 50 million tonnes
• Historically a significant percentage of alumina is made using a sinter route or combined Bayer-sinter route
  – Indigenous bauxites relatively low grade
  – Calcined at ~1,000°C with limestone and soda
  – Results in much higher calcia and silica levels than standard Bayer process and high gibbsitic bauxite
  – High in β-2CaO.SiO₂
  – Low in iron
• 1965 cement plant built to consume residue from Shandong Alumina
  – By late 1990s over 6 million tonnes of residue used to make OPC and oil well cements
• However, standards for cement restricted sodium level content and progressive move to imported bauxites so decline in sinter processing except for chemical grade alumina
• Since 2005 very large scale effort to utilise more bauxite residue in many areas
  – High intensity magnetic separation to concentrate iron
  – Glass ceramics CaO - SiO₂ - Al₂O₃
  – Bricks (with lime fly ash)
  – Polymer filler
• Very demanding Government targets but current (re)use estimate is < 10%
Landfill capping Provence
Landfill capping Provence (methane collection)
Road construction in Western Australia

• Substantial joint work between Curtin University and Alcoa Kwinana
  – Alcoa plants in Western Australia (Kwinana, Pinjarra, Wagerup) - 30,000 t/d of mud and 18,000 t/d of coarse sand residue
  – After carbonation marketed as Red Sand™ or ReadyGrit™

• Target to replace virgin sand and crushed limestone for sub-grade and top dressing
  – For each cubic metre of virgin sand replaced savings of 4.4 and 2.7 MJ respectively in energy conservation
  – Lower carbon footprint
  – Reduces loss of vegetation as avoids use of quarries
  – Cost savings
  – Less water used
  – Reduced eutrophication
Road construction in Western Australia

(slide courtesy of Alcoa)
Pigments for paint
Acid mine drainage – Virotec/Redmedite

- Products made from brine treatment of bauxite residue – Bauxsol® and Redmedite
- Historically a considerable amount of work at Southern Cross University
- Current trials at Wheal Augusta, former barytes mine in UK with Plymouth University on contaminant removal from leachate and remediation of contaminated soil
- Pellets also used for phosphate removal in sewage treatment

Removal of contaminants
- Al – 91%
- As – 65%
- Cd – 73%
- Co – 81%
- Cr – 95%
- Cu – 99%
- Fe – 98%
- Mn - 26%
- Ni - 28%
- Pb – 99%
- Zn – 74%
Acid mine drainage - Redmedite
Challenges to use

- Moisture level
- Sodium content
- pH
- Hazardous categorisation
- Heavy metal content – especially chromium
- Radioactivity
- Location
- Liability concerns
- **Cost**
“The great red mud experiment that went radioactive”

May 2002
Quentin Treasure was a member of a local land-care group when he was approached to take part in an unusual experiment by the West Australian Agricultural Department.
The department wanted to spread a reddish substance over his farmland to see if it would stop unwanted phosphorus from entering waterways.
The bonus, Mr Treasure was assured, was not just environmental. He could look forward to vastly increased crop yields using a soil-improving agent that would cost him just 50 c a tonne.
But this was no ordinary product. It was industrial waste.
The trucks dumping tonne after tonne of the ochre-like material were coming straight from settling ponds at the nearby Alcoa aluminium refinery, which was co-funding the project.

"We never talked a lot about whether it was safe or not," Mr Treasure said. "We were just told it was dirt from the hills that came from Alcoa. And being a little bit naive at the time, that is all we assumed it was."
The experiment, now being used to justify an extraordinary proposal for large-scale use of industrial waste on West Australian farms, remains a bitter memory for a small group of farmers that originally took part.
What Mr Treasure did not fully understand when he agreed to the proposal was that, apart from having fertilising potential, the red mud was also laced with dangerous materials.
Sprinkled over each hectare were up to 30 kilograms of radioactive thorium, six kilograms of chromium, more than two kilograms of barium and up to one kilogram of uranium.
On top of that there were 24 kilograms of fluoride, more than half a kilogram each of the toxic heavy metals arsenic, copper, zinc, and cobalt, as well as smaller amounts of lead, cadmium and beryllium.
## Radioactivity of bauxite residue

<table>
<thead>
<tr>
<th>Bauxite residue</th>
<th>$^{238}\text{U}$ (Bq/g)</th>
<th>$^{232}\text{Th}$ (Bq/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moggety (Jamaica)</td>
<td>0.97</td>
<td>0.32</td>
</tr>
<tr>
<td>Australian coarse fraction</td>
<td>0.005 – 0.2</td>
<td>1 – 1.9</td>
</tr>
<tr>
<td>Australian fine fraction</td>
<td>0.15 – 0.6</td>
<td>0.07 – 0.23</td>
</tr>
</tbody>
</table>
More recent driving forces for dealing with bauxite residue

• Growing desire within the industry to present a favourable public image – referenced in annual environmental reports of all major companies
• Very strong concerns about storage following Ajka
• Strong drive to recover caustic soda
• Government pressure in China to find uses
• Concerns about closure costs – in the early days, no plant was built with the expectation that one day it would close
Future driving forces for affecting bauxite residue use

• Cessation of disposal to the sea - by 2016
• Public attitude to green solutions becoming stronger
• Shareholder pressure on multi-nationals stronger
• Desire to reduce area of land rendered unusable for future use – LCI/LCA driven
• More open attitude to co-operation by producers
• Desire by the major producers to minimise the environmental impacts of generation and substantially increased R&D effort e.g. Rusal - recycling centre in Urals, Alcoa – carbon capture and university support
• Increased use of filtration
• External funding for research available e.g. EU MSCA-ETN REDMUD, BRAVO
Some examples of uses that have been successful for a period

• 1960s - Pigment production in Northern Ireland

• Late 1990s – Clinker in India – 2.5 million tonnes

• 1980s and 1990s – Colourant for bricks UK ~5% addition

• Use in OPC clinker in China

• Use in refractories in Romania 50,000 – 60,000 t/y
Lowering the barriers to use
Lowering the barriers

• Lower moisture contents – easier handling, lower transport cost, reduced energy use in some applications
  – Obtained by air drying if climate appropriate
  – Use of plate and frame filter presses
  – <28% moisture content achievable
• Sodium – reduced contamination or interference in some applications
  – Improved recovery systems within refinery operation
  – Improved filtration so more sodium extracted from residue
  – Improved washing
• Lower pH
  – Neutralisation – acid, sea water or brine
  – Better filtration
  – Accelerated carbonation
  – Alcoa Kwinana carbon dioxide capture
• Radioactivity - more a perception issue that a real issue but can be a problem with some bauxite residue and some bauxite sources
  – Dissemination of the appropriate information
  – Bauxite residue selection
• Hazardous categorisation
  – Testing – eye, skin, transport
  – REACH
• Co-operation – producers, users, universities, networking
• Innovation – new solutions to old problems
Bauxite residue – some further challenges

• Very many ideas have been considered and tried but the results have never been published
  – Confidentiality in some instances
  – Failure in others
  – Partial success but no desire to publish

• Competition
  – In spite of a more open attitude, there is still a reluctance to give away years of hard won information
  – Some industries operate on very narrow financial margins – e.g. cement
  – Some companies have invested substantial sums in R&D and want to see a financial payback

• Focus of large scale producers is on projects that will use large volumes

• Beware of solutions that only utilise part of the residue and leave a less desirable residue
  – Acid or solvent extraction process for REE
In summary

• Despite the enormous amount of work current usage at 2 – 4% is disappointing

• However, conditions never better as increased desire to succeed, lower moisture and soda levels and more funding

• Short term opportunities
  – Cement clinker
  – Building materials – bricks
  – Iron recovery
  – Soil amelioration
  – Capping
  – Road construction

• Medium term opportunities
  – Heavy metal removal, phosphate removal, acid mine drainage
  – Supplementary cementious materials

• Longer term opportunities
  – Scandium and other rare earths
  – Geo-polymers – with silica
Thank you for your kind attention
Background
Special cements

- Calcium sulfo-aluminate/belite based
  - $\text{Ca}_4(\text{AlO}_2)_6\text{SO}_4$
- Reduced carbon dioxide emissions
  - Less carbonate
  - Lower firing temperature
- Rapid setting
- High strength, particularly early strength
- Can use waste from flue gas scrubbing
- Considerable usage in China
- Poor workability
- Up to 10% bauxite residue in one study acceptable
Bauxite residue as a supplementary cementitious material

• Many papers presented in this area – Brazil, China, Greece, India, Spain
• Effective as a pozzolanic material so can be incorporated into cement mixes (mortar and concrete)
• Can be used in cement blends and provide beneficial mechanical properties
• Levels up to 50% possible although most studies show lower levels at 5 to 10%
• Downside:
  – Calcination is necessary in some circumstances, >800°C, some studies up to 1300°C
  – Some studies have used neutralised bauxite residue
Beneficial attributes of bauxite residue

• Ordinary Portland cement composition – 5% Al₂O₃, 3% Fe₂O₃, 21% SiO₂, 62% CaO
• Provides iron – driving force at some plants
• Provides alumina – driving force at some plants
• Optimum ratio iron oxide to alumina from some studies - 0.8:1.2
• Silica and calcia useful although less critical
Alcoa Kwinana - Carbon dioxide capture
Carbon dioxide capture - Alcoa

• The carbon dioxide capture approach has multiple benefits:
  - The residual caustic in the bauxite residue reacts with carbon dioxide
  - Reduces the pH of the bauxite residue hence making it suitable for a road base, soil amelioration, or use in building materials
    - Carbonated bauxite residue is less dusty
    - Carbonated residue has a shorter drying time
• Bauxite residue from Alcoa’s Kwinana plant will lock up 70,000 tonnes per year of carbon dioxide
  - Equivalent to taking 17,500 cars off the road
Alcoa Kwinana carbon dioxide capture (slide courtesy of Alcoa)