



TECHNOLOGY ROADMAP

MAXIMISING THE USE OF BAUXITE RESIDUE IN CEMENT



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WORLD
ALUMINIUM

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Current IAI membership represents over 60% of global bauxite, alumina and aluminium production. Since its foundation in 1972, members of the IAI have been companies engaged in the production of bauxite, alumina, aluminium, the recycling of aluminium, or fabrication of aluminium or as joint venture partners in such. The key objectives of the Institute are to:

- Increase the market for aluminium by enhancing world-wide awareness of its unique and valuable qualities;
- Provide the global forum for aluminium producers on matters of common concern and liaising with regional and national aluminium associations to achieve efficient and cost-effective cooperation;
- Identify issues of relevance to the production, use and recycling of aluminium and promoting appropriate research and other action concerning them;
- Encourage and assisting continuous progress in the healthy, safe and environmentally sound production of aluminium;
- Collect statistical and other relevant information and communicating it to the industry and its principal stakeholders; and
- Communicate the views and positions of the aluminium industry to international agencies and other relevant parties.

Through the IAI, the aluminium industry aims to promote a wider understanding of its activities and demonstrate both its responsibility in producing the metal and the potential benefits to be realised through their use in sustainable applications and through recycling.

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EXECUTIVE SUMMARY

CHALLENGE

Aluminium demand is expected to increase over the next 20 years. Even with high recycling rates, primary metal production will still be needed to meet this demand. Consequently, global metallurgical alumina production is forecasted to grow from 124 million tonnes in 2019 to 178 million tonnes by 2040¹.

As alumina production increases so too will the production of bauxite residue (BR) which is generated by the extraction of alumina from bauxite during the Bayer process. Current scenarios based on the International Aluminium Institute's dynamic material flow model indicate a global inventory of BR of 7 to 8 billion tonnes by 2040¹.

PURPOSE

The purpose of this roadmap is to maximise the use of BR in cement and concrete products by providing information and support to address concerns, prejudices, technical and legislative barriers. It is aimed at the alumina sector - calling the industry to action, while also engaging others who can help deliver success.

SUSTAINABLE DEVELOPMENT GOALS

The 17 Sustainable Development Goals (SDGs) set by the United Nations (UN) in 2015 are the blueprint to achieve a better and more sustainable future for all².

The use of BR in cement and concrete products can directly play a role in two priority SDGs. Responsible consumption and production (SDG 12) is about promoting resource and energy efficiency to provide a better quality of life for all. This will require partnerships (SDG 17) between multiple stakeholders built upon a shared vision and goal. In addition, use of BR in cement and concrete products can contribute towards further SDGs.

IMPACT OPPORTUNITIES

The use of BR in Portland Cement Clinker (PCC) and Supplementary Cementitious Materials (SCM) for blended cements have been identified as high impact opportunities.

Use of BR in these cement and concrete products has the potential to contribute towards:

- energy and CO₂ reduction;
- natural resource utilisation reduction; and
- BR storage reduction.

Portland Cement Clinker



Maximise use of BR at as many sites as possible

BR is already being used in PCC, but further work is needed to encourage other plants to adopt it. Use of BR in PCC can contribute to improved energy efficiency and resource utilisation during clinker production.

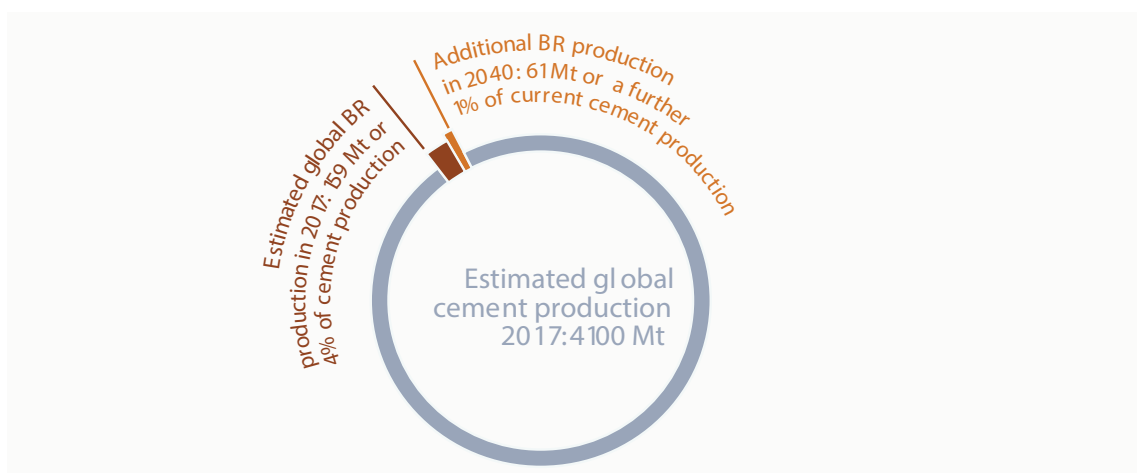
SCM for blended cements



Identify necessary work to complete gaps & overcome legislative barriers/standards, undertake R&D

Depending on any additional processing of the BR, using BR as an SCM for blended cements could contribute to the cement industry goals of reducing the clinker to cement ratio and increased use of low-CO₂ supplements.





In theory, global cement production is large enough to utilise global BR production on an annual basis. BR production in 2017 is estimated to have been 159 Mt – this accounts for only 4 % of global cement production. BR production is expected to increase to 220 Mtpa by 2040¹. Even if global cement production remains the same, the increased amount of BR could still be consumed. Obviously, several constraints and barriers need to be overcome for this to be possible – and this is the objective of the Roadmap.

ROAD TO PROGRESS

Six key pathways have been established:

1. Provide solutions to existing barriers and fill knowledge gaps;
2. Establish joint research projects between alumina and cement & concrete producers to investigate the use of BR in PCC or SCM for blended cements and develop technical approval documents;
3. Demonstrate benefits in carbon dioxide emission reduction that can be achieved using BR in PCC & SCM for blended cements;
4. Establish the level of interest & preparedness in incorporating BR in PCC & SCM for blended cements;
5. Encourage the use of BR in cement & concrete products to further the circular economy; and
6. Promote the use of BR in PCC and SCM for blended cements in sourcing & public procurement policies;

Successful implementation of these pathways requires collaboration between several stakeholders and commitment across:

- Product development – to address barriers and knowledge gaps;
- Process innovation – to improve the way stakeholders operate to allow for greater use of BR;
- Partnership building – to leverage collective resources; and
- Promotion – to encourage the use of BR.



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MAXIMISING THE USE OF BAUXITE RESIDUE IN CEMENT

1. INTRODUCTION

Aluminium demand is expected to increase over the next 20 years. Even with high recycling rates, primary metal production will still be needed to meet this demand. Consequently, global metallurgical alumina production is forecasted to grow from 124 million tonnes in 2019 to 178 million tonnes by 2040¹. As alumina production increases so too will the production of bauxite residue (BR), which is generated by the extraction of alumina from bauxite during the Bayer process. The composition of BR is dictated by the bauxite source and the extraction conditions. Further information is available in Appendix A.

The International Aluminium Institute (IAI) estimates that BR production will be approximately 160 million tonnes (Mt) during 2020¹. Current scenarios based on the Institute's dynamic material flow model indicate a global inventory of BR of 7 to 8 billion tonnes by 2040¹. The methods of safe storage of BR have improved enormously in the last two decades but it is recognised that BR has valuable components and properties that could be effectively used in the move towards a circular economy.

2. PURPOSE

The purpose of this roadmap is to maximise the use of BR in cement and concrete products by providing information and support to address concerns, prejudices, technical and legislative barriers. It is primarily aimed at the alumina sector – calling the industry to action while also engaging others who can help deliver success. It provides information for all stakeholders on how cross-sectoral collaboration can contribute to their priority SDGs.

During the roadmap development, the potential for using BR in Portland Cement Clinker (PCC) and Supplementary Cementitious Materials (SCM) for blended cements was reviewed, as shown in Figure 1.

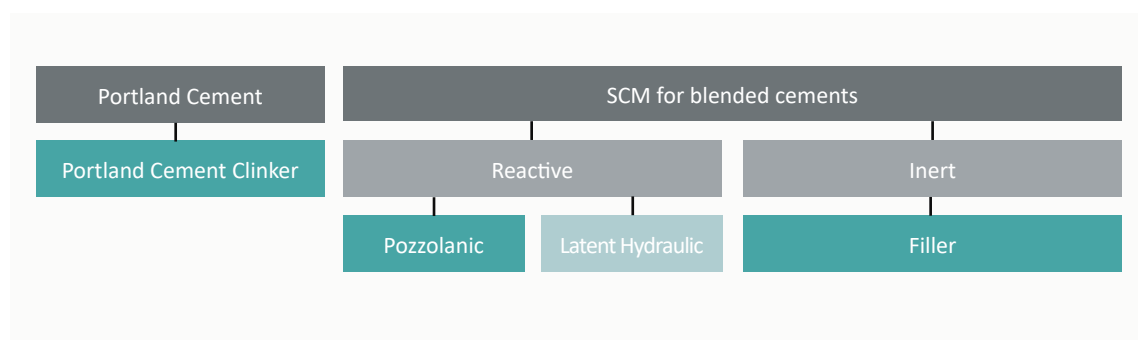


Figure 1: Cement materials reviewed during roadmap development

1. Portland Cement Clinker (PCC)

Clinker is the binding material in cement. It is formed in a kiln by heating the raw meal and then rapidly cooling it. PCC refers specifically to the clinker in Portland cement; the most common cement type globally. When combined with sand, coarse aggregates and water, Portland cement forms concrete and provides the main cementitious material in the mix.

Opportunity: Raw meal component - the iron and aluminium compounds contained in BR can provide valuable additions to the raw meal.

2. Supplementary Cementitious Materials (SCM) for blended cements

These are materials which make up a proportion of the cementitious component of blended cements and are often formed from other processes (e.g. fly ash, Ground Granulated Blast Furnace Slag (GGBFS)). They can be reactive – activated by alkali (pozzolanic) or water (latent hydraulic); or inert and used as a filler.

The addition of these materials and the processes to incorporate them (grinding, mixing and transport) use very little energy compared to the clinker process, leading to significant reductions in CO₂ emissions.

Opportunity: Pozzolanic - BR, normally after activation by heat, can provide pozzolanic activity. It can play a valuable role in mortars or concrete as a replacement of clinker, either alone or in combination with other pozzolanic and hydraulic additives.

Opportunity: Filler, due to its characteristics and fine particle size, in some cases, BR has been shown to play a useful role in mortars or concrete as a replacement for clinker. It can improve some properties such as compressive strength. This may be due to its ability to improve the packing characteristics and/or rheological behaviour of a blended cement mix or providing a role in cement hydration.

Use of BR in these materials has the potential to contribute towards:

- energy and CO₂ reduction;
- natural resource utilisation reduction; and
- BR storage reduction.

3. METHOD AND APPROACH

The 17 SDGs set by the UN in 2015 are the blueprint to achieve a better and more sustainable future for all². With the goal to support businesses address these challenges, the World Business Council for Sustainable Development (WBCSD) has developed the SDG Sector Roadmaps framework³.

Although this Roadmap does not have the same objective as one for an entire sector, the WBCSD 3-step framework has been used where applicable:

1. Establish current position > identify priority SDGs and their underpinning target goals;
2. Identify key impact opportunities;
3. Call to action > develop pathways and an action plan.

The main steps undertaken to develop this Roadmap are outlined in Figure 2.

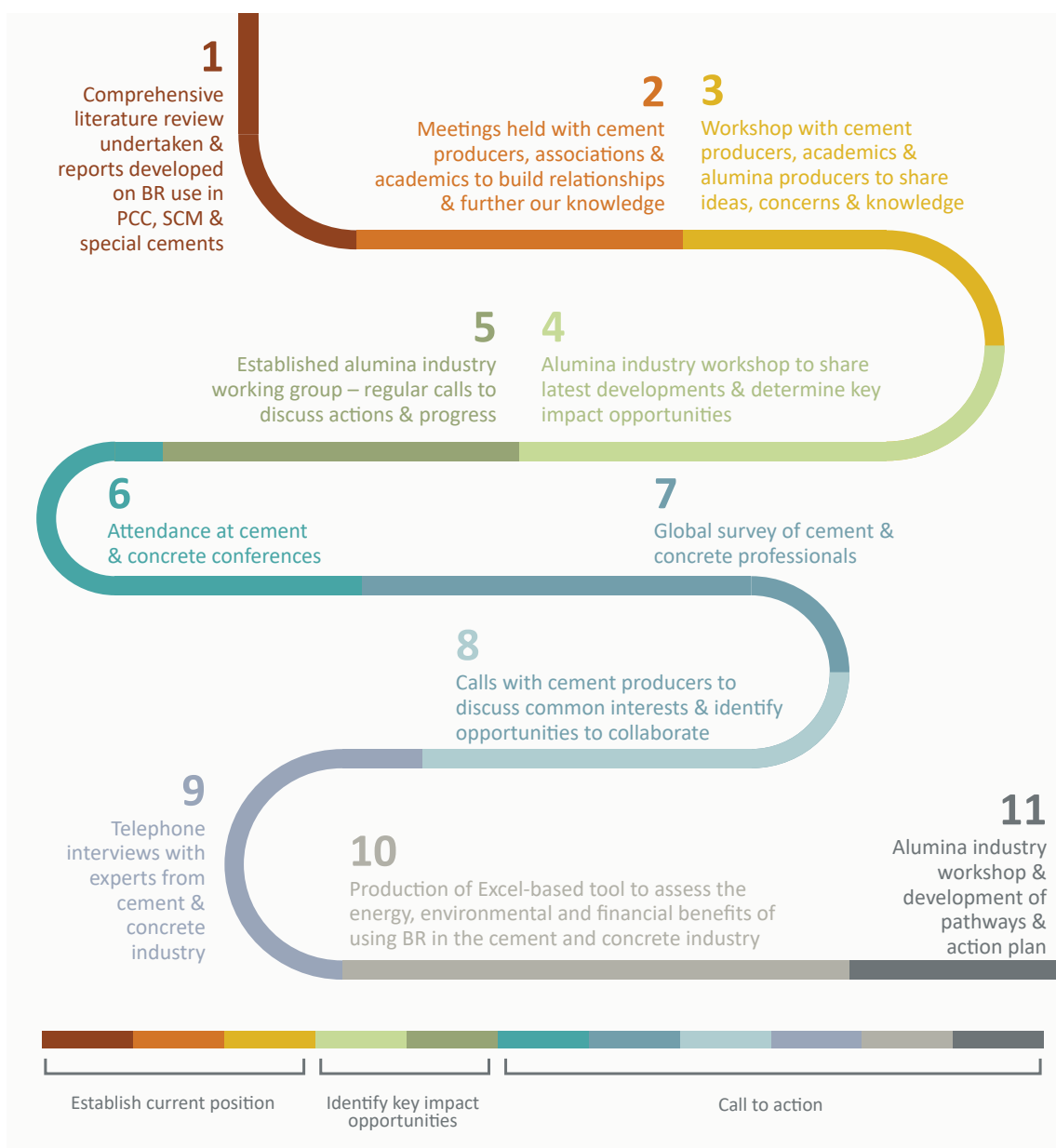


Figure 2: Roadmap development

In 2017, United Nations Environment Programme (UNEP) released a report summarising the main conclusions of a review on low-CO₂, eco-efficient cement-based materials⁴. In 2018, the International Energy Agency (IEA) and Cement Sustainability Initiative (CSI) updated the 2009 Technology Roadmap for a low-carbon transition in the cement industry⁵. These reports were reviewed as part of the 3-step framework to help identify potential co-benefits and key impact opportunities.

This Roadmap has been identified as a pathway to the achievement of ‘minimisation of the volume of residue to be stored’, an impact opportunity within the Residue Theme of the sector roadmap, ‘The Alumina Technology Roadmap for the 4th Industrial Revolution’ (ATR 4.0) (currently under development).

4. CURRENT STATUS OF BR USE IN PCC

PCC producing plants in Belarus, China, Ukraine, India, Russia, Romania, Georgia, Moldova, Cyprus and Greece are currently using unmodified BR as a raw material. It is estimated that over 3 million tonnes of BR is currently used in the production of clinker. Some examples are summarised in Table 1.

Alumina refinery	Mykolaiv	Mytilineos	Multiple
Country	Ukraine ⁶	Greece ⁶	India ⁶
Amount BR supplied	<ul style="list-style-type: none"> Maximum ~250 ktpa 	<ul style="list-style-type: none"> 2019: ~80 kt 	<ul style="list-style-type: none"> Hindalco's 4 refineries 2020: estimated 2000 kt Lanjigarh: ~100 ktpa
Cement plants supplied	<ul style="list-style-type: none"> Historical: 10 plants in Ukraine, Russia, Georgia, Moldova and Belarus Current: Due to economic situation reduced to 6 	<ul style="list-style-type: none"> 2018: 2 plants in Greece and 1 plant in Cyprus 2019: 3 plants in Greece and 1 plant in Cyprus 	<ul style="list-style-type: none"> 2020: Hindalco > 40 plants in India 2019: Lanjigarh 1 plant in India
Distance BR transported	<ul style="list-style-type: none"> Up to 1200 km 	<ul style="list-style-type: none"> Up to 1000 km 	<ul style="list-style-type: none"> Up to 900 km
Typical BR composition & range	<ul style="list-style-type: none"> 15 % Al₂O₃ (6 - 20 %) 47 % Fe₂O₃ (34 - 55 %) 3.3 % Na₂O (0.5 - 7.5 %) 12 % moisture (7 - 20 %) 	Depends on bauxite mix, average values: <ul style="list-style-type: none"> 15.2 % Al₂O₃ 42 % Fe₂O₃ 6.9 % SiO₂ 2.8 % Na₂O 12.5 % CaO 6.1 % TiO₂ 	Differs at each refinery, ranges from: <ul style="list-style-type: none"> 11 - 23 % Al₂O₃ 35 - 70 % Fe₂O₃ 3 - 14 % SiO₂ 3 - 16.5 % TiO₂ 4 - 8 % Na₂O 0.5 - 4.5 % CaO 18 - 26 % moisture LOI 6 - 12 %
BR processing	<ul style="list-style-type: none"> Use of solar drying to reduce moisture content BR blended to provide a consistent mix 	<ul style="list-style-type: none"> Use of filter press to achieve a low moisture content ~25 - 28 % After solar drying for 20-30 days this drops to ~18 % 	<ul style="list-style-type: none"> Progressive move to use of filter presses to achieve a low moisture content ~20 - 25 %
BR requirements	<ul style="list-style-type: none"> Iron oxide content > 51 % Soda content < 2 % (higher is a problem in cement) Moisture < 25 % Silica content 3 - 4 % 	<ul style="list-style-type: none"> Moisture < 20 % due to cost of transport Soda content < 3 % 	<ul style="list-style-type: none"> Prefer moisture < 20 % due to cost of transport Can accept moisture content up to 25 % without creating problems in the clinker production system
Barriers & complications	<ul style="list-style-type: none"> Problems due to freezing (Jan & Feb) and high rainfall (March, Nov, Dec) No complications in clinker process It does not require additional equipment The cake is free flowing No caking or bridging occurs when it is fed in the pyritic slag chain 	<ul style="list-style-type: none"> Unloading, storage and handling of BR at the cement plant (avoidance of dusting) Transport viable only by sea and only at cement plants with own harbour. EU Waste transport legislation 	<ul style="list-style-type: none"> Problems due to high rainfall during some seasons which slows cement production Transportation logistics
Advantages of BR	<ul style="list-style-type: none"> Increased Al₂O₃ content (+ 12 - 20 % on reference) optimises C3A content and increases reactivity This normalises the cement phase composition - especially important for cement plants utilising argillaceous raw materials with reduced aluminium in its composition Clinker produced containing these levels of BR has good granulation, reduced fines and activity 	<ul style="list-style-type: none"> Used as a clinker raw meal component between 1 - 3 wt % for PCC production Iron and alumina content 	<ul style="list-style-type: none"> Used as a clinker raw meal component between 0.8 - 3.5 wt % for PCC production Primarily as a replacement for laterite, lithomarge and sub-grade bauxite Typical comparative levels of silica, alumina and iron oxides are 22.9 - 17.1 %; 18.9 - 17.4 %; and 41.0 - 36.5 % for laterite and BR respectively Alkali content beneficial in the cement production process as it aids desulfurisation of petroleum coke

Table 1: Countries where BR is currently being used in cement production

5. OVERVIEW OF MAJOR STUDIES OF BR IN SCM FOR BLENDED CEMENTS

BR, in some cases after treatment, can improve the packing characteristics or rheological behaviour and can play a valuable role in mortars or concrete as a replacement of clinker or in combination with pozzolanic and hydraulic additives. There have been many studies demonstrating the possible benefit and some of the most significant ones are summarised below in Table 2. Further details of the studies are provided in Appendix F.

Study	BR processing & amendment	Results	Comments / Questions
University of Aveiro⁷	Unmodified BR.	Up to 7% BR in mortar gave similar compressive strengths, but workability was degraded.	More information on strength development needed.
NALCO⁷	HCl neutralised.	Up to 15 % BR in cement could be beneficial (stronger) and economic (8 % cheaper).	Economics need to be checked. Presence of chlorides would make the application in reinforced concrete impossible (risk of chloride induced rebar corrosion).
University of Beijing⁷	Bayer sinter residue from Shandong alumina plant; calcined between 400 °C and 900 °C.	The resulting materials were mixed with cement clinker and gypsum in the ratio 50:45:5; a 28-day compressive strength of 34.15 MPa was obtained after calcination at 600 °C.	Bauxite sinter residue containing 35 % calcium oxide. Availability is limited for this type of BR.
MALCO⁷	Neutralised during the calcination process by the sulfur dioxide from the petroleum coke.	Up to 15 % BR is beneficial (21 % stronger) and “nearly 7.5 % more economic”.	Economics need to be checked.
UNESC⁷	Dried, milled, blended with clay then fired at 1300 °C and annealed at 1200 °C.	The higher the temperature up to 1300 °C, the greater the pozzolanic activity, and acceptable to NBR 12653. A 70:30 mix of BR and clay gives a mortar of acceptable strength and leachability.	Cost of calcination and soak time to be taken into account and alkalinity level.
Votorantim⁷	Mixed with clay and limestone then calcined at 1150 °C and milled.	The resulting mixture had good pozzolanic properties and up to 30 % of PCC could be replaced whilst maintaining acceptable properties.	
University of São Paulo⁷	Calcined at 800 °C and/or in field conditions mixed with ashes, calcium carbonate or combined with GGBFS.	Formulations up to 20 - 25 wt.% (in-natura) of substitution of clinker without needing extra water. Larger replacement possible with calcined BR. Control of particle packing, dispersion and chemical interactions allow the production of low-clinker cement. Development of several concretes, mortars and components with acceptable performance were achieved. Stabilisation routes of BR cement made its solubility and rheology comparable to regular cement, allowing all kinds of cement-based products. Calcination was used in trials to fix alkalis and reduce surface area.	Stabilisation routes of BR cement made its solubility and rheology comparable to regular cement, allowing all kinds of cement-based products. Calcination was used in trials to fix alkalis and reduce surface area. Further research on durability of steel reinforcement is needed. <0.5 % superplasticiser is needed for adding up to 15 % BR. Whilst this will increase the cost, this will probably be offset by the cost reduction of clinker replacement.
Hydro Alunorte⁷	As produced (22 % moisture), BR was tested in combination with blended cements up to a level of 20 %.	BR gives a strength boost at 1 day and reaches the same strength at 28 days when clinker is replaced by the combination of 20 % BR and 5 % of limestone in two kinds of Portland cement (CEM I and CEM II/B-M). Performance is slightly better when fly ash is involved in CEM II/B-M since fly ash reactivity is apparently activated by higher pH.	Aspects related to sodium trapping and durability (AAR) need to be evaluated.
Belagavi⁷	Pressure filtration of BR to recover free caustic.	Can use 25 % BR to make red cement for non-structural applications.	Strength is an issue; ‘superplasticisers’ needed for workability. Colour is a restriction.

Table 2: Summary of work on evaluating BR in SCM for blended cements

6. PRIORITY SDGS

The UN 17 SDGs are part of the 2030 Agenda for Sustainable Development⁸ which set out a 15-year plan to achieve the Goals.

The use of BR in cement and concrete products can directly play a role in two priority SDGs. Responsible consumption and promotion (No.12) are about promoting resource and energy efficiency to provide a better quality of life for all. This will require partnerships between multiple stakeholders built upon a shared vision and goal (No.17):



“Sustainable consumption and production is about promoting resource and energy efficiency, sustainable infrastructure, and providing access to basic services, green and decent jobs and a better quality of life for all.”



“A successful sustainable development agenda requires partnerships between governments, the private sector and civil society. These inclusive partnerships built upon principles and values, a shared vision, and shared goals that place people and the planet at the centre, are needed at the global, regional, national and local level.”

These are unpinned by four goal targets to which using BR in cement and concrete products can contribute:

12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse

12.6 Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle

17.6 Enhance North-South, South-South and triangular regional and international cooperation on and access to science, technology and innovation and enhance knowledge sharing on mutually agreed terms, including through improved coordination among existing mechanisms, in particular at the United Nations level, and through a global technology facilitation mechanism

17.16 Enhance the global partnership for sustainable development, complemented by multi-stakeholder partnerships that mobilise and share knowledge, expertise, technology and financial resources, to support the achievement of the sustainable development goals in all countries, particularly developing countries.

Use of BR in cement and concrete products can contribute towards three additional SDGs:



“Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation”



“Take urgent action to combat climate change and its impacts”



“Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss”

7. INPUT FROM PROFESSIONALS OF THE CEMENT AND CONCRETE INDUSTRY

Information on the interest of the cement and concrete industry to use BR in PCC and SCM/blended cements has been collected in several ways. These include: a workshop with alumina producers, cement producers and academics; a survey undertaken by Gerson Lehrman Group (GLG); attendance at cement and concrete conferences; and follow up discussions with cement producers and academics.

These have all contributed to the collective understanding of the barriers and knowledge gaps preventing greater use of using BR in cement and concrete products.

A key message from attending cement and concrete conferences is the importance of promotion amongst cement and concrete producers and those working at relevant universities/institutes.

The workshop with alumina producers, cement producers and academics entailed a comprehensive discussion on the importance of technical standards, which are viewed as a critical area for progression; requiring investment, long term durability testing, lobbying and cement industry support. The main issues raised during the workshop are outlined in Figure 3.

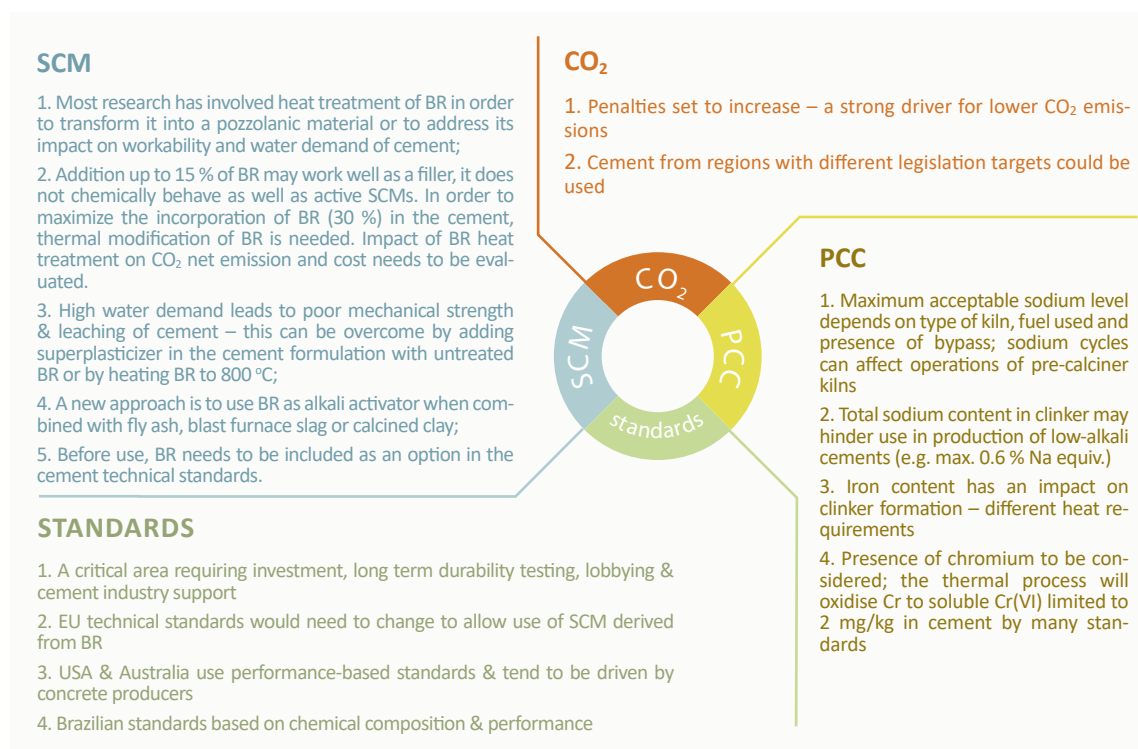


Figure 3: Main issues raised at workshop

GLG is an international organisation that has access to a network of over 650,000 seasoned professionals who can be contacted to seek an opinion on areas of interest. Questions relevant to the opportunities/barriers for using BR in PCC and SCMs were submitted to approximately 100 cement and concrete professionals in the GLG network and responses obtained from 62 people, of which, 10 were from China. Key findings from the survey are shown in Figure 4. Full results from the survey are available in Appendix E.

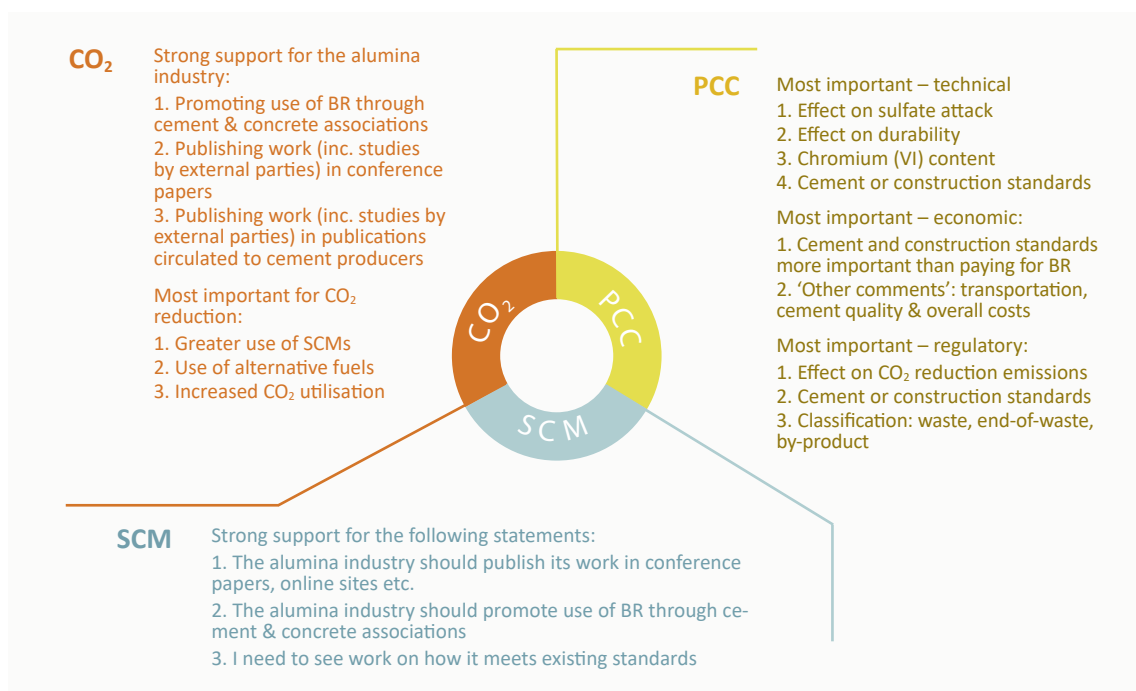


Figure 4: Key findings from GLG survey

Developing standards and regulatory frameworks and the promotion of BR were viewed by all as critical to increasing the use of BR in cement and concrete products. The time taken to develop and modify standards was accepted. Work with all parties should be encouraged to develop them but a proactive approach to build up the necessary data to submit a case, initially in Europe, was proposed as the best way forward. Use of BR as an SCM for blended cements was of most interest to the cement industry as it offers a greater opportunity for CO₂ reduction than use of BR in PCC.

8. FREQUENTLY ASKED QUESTIONS

Cement producers frequently asked the same questions when assessing the potential for using BR in cement production. Key to developing opportunities is the provision of BR compositional data and environment, health and safety information by the alumina industry.

Below are the most common questions asked by cement producers with some general answers, but each alumina refinery should prepare detailed information specific to their own BR.

What PPE do users need to wear when handling BR?

BR does not require additional precautions when compared to other commonly used alternative raw materials. PPE that should be worn include gloves and goggles to minimise skin and eye contact and dust masks to prevent inhalation of dust.

What safety precautions do I need to take when storing or handling BR?

A material safety sheet will be provided with all samples and when a supplier provides BR. BR should be stored separately from other materials; the storage area should display the correct PPE that should be worn. In the case of outdoor storage, containment of any runoff in the event of rain should be provided such that it is not allowed to leach to the environment.

Is respirable crystalline silica a concern?

Many bauxites contain crystalline silica but it is normally present as a very coarse fraction and testing has shown that the respirable fraction is considerably below levels of possible concern. Most BR will contain some crystalline silica, but, as with bauxite, it is in a very coarse form. Testing on a number of BRs, has shown the level of respirable crystalline silica to be negligible but it is

important to discuss the matter with the BR supplier. The appropriate dust masks should always be worn when working in a potentially dusty environment.

Is alkalinity a concern?

BR which is supplied in a damp form will contain a small residual level of soluble sodium compounds, which will depend on processing conditions, and will have a moderately high pH. Skin and eye irritation tests and skin sensitisation tests (to OECD guidelines) on many BRs has shown them not to cause skin or eye irritation, however, it is important to discuss the matter and observe the Safety Data Sheets (SDS) precautions with the potential BR supplier.

Is titanium dioxide a concern?

Almost all BRs contain more than 1 % titanium dioxide and some BRs will contain more than 1 % of titanium dioxide particles with a respirable particle diameter of 10 µm or less. As the composition of BRs from different manufacturers will vary, it is important to observe the guidance in the SDS provided by the BR supplier. BR is always sold as a moist material and when tested to a standard such as EN 15051-2, is classified as having 'very low' dust.

Is chromium a concern?

The chromium level should be compatible with the levels introduced by other raw materials and cement constituents. Soluble chromium should be as low as possible. The maximum chromium level in cement in Europe is 2 mg/kg according to EN197.1. Additives can be used to reduce chromium (VI) to insoluble forms but they add to the overall production cost so cement producers are reluctant to accept high chromium-bearing materials. Chromium can also enter the raw meal via other sources so it is important that the chromium level is kept as low as possible in the BR. As a rule-of-thumb, 40 % of total chromium is converted to chromium (VI) during the burning process.

Does BR contain NORMS?

All bauxites will contain very low levels of radioactive elements, termed NORM (naturally occurring radioactivity material) in particular ²³⁸U and ²³²Th, and their levels will be increased in the corresponding BR as most of the radionuclide species collect in the BR, these are termed TENORMS (technologically-enhanced NORMS). According to the European Basic Safety Standard (BSS)(European Parliament, 2014), materials containing ²³⁸U and ²³²Th (and their decay products) below 1000 Bq/kg as well as ⁴⁰K below 10000 Bq/kg are exempt from any radiological characterisation as they are unlikely to cause increased radiological exposure. Radionuclide concentrations in a recent study looking at different BRs remains well below legislative limits.

How stable is BR when stored?

Depending on the exposure, the surface layers of the BR will slowly react with carbon dioxide and form sodium carbonate. Moisture will also evaporate. Over a long period, normally years, some of the desilication products such as sodalite, sodium aluminium silicate, cancrinite etc. will react and release soluble sodium species.

What elements are likely to leach from stored BR?

If the BR is stored as received with a typical moisture content of 20 to 25 % moisture content, then very small amounts of soluble sodium species, such as sodium carbonate, could possibly leach out. If stored under conditions where rain could fall on the material, then the level of soluble sodium species could rise substantially. In addition, low levels of some other constituents in the BR could also leach out under high pH conditions. The trace levels of the heavy metals present would depend on the bauxite and the processing conditions, but the most likely contaminants would be arsenic, chromium and vanadium. It is important to establish the likely levels with the alumina producer whose material is being used.

How variable is the composition of BR?

The chemical and mineralogical composition of the BR is dictated by the bauxites used, the extraction conditions adopted, the use of additives, such as lime for desilication, and any final

washing or neutralisation stage. The alumina industry recognises the needs from users for tight control of the composition of the main elements such as aluminium, iron, silicon, calcium, and sodium and in most instances a refinery is able to control the levels of aluminium oxide and iron oxide to $\pm 2\%$, for calcium oxide and silica to $\pm 1\%$ and for sodium oxide to $\pm 0.5\%$, however, this should always be discussed with the refinery and established during trials.

What trace metals are in BR?

The presence of trace metals in BR will vary from one alumina supplier to another but is primarily dictated by the bauxite feed used. It is important for the user to discuss specific concerns with the BR supplier but for elements which might be of concern, some typical levels found across a wide range of BRs are: As - 35, Cd - 400, Cu - 50, Co - 50, Cr - 500, Hg - 0.02, Ni - 250, Pb - 120, Sb - 0.8, Zn - 100, all expressed as mg/kg.

What are the particle size & grinding characteristics of BR?

The particle size range of BR can vary substantially within the range of 0.1 μm to 200 μm ^{12,13}. This depends on whether the coarse fraction is removed during processing. However, the median particle size of BR is typically in the range 2 to 7 μm . The crystalline silica fraction is the hardest component and all other constituents are expected to present no issues during grinding processes. When BR is used as a filler, it will not play any role in the development of late strength. However, thanks to its extreme fineness, BR can boost early hydration reactions acting as nucleation seed and therefore increase the very early strength development. Additionally, the presence of very fine BR particles can contribute to the improvement of the particle grading of cement with positive impact on packing density of concrete.

How does the leaching behaviour of BR compare with other constituents that might be used in blended cements or as SCMs?

It is important that any assessment of leaching takes into account the expected environment that the materials might be exposed to. EN 12457-1:2002 (Characterisation of waste - Leaching), EN 14405 (Characterisation of waste - Leaching behaviour test - Upflow percolation test), the Synthetic precipitation leaching procedure (SPLP), toxicity characteristic leaching procedure (TCLP), and pH-dependent leaching (USEPA Method 1313) tests are all used for different conditions. In general for BR under conditions such as exposure to rainfall, the runoff will be mildly alkaline, assuming a reasonable volume of rain, and the level of sodium will increase. Slags emanating from blast furnaces such as GGBFS, ACBFS has reasonably low levels of contaminants in near neutral conditions but will rise at higher pHs. Leaching of sulfur compounds can be an issue.

What is the possible role of blast furnace slags in conjunction with BR in SCMs

Blast furnace slags, especially Ground-granulated blast-furnace slag (GGBS or GGBFS) is highly cementitious and high in CSH (calcium silicate hydrates) which is a strength enhancing compound which improves the strength and durability of concrete. There is a growing limitation on its availability and promising has shown the potential for blends of GGBFS and BR in SCM formulations. GGBS is obtained by grinding the slag produced by quenching molten slag from iron and steel making with water or rapid air cooling.

Blast furnace slags vary in composition widely with typical ranges for CaO of 30 - 50 %, SiO₂ 28 - 38 %, Al₂O₃ 8 - 24 %, and MgO 1 - 18 %. Increasing the CaO content of the slag raises the slag basicity and increases the compressive strength of the mix. The MgO and Al₂O₃ content show similar trends up to 10 - 12 % for MgO and 14 % for Al₂O₃, beyond which no further improvement is obtained. The TiO₂ level can also vary depending on the addition of Ti to extend lifetime of the refractories.

The glass content of slags suitable for blending with PCC typically varies between 90 - 100 % (the minimum required by several standards is 67 %) and depends on the cooling method and the temperature at which cooling is initiated. The glass structure of the quenched glass largely depends on the proportions of network-forming elements such as Si and Al over network-modifiers such as Ca, Mg and to a lesser extent Al.

Use of GGBS significantly reduces the risk of damage caused by alkali–silica reaction (ASR), provides higher resistance to chloride ingress — reducing the risk of reinforcement corrosion — and provides higher resistance to attacks by sulfate and other chemicals.

Slow air-cooled slag (ACBFS) is relatively crystalline and non-reactive with water. Common crystalline constituents of blast-furnace slags are merwinite and melilite. Other minor components which can form during progressive crystallisation are belite, monticellite, rankinite, wollastonite and forsterite.

9. IMPACT OPPORTUNITIES

12.5 | 12.6 Identifying impact opportunities to address SDG goal targets 12.5 & 12.6



The IEA & CSI Technology Roadmap⁵ identified four ‘carbon emissions mitigation levers’ for the cement industry as shown in figure 5.

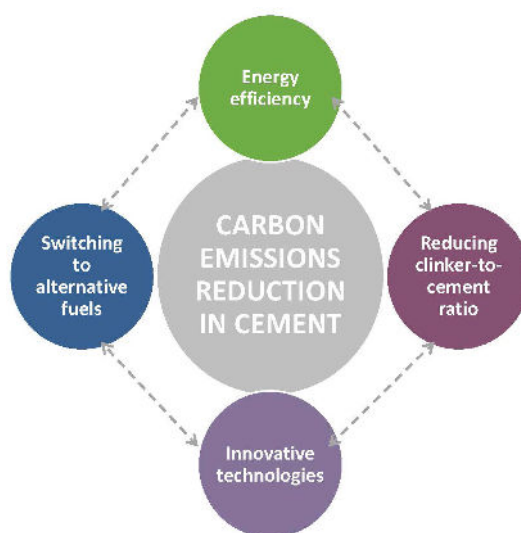


Figure 5: Cement industry carbon emission mitigation levers⁵

UNEP Eco-efficient cements⁴ outlines two key areas that can deliver CO₂ emissions reductions related to cement and concrete:

1. The increased use of low-CO₂ supplements (SCMs) as partial replacement for PCC;
2. More efficient use of PCC in mortars and concrete.

Recent studies have shown that a blend of calcined clay and limestone has great potential to be used in percentages of up to 45 % replacement of clinker in cement, with compressive strength equal or superior to Portland cement. This new cement was developed and named LC3 (calcined clay limestone cement) by LC3 group from Ecole Polytechnique Fédérale de Lausanne (EPFL).

The incorporation of BR into LC3 could be investigated to see if BR may promote benefits for cement final properties, such as: packing optimisation and solubility increase of aluminosilicate from metakaolin (calcined clay).

Two high impact opportunities for the short to medium-term have been identified for use of BR in cement production which can contribute to the goals outlined by the cement industry; whilst simultaneously making the most transformative contributions to the priority SDGs identified by the alumina sector (Figure 6). Using BR in special cements and geopolymers is recognised as having the potential to contribute over the long-term but is not covered by this Roadmap. Further information on the opportunities for use of BR in special cements is available in Appendix F.

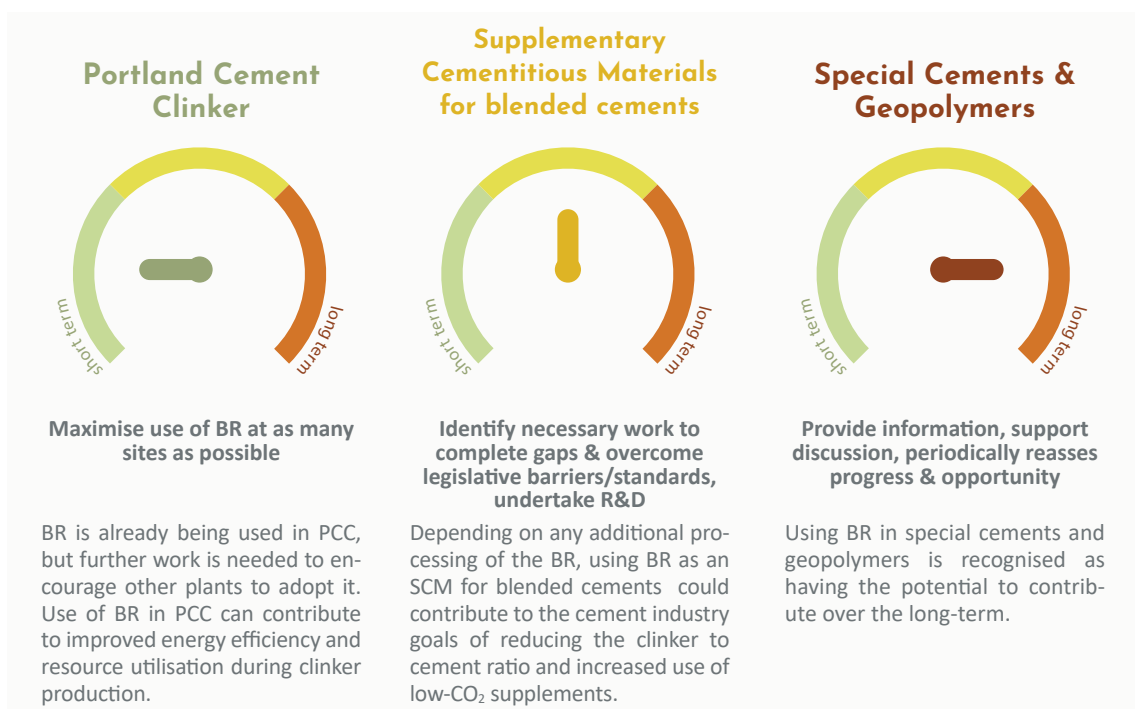


Figure 6: Impact opportunities

An Excel-based tool has been developed to assess the energy, environmental and financial benefits of using BR in cement (see page 30 for further information). The tool was run based on the assumption of a cement plant operating in Germany, producing 1,000,000 t of clinker per year, the raw meal of which contains 84 % wt. limestone and is produced in coke-fired rotary kilns. Results show that 5 % addition of BR in PCC has the potential to reduce CO₂ emissions during the clinker production process by nearly 8,000 tonnes CO₂-e per 1,000,000 tonnes of clinker per year (Figure 7). Energy savings totaling over 85 MWh are possible, predominantly due to savings during raw material grinding (Figure 8).

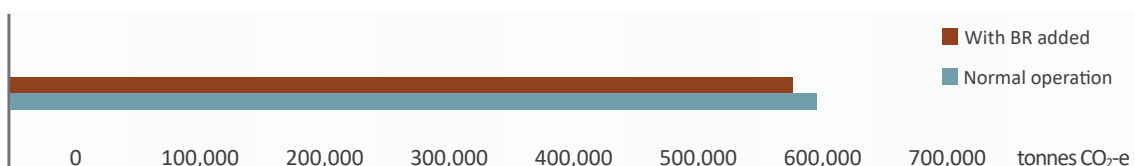


Figure 7: Total emissions of clinker production with and without BR addition (tonnes CO₂-e) based on the assumption of 1,000,000 t of clinker per year, the raw meal of which contains 84 % wt. limestone and is produced in coke-fired rotary kilns.

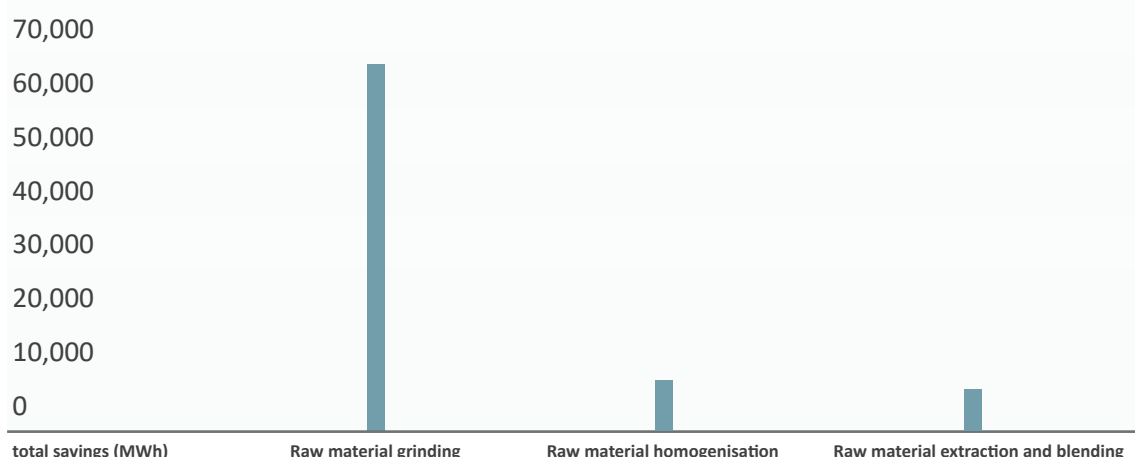


Figure 8: Energy savings per stage of production (MWh) based on the assumption of 1,000,000 t of clinker per year, the raw meal of which contains 84 % wt. limestone and is produced in coke-fired rotary kilns.

Using 10 % of BR as SCM could replace 73,500 tonnes of clinker. This would result total emissions savings of nearly 125 kg CO₂-e/tonne of cement (Table 3). Energy savings are directly related to the percentage of BR added (Figure 9). A substitution of 30 % BR could result in saving nearly 20,000 MWh of energy.

Type of emissions	Total emissions (tonnes CO ₂ -e)		
	Normal operations	With BR added (10%)	Emissions avoided
From clinker production – raw meal calcination	827.4	703.3	124.1
From electricity	0.1	0.1	0.1
Total	827.4	703.3	124.2

Table 3: Total emissions saved by replacing 73,500 tonnes of clinker with 10 % of BR as SCM

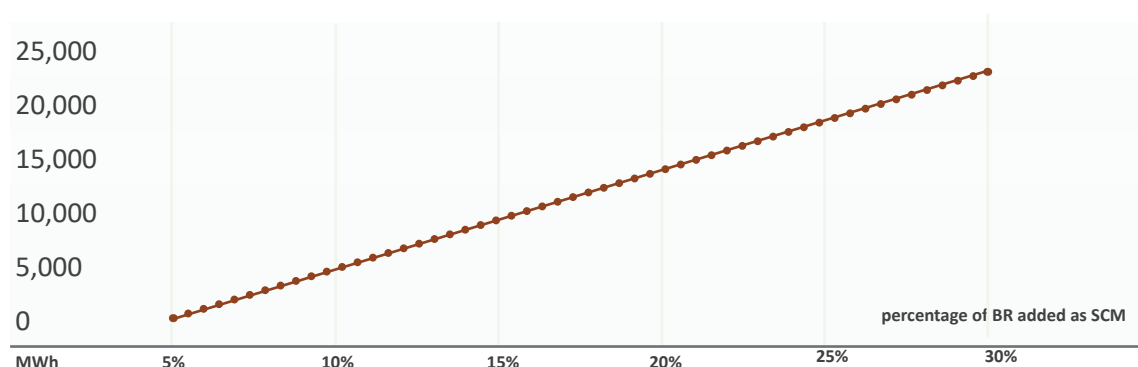


Figure 9: Energy savings are directly related to the percentage of BR added as an SCM

10. POTENTIAL UTILISATION OF BR

Potential utilisation of BR in cement production has been calculated on a ‘best case scenario’ basis - assuming all BR can be utilised without consideration of limiting factors such as logistics, technical issues or raw materials requirements. Cement production data from Cembureau and U.S Geological Survey (USGS) for 2017 has been used, with Cembureau data taking precedence where production figures differ. Historical and future BR production data was estimated using the IAI material flow model. All data is estimated. Countries have been grouped to align with IAI regional models.

In theory, global cement production is large enough to utilise global BR production on an annual basis. BR production in 2017 is estimated to have been 159 Mt – this accounts for only 4 % of global cement production. BR production is expected to increase to 220 Mtpa by 2040¹. Even if global cement production remains the same the increased amount of BR could still be consumed (Figure 10). Obviously, this does not take into account any limiting factors which would all need to be overcome for this to be possible.

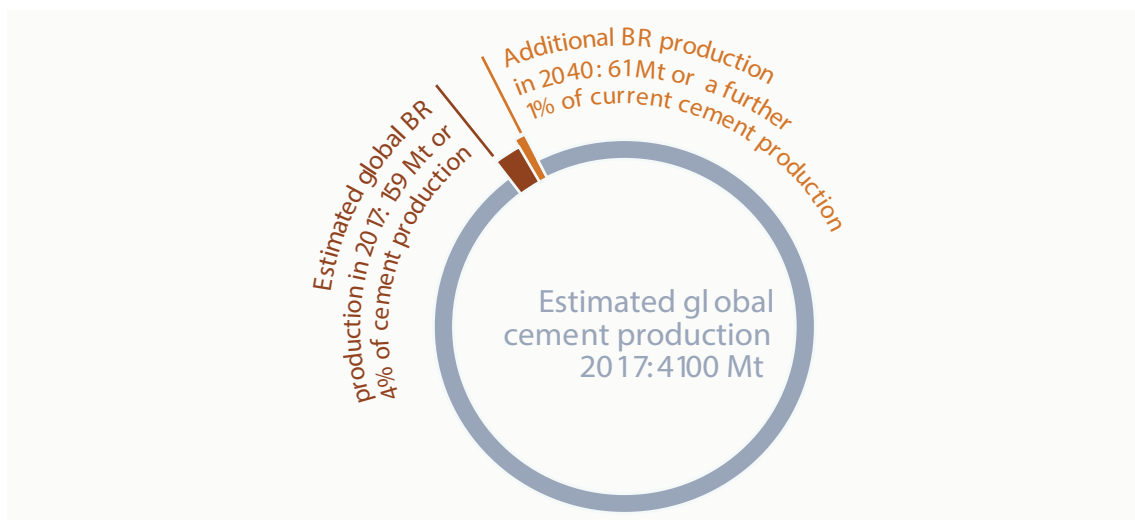


Figure 10: Estimated global BR and cement production. Sources: USGS⁸, Cembureau⁹, IAI¹

BR is already being used as a raw meal component at several cement plants in PCC production at rates of 2.5 % or greater. Whilst global cement has the potential to utilise 103 Mtpa of BR in PCC this doesn't consider the location of the cement plants in relation to the BR storage areas. Potential utilisation of BR in PCC at a 2.5 % utilisation rate by region indicates that up to 84 Mtpa or over 50 % of BR production could be consumed (Figure 11).

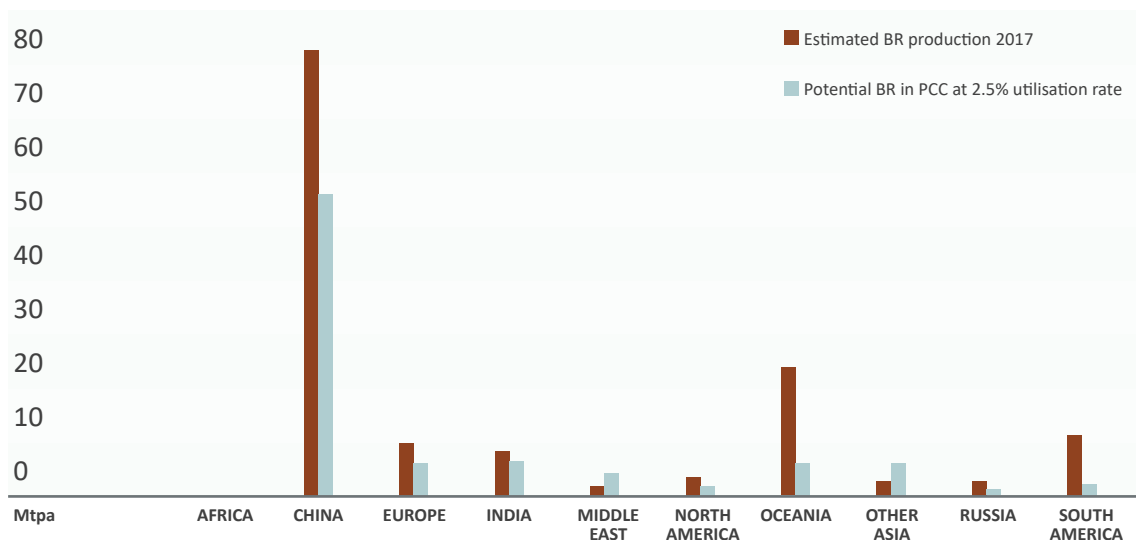


Figure 11: Potential utilisation of BR in PCC by region. Sources: USGS⁹, Cembureau¹⁰, IAI¹

If BR can be used as an SCM for blended cements then the potential is greater. Utilisation rates of up to 10 % would allow for over 130 Mtpa or nearly 85 % of BR production to be used regionally (Figure 12). Under this scenario there would be sufficient potential utilisation in SCM in all regions except Oceania. However, in certain circumstances transporting BR may be possible.

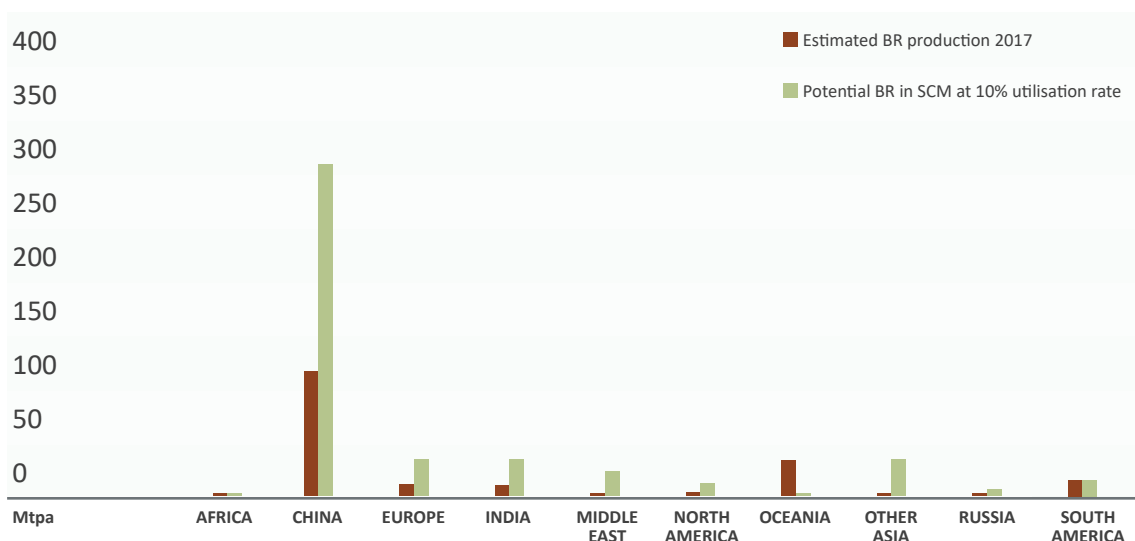


Figure 12: Potential utilisation of BR in SCM for blended cements by region. Sources: USGS⁹, Cembureau¹⁰, IAI¹

17 PARTNERSHIPS FOR THE GOALS



17.6 | 17.16 Identifying impact opportunities to address SDG goal targets 17.6 & 17.16

In order to encourage international co-operation, this Roadmap and technical information on the use of BR will be shared with all alumina producers; including new or smaller alumina producers in Turkey, Malaysia, Guinea, Vietnam and India. Guidance will be given on how to approach local cement producers. Where confidentiality allows, all technical information on the use of BR in PCC and SCM for blended cements will be widely disseminated to alumina producers and other interested parties, including those in developing countries.

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE



Contributing towards SDG 9

The use of BR in the raw meal or as clinker replacement in SCM for blended cements may support sustainable industrialization and innovation for two of the biggest manufacturing industries. This is particularly true for undeveloped and developing countries, whose demand for cement and aluminium derived materials is expected to increase. In addition, particularly in the case of SCM for blended cements, it may directly reduce carbon dioxide emissions.

13 CLIMATE ACTION



13 Contributing towards SDG 13

The use of BR in cement and concrete product may directly reduce carbon dioxide emissions.

15 LIFE ON LAND



15 Contributing towards SDG 15

A reduction in BR storage areas will also reduce the risk of degradation of land and underground water flows as well as reduce impacts on biodiversity.

11. KNOWLEDGE GAPS & BARRIERS PREVENTING GREATER USE OF BR

Despite the discussions held with users/potential users and the work undertaken to date, some gaps in knowledge relating to increased usage in PCC and implementation of usage in SCMs still exists. The key areas where questions remain are:

1. Sodium and the relative importance of the soluble sodium species

The soluble soda can be reduced by improved washing on the filter press, but the sparingly soluble soda species can only be removed by treatment with calcium hydroxide or similar route. More information on what happens to the soluble sodium and also to the sodium bound in sodium aluminosilicate, cancrinite etc at different stages of treating and using SCMs is needed.

2. BR activation

The optimum activation conditions for different BRs need to be defined and the following questions answered:

- What happens during activation of the BR?
- What is the effect on strength?
- What is the effect on durability and other important cement characteristics?

3. Benefits BR might have in SCM for blended cements

The benefits need to be determined:

- Can BR be used as a pozzolanic agent?
- Can BR be used simply as a filler, where its particle size distribution could lead to better packing density?
- How much value does the latter benefit the industry?
- Do the potential downsides outweigh the benefits?

4. Standards relating to PCC and SCM for blended cements

As there are no standards currently existing for using BR in SCM for blended cements, work will be required to assess their performance based on different pre-treatments, addition levels and other components used, strength development and the durability of the final products.

5. Leaching characteristics and tests

There are two knowledge gaps which need completing:

- Leaching characteristics
- Most appropriate test methods to be used

Additional barriers to greater use of BR in PCC and SCM for blended cements are summarised in Table 4.

Barrier	Details and/or target	Action required
TECHNICAL - PCC		
Sodium level & form	<p>Different for different plants (depending on the type of PCC being produced and the type of kiln).</p> <p>Total sodium level is the most important, but sodium cycles can be a problem at the pre-calciner stage.</p>	<p>Soluble sodium compounds can be reduced by washing the BR and the use of press filters to minimise the liquor content.</p> <p>Investigate effectiveness of reducing total sodium in BR by modification of Bayer process.</p> <p>Obtain information from local cement producers on an ad hoc basis.</p>
All levels of impurities	The presence of trace metals in BR will vary from one alumina supplier to another but is primarily dictated by the bauxite feed used.	Obtain information from local cement producers on an ad hoc basis.
Moisture level	<p>Affects energy and transportation costs.</p> <p>< 20 % is acceptable for most clinker production systems; < 15 % is preferred at some locations (this may lead to dust issues in some places); 15 - 18 % is the optimum level when the BR has a fine PSD.</p>	Use moisture reduction processes e.g. filter press, mud farming, solar drying.
Al/Fe ratio limitations	Standards are different in different countries.	Obtain information from local cement producers on an ad hoc basis.
Level of radioactivity	May affect handling/transportation and/or public perception. However as low levels of BR are used, no issues foreseen.	<p>The levels of radionuclides in BR will vary so users should discuss the particular BR with the supplier. Specific regulations in the country will also need to be considered.</p> <p>IAI to prepare information for publication.</p>
Leaching	<p>Leaching from cements made from BR needs to be reviewed further, especially chromium which could be converted to chromium (VI) in the kiln.</p> <p>Leaching from BR stored at cement plants must also be considered.</p>	<p>Undertake work to further our understanding of leaching behaviour of specific contaminants from PCC containing BR; determine levels for specific critical elements such as chromium.</p> <p>The leaching characteristics of specific BRs should be determined.</p>
Colour	In some countries, darker cements are perceived to be 'stronger'. However, darker colours are also a disadvantage in hot countries due to heat absorbing characteristics.	<p>Undertake relevant testing on heat absorption potential.</p> <p>Testing of colour should be done on a case by case basis to see the impact of BR in cement at various percentages.</p>
TECHNICAL - SCM FOR BLENDED CEMENTS		
Sodium level & form	<p>Soluble sodium can increase risk of alkali silica reaction (ASR).</p> <p>Sodium level is also limited by some standards.</p>	Investigate effectiveness of reducing total sodium in BR by modification of Bayer process.
Additional processing	Need for additional processing of BR such as calcination.	Undertake research to determine optimal BR calcination conditions (regarding final composite cement properties) alone and together with clays.
Standards	Not available.	<p>As a first potential step, develop technical standards.</p> <p>Encourage work to develop standards.</p>
Moisture level	Higher moisture leads to higher energy utilisation to dry BR which increases carbon dioxide emissions. If there is additional treatment such as calcination or pyrometallurgy, then there is no residual moisture.	BR produced by farming or using a press filter is likely to have a moisture content of 23- 27 %. Spreading/ solar drying can also be used to reduce the moisture content to 20 % or less.

Barrier	Details and/or target	Action required
Durability	<p>Production and use of blended cements including BR as cement constituent has to be tested for durability.</p> <p>Targets are linked to standards.</p> <p>Alkali-silica reactions.</p> <p>Sulfate attack.</p>	<p>Besides contribution to strength development, durability of cement/concrete must be tested according to applicable local standards; this includes, among others, alkali-silica reaction, carbonation, sulfate & chloride attack, and heat of hydration.</p>
Level of radioactivity	<p>U and Th contents a potential concern.</p> <p>May affect handling/transportation and final content since will be used at a higher level than in PCC.</p>	<p>IAI to prepare information for publication.</p> <p>The levels of radionuclides in BR will vary so users should discuss the particular BR with the supplier. Specific regulations in the country will also need to be considered.</p>
Colour	<p>In some countries, darker cements are perceived to be 'stronger'. However, darker colours are also a disadvantage in hot countries due to heat absorbing characteristics.</p> <p>The final colour of the SCM will depend on processing. Acceptability of this colour will depend on the region and application.</p>	<p>Undertake relevant testing on heat absorption potential.</p> <p>Testing of colour should be done on a case by case basis to see the impact of BR in cement at various percentages.</p>
PLANT SPECIFIC		
Dust management	<p>Dusting during handling is known to be an issue, which is worsened by the very visible BR colour.</p>	<p>Whilst BRs are not expected to be dusty when sold, appropriate dust masks, and other PPE, should always be worn when working in potentially dusty environments.</p> <p>Advise cement plants on suitable storage/additional silos and feeders to match specific local conditions.</p>
Cement mix	<p>Availability, cost and market of regular SCM e.g. fly ash, GGBFS, calcined clay.</p>	<p>Understand the competition.</p>
Alkalinity/Na	<p>Potential H&S issues if pH is high. Inefficient treatment can result in high levels of residual liquor leading to skin or eye corrosivity/irritation/sensitization, and failure in UN Section 37, class 8 tests for transportation.</p> <p>Possibly refractory issues, cement rings formation.</p> <p>Influence on viscosity in clinker production</p>	<p>Use processes to reduce soluble sodium species e.g. filter press, mud farming, neutralisation with acid (note chlorides not acceptable), CO₂.</p>
BR composition	<p>Each cement plant will have its own specific requirements and BR from different alumina plants will have different chemical/mineralogical compositions.</p>	<p>Evaluate the variability of the most important physical and chemical parameters of BR and its impacts on cement producers' needs.</p>
REGULATORY		
Hazard classification of BR	<p>Different in different countries, it substantially increases transport costs if rated hazardous.</p>	<p>Aim to seek a new classification for these materials or appropriate 'End of Waste' Directive. An alternative approach is to seek to regard BR as a product and undertake the necessary testing to apply for REACH registration.</p> <p>EU RemovAL project¹¹ has prepared a policy document for Filtered, Farmed & Conditioned BR which has a lower pH, moisture level and soda level. The objective is to seek a new classification and establish a protocol to facilitate sales.</p>
Chromium level	<p>Could be present from many sources.</p> <p>Oxidised to chromium (VI) in the kiln.</p> <p>Sodium increases solubility of chromates.</p> <p>Target: < 2 mg/kg in cement (acc. EN 197/1).</p>	<p>Use metal sulfates to reduce chromium level.</p>

Barrier	Details and/or target	Action required
Standards	Widespread variation globally with different drivers. Technical standards would need to change to allow use of SCM. Long term durability studies needed to enable use of BR. Currently a significant impediment.	Work with the cement/concrete industry to influence regulators for implementing changes in standards. As a first potential step, develop technical standards.
Transport	Different requirements internally within a country. Different transport requirements internationally.	Focus on local synergies – look for alumina and cement plants close together. Learn from sites where BR is successfully used in cement production.
Respirable titanium dioxide levels	Proposed new EU legislation may affect classification of BR if respirable titanium dioxide levels are > 1 %.	Undertake testing on respirable titanium dioxide levels in the BR and compounds/phases present. Whilst BRs are not expected to be dusty when sold, appropriate dust masks, and other PPE, should always be worn when working in potentially dusty environments.
PREJUDICE		
Image of BR	Often regarded as a toxic, slurry/mud, hazardous material.	Produce information addressing concerns.
Radioactivity	Concerns about radioactivity of the final products.	Need data for the requisite BR to prepare the necessary documentation. IAI to prepare information on risks relating to using BR.
COMMUNITY		
Dust management	Community concerns about hazards of the dust during storage/loading/unloading.	Advise cement plants on suitable handling facilities/storage/additional silos and feeders to match specific local conditions IAI to prepare information for publication.

Table 4: Summary of the barriers to greater use of BR in PCC and SCM for blended cements.

Knowledge gaps and barriers exist in multiple disciplines providing a further challenge as collaboration and support will be required by multiple stakeholders. These relationships are explored in Figure 13. The IEA & CSI Technology Roadmap⁵ identified similar cross-cutting barriers for implementing greater use of SCM for blended cements. Market awareness and acceptance of new products, regional variation in building standards and logistics will all be a challenge. A combined effort from both sectors will be needed to deliver success.

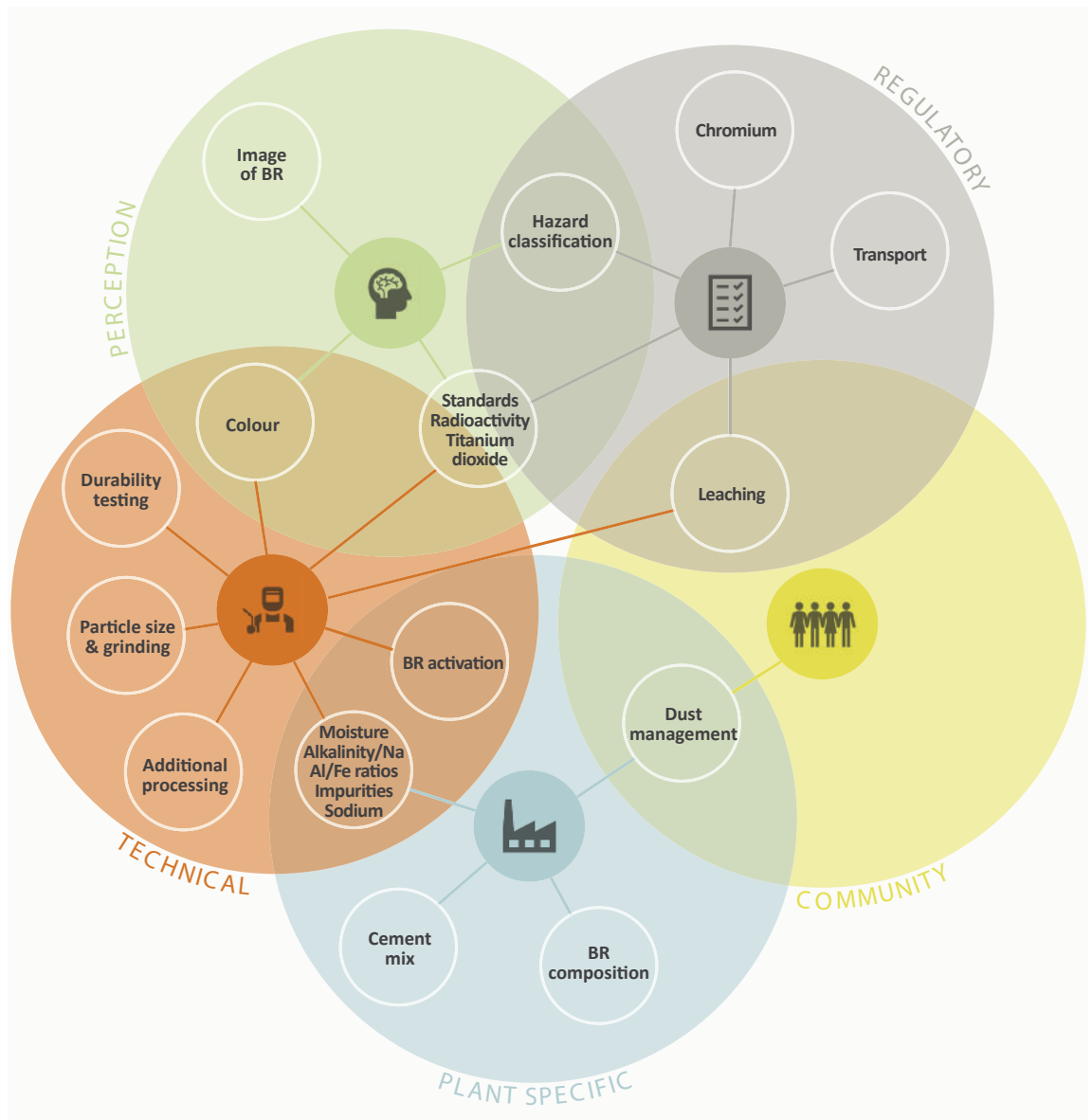


Figure 13: Knowledge gaps and barriers preventing greater use of BR

12. CLOSING KNOWLEDGE GAPS AND OVERCOMING BARRIERS

A systematic approach will be used to address each of the issues identified and how they can be better understood, eliminated or mitigated.

Sodium/high alkalinity

The high pH is a problem from both a health and safety aspect and potentially adverse effects in cement production and performance. During clinker production, the high sodium may attack the refractory lining or affect viscosity control. Meanwhile, in blended cement formulations, a reaction or leaching may be an issue. High soluble alkali levels give high early strength development but are known to decrease the compressive strength in the longer term.

The nature of the sodium present also needs to be considered in detail. The sodium may be present in a highly soluble form or as a sparingly or as an insoluble/sparingly soluble form. The highly soluble residual sodium will lead to an elevated pH and could lead to a hazardous rating which will affect transport costs. Both high sodium levels and high pH may be reduced when press filters are used. Washing the bauxite residue, accelerating carbonation using carbon dioxide, intensive farming or acid neutralisation could also be considered to reduce the pH.

From the clinker chemistry point-of-view, reactions during sintering will destroy almost all existing mineral structures and form new clinker minerals. After that, sodium can be bound in different compounds, of which typically 50 % is soluble, hence the issue of limiting overall sodium content to avoid risk of alkali-aggregate reaction in the presence of reactive (amorphous) aggregates. The general accepted level of soda in BR used in clinker is < 3.0 %; however, in certain situations, higher levels have been found to be beneficial.

Another issue of concern is the effect on the final products is the Alkali-Silica Reaction (ASR), or Alkali-Aggregate Reaction (AAR), which adversely affects durability of concrete and can be catalysed by too high concentrations of alkali hydroxides. ASR needs a minimum of three conditions to happen: the presence of reactive aggregates; presence of soluble alkali; and the presence of water in hardened structures. Reactive aggregates contain certain amounts of reactive silica, i.e. amorphous silica/silicoaluminous glass, or microsilica particles able to react in the presence of alkali in a high pH environment.

Meanwhile, in pozzolanic cement, the pozzolan is finely ground and therefore its reaction in concrete will take place throughout the hardened paste and produce a finely dispersed gel which will close concrete pores improving durability without any risk to structural properties, the ASR involves the surface of reactive aggregate granules. In that case this topochemical reaction is limited to a specific area and the expansive reaction products will not have space to grow, thus leading to concrete cracking. As discussed elsewhere in the document, not all alkalis in clinker/cement are soluble, so referring to $\text{NaO}_{2\text{eq}}$ or sodium equivalent ($\% \text{Na}_2\text{O} + 0.658 \times \% \text{K}_2\text{O}$) on the basis of the total Na_2O and K_2O is a mistake, since only the soluble part can contribute to ASR. Unfortunately, standards for low alkali cement still consider the “wrong” formula and therefore the limit of e.g. 0.60 % is based on total alkali content. Thus, it is important to determine sodium and potassium in cement and other materials for quality control of the products.

The level of di-potassium oxide in BR is always very much lower than di-sodium oxide, typical levels are 0.04 %.

High alkali levels in Portland Cement must be avoided, due to the risk of heavy efflorescence, whilst this is not harmful in itself, aesthetically it is not acceptable. The situation of alkali contained in BR-derived SCM has to be considered on a case-by-case basis.

Chromium

With regard to chromium and health and safety aspects, the water-soluble compounds of chromium in cement are most relevant, specifically compounds of the form chromium (VI). Chro-

mium in the cement can originate from: raw materials; fuel; magnesia-chrome kiln refractory brick; metal pick up from the grinding process, if chromium alloys are used; and additions such as gypsum, pozzolans, GGBFS, mineral components, and cement kiln dust. The cement process, specifically kiln conditions, can influence how much chromium (VI) will form. In the kiln, the oxidising atmosphere will play the largest role, with more oxygen in the burning zone leading to increased chromium (VI) formation. Alkali concentration is also of importance, since chromium (VI) in clinker is primarily in the form of chromates. In the finishing mill, thermodynamically favourable conditions for oxidation to chromium (VI) exist, including high air sweep, moisture from gypsum dehydration, cooling water injection, and grinding aids, along with the high pH of the cement. Several materials have been used to reduce the level of soluble chromium (VI) in cement. The most widely used material is ferrous sulfate; other materials include stannous sulfate, manganese sulfate, and stannous chloride. Some of these materials have limitations such as limited stability, limited supply, and possible influence on cement performance. In all cases, some form of dosing and mixing equipment is required.

Leaching

The presence of trace metals in BR will vary from one alumina supplier to another but is primarily dictated by the bauxite feed used. In BR, almost all of these species are only soluble under conditions of 'very high' or 'very low' pH. The form of these species is likely to be affected by further processing and testing should be carried out on the final product to assess any leachability issues. It is important for the user to discuss specific concerns with the BR supplier for elements which might be of concern, some typical levels found across a wide range of bauxites residues are: As - 35, Cd - 400, Cu - 50, Co - 50, Cr - 500, Hg - 0.02, Ni - 250, Pb - 120, Sb - 0.8, Zn - 100, all expressed as mg/kg.

Transportation

The transport cost will be dictated by the distance, moisture level, method of transport, the classification of the BR and local/national/international regulations. Material with a lower moisture is obviously a considerable advantage and press filtered, farmed and air-dried BR are all steps in the right direction to achieve a lower cost. In some cases, a moisture content of < 20 %, can result in dusting issues during handling of BR. 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, if the alkalinity is too high, it can cause pitting of aluminium which is a part of the UN transport code test procedure.

Details of transport regulations for Australia, Canada, the EU, Greece, India, and Ireland are summarised in the Appendices B and G.

Standards relating to BR in Portland cement clinker and SCM for blended cements

The full chemical and mineralogical composition, and the range of values likely to be found, should be provided to potential users. As well as all the major constituents, this should include all minor elements, especially chromium, potassium and phosphorus. It is important that potential users satisfy themselves that based on this chemical and mineralogical information the cement produced will meet all the national and international standards that they require.

It is essential that the incorporation of BR in Portland cement clinker satisfies the local requirements for cement: in most cases this is the case, but it is important to ensure that the chemical/ mineralogical composition of the BR being used meets the national or international requirements for the cement being manufactured. To date the use of BR has neither been approved as an addition for blended cements nor in concrete.

Some of the key standards are summarised in the "Appendix C: Standards".

Economics

The costs related to BR disposal vary enormously between plants and are dependent on a number of factors including, the availability of a safe suitable disposal site, the use or otherwise of drum or press filters, the distance from the plant to the disposal area and the method of conveying used; this is normally by pumping, but occasionally by conveyor belt or truck. It should be noted that pumping over long distances can be achieved, even in excess of 50 km, but such long distances are rare. Local terrain, climatic conditions, monitoring requirements and legislative factors will all influence the disposal cost. It is estimated to be between 1 and 3 % of the total production cost, equating to an operating cost of perhaps US\$5 to 15 /t of alumina produced although it can be significantly higher for some plants. In addition to these operating costs, final closure of the site needs to be considered. These closures will vary significantly and will be dictated by the terrain of the site, the storage method used, climatic conditions, national closure requirements, final end use, land ownership, monitoring of any leachate, ongoing inspection of any dams or embankments and post closure land maintenance.

The value of the BR to a cement producer or user will depend on the contribution the BR makes to the cement properties, and the availability/cost of other materials that might be used. The costs paid for the BR vary widely, ranging from cases where cement plants have requested 'gate fees' for processing BR, to cases where the transportation cost has been paid, through cases where compensation for the iron and aluminium has been paid.

Cost and availability of other additives in SCMs such as fly ash, GBFSS and gypsum vary markedly between countries and regions as well as the distance from the user, but are typically in the range €20 to 35/t.

Embodied energy

The energy, environmental and financial benefits of using BR in the cement and concrete industry are not well understood. Ecole de Technologie Supérieure (ÉTS), an entity within the Université du Québec network, in Canada, were engaged to produce an Excel-based tool to assess these benefits.

The tool provides a simple assessment of the possible applications of BR in both production of PCC and the use of BR in SCMs at different stages of the process. It evaluates electricity use, fuel consumption, expected emissions and related costs per tonne of material produced, comparing all possible scenarios of adding BR to the baseline of normal operation of the cement plant. In addition, the tool assesses the logistical expenses and potential cost avoidances and revenues that are possible for the BR producer.

The tool can calculate the optimum addition of BR to the cement raw mix in PCC production. The BR is evaluated on its chemical composition and the amount of BR that can be added is determined in combination with the raw mix composition and raw meal factors (alumina modulus, silica modulus, lime saturation factor). Figure 14 demonstrates potential data inputs from the cement industry. The tool assesses both emissions and energy savings for BR as SCM. It limits the addition of BR to a maximum of 30 % - in accordance with literature and sector standards.

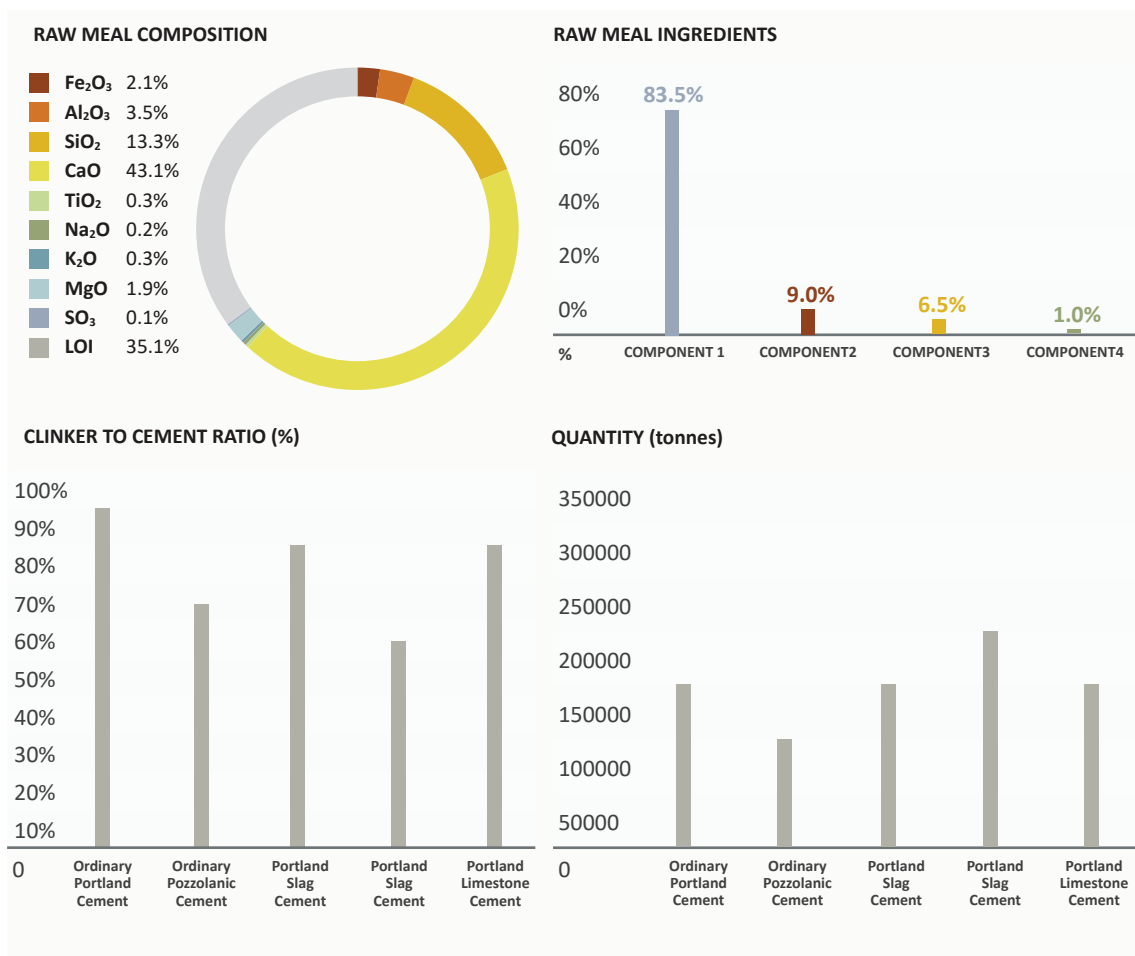













Figure 14: Example of cement industry data inputs in the excel-based tool, showing raw meal composition and ingredients.

The countries included are Australia, Brazil, Canada, France, Germany, Greece, India, Jamaica, Romania, Spain and the USA. Some example findings are discussed under 'Impact Opportunities' on page 17. The full calculation tool and user manual are available in Appendix D.

13. PATHWAYS

This Roadmap identifies a series of key pathways (Table 5), partners and actions (Figure 15) to deliver on the key impact opportunities. Successful implementation of the pathways requires collaboration between several stakeholders and commitment across:

1. Product development – to address technical barriers and knowledge gaps identified in the Roadmap;
2. Process innovation – to improve the way the alumina sector and governments/regulators operate to allow for greater use of BR in cement and concrete products;
3. Partnership building – to leverage collective resources and drive mutual value propositions, and
4. Promotion – to encourage the use of BR in cement and concrete products by demonstrating the benefits.

Key pathways	Category	Key partners	SDGs	Action (fig. 15)
1. Provide solutions to existing barriers & fill knowledge gaps.	Product development	Alumina industry Research institutes Cement producers Concrete producers	12.5	 2 3 4 5
2. Establish joint research projects between alumina and cement & concrete producers to investigate use of BR in PCC or SCM for blended cements & develop technical approval documents	Product development & Partnership building	Alumina industry Governments Cement producers Concrete producers BR processing technology suppliers Research institutes	17.6 17.16 12.5	 3 4 5  5 6
3. Demonstrate benefits in carbon dioxide emission reduction that can be achieved using BR in PCC & SCM for blended cements.	Promotion	Alumina industry Cement producers Concrete producers Cement associations Concrete associations Regulatory bodies BR processing technology suppliers	12.6	 3 5 6
4. Establish level of interest & preparedness in incorporating BR in PCC & SCM for blended cements.	Partnership building	Alumina industry Cement producers Concrete producers Cement & concrete users	17.6 17.16	 1 2
5. Promote the use of BR in PCC and SCM for blended cements in sourcing & public procurement policies.	Promotion & Process innovation	Alumina industry Cement producers Concrete producers Governments Regulatory bodies	12.5 12.6	 1  1 2 6  4 5
6. Encourage the use of BR in cement and concrete products to further the circular economy.	Promotion	Alumina industry Cement producers Concrete producers Cement associations Concrete associations Regulatory bodies BR processing technology suppliers	12.6	 2  4 5 6  1 2 3 4 5 6



Engage stakeholders



Promote BR use



Progress knowledge

Table 5: Pathways

Actions have been developed to address the cross-cutting barriers identified in figure 13. Time-frames and key partners for implementing the actions are shown in the action plan in figure 15.




Action	Key partners	Short-	Medium-	Long-term
 ENGAGE STAKEHOLDERS	1 Follow up with cement companies & academics who have expressed interest	IAI & alumina producers		
	2 Alumina producers to liaise with local cement companies & users to gain knowledge	Alumina producers		
	3 Circulate embodied energy model to all stakeholders	IAI & alumina producers		
	4 Regularly update cement & concrete associations of progress	IAI, alumina producers & academics		
	5 Prepare a document paralleling long term synergies on sustainability challenges for the alumina & cement industries	IAI & cement associations		
	6 Encourage publications of success stories in conferences held for the cement & concrete industry	Alumina producers & academics		
 PROMOTE BR USE	1 Update documents on use of BR in cements	IAI & alumina producers		
	2 Improve IAI webpage on BR reuse (add contacts, FAQs, other resources)	IAI		
	3 Share knowledge on transportation, handling & regulation to all interested stakeholders	IAI		
	4 Encourage regulators to promote the use of 'waste'	All stakeholders		
	5 Encourage regulators to improve transport regulation	All stakeholders		
	6 Find external advocates	All stakeholders		
 PROGRESS KNOWLEDGE	1 Identify & encourage work to develop standards	Alumina producers in their respective countries		
	2 Prepare information on BR & health to address concerns	IAI		
	3 Undertake research to further understand leaching behaviour, sodium, chromium & phosphate	Alumina producers & academics		
	4 Undertake research to determine benefits BR might have in SCM for blended cement	Alumina, cement & concrete producers, academics		
	5 Undertake research to define optimum activation conditions for BR	Alumina, cement & concrete producers, academics		
	6 Review opportunities for collaboration	IAI & alumina producers		

Figure 15: Action plan

APPENDICES

REFERENCES

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3. World Business Council for Sustainable Development, SDG Sector Roadmaps 2018 https://docs.wbcsd.org/2018/04/SDG_roadmap%20Guidelines.pdf
4. United Nations Environment Programme, Eco-efficient cements: potential economically viable solutions for a low-CO₂ cement-based materials industry 2017 https://wedocs.unep.org/bitstream/handle/20.500.11822/25281/eco_efficient_cements.pdf
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APPENDIX A: BR COMPOSITION

Component	Typical range (wt%)
Fe ₂ O ₃	5 - 60
Al ₂ O ₃	5 - 30
TiO ₂	0 - 15
CaO	2 - 14
SiO ₂	3 - 50
Na ₂ O	1 - 10

Table 6: Chemical composition, expressed as oxides, commonly found in BR

Component	Typical range (wt%)
Sodalite (3Na ₂ O·Al ₂ O ₃ ·2SiO ₂ ·0-2H ₂ O·2NaX where X could be CO ₃ ²⁻ , Cl ⁻ , OH ⁻ , SO ₄ ²⁻ , or Al(OH) ₄ ⁻)	4 - 40
Haematite (Fe ₂ O ₃)	10 - 30
Al - goethite ((Fe, Al) ₂ O ₃ ·nH ₂ O)	10 - 30
Magnetite (Fe ₃ O ₄)	0 - 8
Silica (SiO ₂) crystalline and amorphous	3 - 20
Calcium aluminate (3CaO·Al ₂ O ₃ ·6H ₂ O)	2 - 20
Boehmite (AlOOH)	0 - 20
Titanium Dioxide (TiO ₂) anatase and rutile	0 - 15
Muscovite (K ₂ O·3Al ₂ O ₃ ·6SiO ₂ ·2H ₂ O)	0 - 15
Calcite (CaCO ₃)	2 - 20
Kaolinite (Al ₂ O ₃ ·2SiO ₂ ·2H ₂ O)	0 - 5
Gibbsite (Al(OH) ₃)	0 - 5
Perovskite (CaTiO ₃)	0 - 12
Cancrinite (Na ₆ [Al ₆ Si ₆ O ₂₄] · 2CaCO ₃)	0 - 50
Diaspore (AlOOH)	0 - 5
Ilmenite (FeTiO ₃)	0 - 5

Table 7: Typical range of components found in BR

Further information is available in the following documents:

- International Aluminium Institute: Opportunities for using of bauxite residue in Portland cement clinker production 2020 http://www.world-aluminium.org/media/finder_public/2020/03/16/opportunities_for_use_of_bauxite_residue_in_portland_cement_clinker_2020.pdf
- International Aluminium Institute: Opportunities for use of bauxite residue in Supplementary Cementitious Materials 2020 http://www.world-aluminium.org/media/finder_public/2020/03/16/opportunities_for_use_of_bauxite_residue_in_supplementary_cementitious_materials_2020.pdf

APPENDIX B: EU LEGISLATION ON WASTE SHIPMENTS

Further information is available from the following websites:

- <http://ec.europa.eu/environment/waste/shipments/legis.htm>
- <http://ec.europa.eu/environment/waste/shipments/links.htm>

APPENDIX C: STANDARDS

Australia

AS 3972-2010 General purpose and blended cements

This Standard specifies minimum requirements for hydraulic cements including general purpose and blended cements.

AS 1316-2003 Masonry cement

This Standard specifies requirements for masonry cement, a hydraulic cement intended for use in mortars for masonry construction in conjunction with masonry units of clay, calcium silicate, concrete and square dressed natural stone.

Brazil

NBR 16697:2018 Portland Cement requirements

The standard increases the limestone filler content in various types of cement. This modernisation aims to be aligned with international regulatory standards and meets the guidelines of the International Energy Agency (IEA) and the Cement Sustainability Initiative (CSI), which encourage the adoption of more advanced alternatives or technologies to reduce specific CO₂ emissions per tonne of cement. Beside this, it meets the assumptions recommended by the Cement Technology Roadmap Brazil 2050.

NBR 12653:2014 Pozzolanic materials for concrete and mortar

This Standard establishes the requirements for pozzolanic materials intended for use with Portland cement in concrete, mortar and paste. This Standard does not apply to active silica, metakaolin or to pozzolanic materials used as an addition during the manufacture of Portland cement.

Canada

CSA 3000: 2018 Cementitious materials compendium

This Standard addresses the following aspects of cementitious materials: definitions; chemical, physical, and uniformity requirements; tests; inspection and sampling; packaging, marking, and storage.

The cementitious materials for use in concrete are classified as follows: Portland cement; blended hydraulic cement; Portland-limestone cement; supplementary cementitious materials; and blended supplementary cementitious materials.

Europe

EN 197-1:2011 Composition, specifications and conformity criteria for common cements

This Standard defines and gives the specifications of 27 distinct common cements, 7 sulfate resisting common cements as well as 3 distinct low early strength blast furnace cements and 2 sulfate resisting low early strength blast furnace cements and their constituents.

EN413-1:2011 Masonry cement - Part 1: Composition, specifications and conformity criteria

This Standard specifies the definition and composition of masonry cements as commonly used in Europe to produce mortar for bricklaying and block laying and for rendering and plastering. It includes physical, mechanical and chemical requirements and defines strength classes.

India

IS 269: 2013 Ordinary Portland Cement, 33 Grade

This standard covers the manufacture and chemical and physical requirements of 33 grade ordinary Portland cement.

IS 8112: 2013 Ordinary Portland cement, 43 Grade

This standard covers the manufacture and chemical and physical requirements of 43 grade ordinary Portland cement.

IS 12269: 2013 Ordinary Portland Cement, 53 Grade

This standard covers the manufacture and chemical and physical requirements of 53 grade ordinary Portland cement.

APPENDIX D: BR REUSE IN CEMENT EMBODIED ENERGY MODEL

<http://www.world-aluminium.org/publications>  : Bauxite residue in cement tool

APPENDIX E: BR - CEMENT - CONCRETE INDUSTRY TRENDS

Cement Industry Trends Survey Outcomes 

APPENDIX F: OPPORTUNITIES FOR USE OF BAUXITE RESIDUE SPECIAL CEMENTS

Further information is available in the following document:

- International Aluminium Institute: Opportunities for use of bauxite residue special cements 2020 http://www.world-aluminium.org/media/filer_public/2020/03/16/opportunities_for_use_of_bauxite_residue_in_special_cements_2020.pdf

APPENDIX G: TRANSPORTATION REGULATION

Country	Domestic transportation	International transportation
Australia	<p>Waste: Depends, would need to assess against Factsheet based on commercial arrangement and any treatment.</p> <p>Controlled waste: Regulated as C100 Commonwealth Legislation Dangerous Goods – Class 8 PG III Controlled Waste - Regulated as C100 International Dangerous Goods – Class 8 PG III.</p> <p>Hazardous waste: Based on the Basel Convention, BR would be subject to the convention unless it is not corrosive and is below pH 10.5. Reuse is still considered disposal in the convention.</p>	<p>Logistically airfreight is difficult – restricted to limited quantities.</p> <p>Sea freight is easier, and road transportation packaging standards are typically used. The material would need to be a registered product with the International Maritime Organisation (IMO) with individual port approval for each destination.</p>
Brazil	<p>The process for licensing for transportation is strongly dependent on the classification as hazardous or non-hazardous under the solid waste legislation. The logistic companies need to have a specific license according to the classification. Usually, the legal process for transportation, handling and utilisation of non-hazardous residue are simpler and quicker.</p>	<p>Part of Basel Convention, which restricts or prohibits the importation or exportation of hazardous wastes or other wastes.</p>

Country	Domestic transportation	International transportation
Canada	<p>Under UN code No.3244.</p> <p>Hazardous good - Class 8 (corrosive material) substance, under dangerous goods transport regulation, section 2.40-2.42.</p> <p>Requires specific packaging and use of UN compliant containers for all sizes of shipment.</p>	<p>Airfreight is quite difficult, except in limited quantities.</p> <p>Sea freight is easier, and road transportation packaging standards normally used.</p>
Ireland	<p>Classified as waste so Trans-frontier shipment (TFS) of waste regulations apply: the receiving outlet needs to be approved in advance by the EPA & have a permit/licence to accept BR. The hauliers will have to have a waste permit for transporting the waste.</p> <p>Road transportation: ADR regulations (Carriage of Dangerous Goods by Road Regulations).</p> <p>Rail transportation: Transport of Dangerous Goods by Rail Regulations.</p>	<p>Export of materials out of the country across our border come under TFS regulations, controlled from the TFS Office in Dublin. Usually this is managed by a broker/specialised waste contractor to organise the TFS documentation.</p>
India	<p>High volume low effect waste, non-hazardous.</p> <p>For transportation by railways, it is categorised under clays & sand with a classification of 130.</p>	<p>No regulations.</p>
Germany	<p>Dry BR with a pH < 11.5 is not a hazardous waste and therefore isn't a dangerous good.</p> <p>BR containing caustic (pH > 11.5) is "metal corrosive" (H290) and a dangerous good within UN 3262.</p>	<p>Within Europe must fulfill the same requirements as for domestic transportation. If handled as a waste them directive (EWG) Nr. 259/93 applies.</p>
Greece	<p>Non-hazardous waste: US 50910/2727/2003, Directive 2008/98 / EC et al.</p> <p>Operator must hold a Waste Collection and Shipment License, valid for the country in question. When the waste reaches the final recipient, it is obliged to issue a certificate of acceptance and recovery of the waste. At the end of each year, the quantities of waste generated, transported, recovered or deposited shall be reported to the RWC Electronic Waste Register.</p>	<p>Non-hazardous waste is subject to Law 24040/2013.</p> <p>Country within EU: Greek Ministry of Environment notified of the Transboundary Waste Shipment Announcement Form and completed form ANNEX VII. After shipment, the completed ANNEX VII form is sent by the waste consignee and this file is forwarded to the RIS. Shipment must be made within three months of the date of export without delay.</p> <p>Country outside EU: If the Organization for Economic Cooperation and Development (OECD) decision is not implemented in the country, the procedure of prior written notification and consent shall be followed, in accordance with paragraph 2 of Rule 37 of Regulation 1013/2006. Otherwise, the same procedure as per within EU.</p>

Table 8: Summary of transport regulations in certain countries