UNDERSTANDING BAUXITE RESIDUE: A REVIEW OF ITS HISTORICAL EVOLUTION AND POTENTIAL IN SUSTAINABLE CONSTRUCTION

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Abstract

Bauxite residue (BR) also known as bauxite tailings, an abundant by-product of the Bayer process for alumina production, presents a global environmental challenge with over 4 Gt currently stored in landfills. This review covers the historical evolution of BR generation, noting that bauxite residue generation was recognized as an environmental issue around 1980, highlighting the relatively recent emergence of this concern. It provides a detailed overview and comparison of BR utilization pathways as a supplementary cementitious material (SCM). While raw BR incorporation is limited (up to 5%), advanced processing techniques enable significantly higher substitution levels while meeting standard strength classes. The review discusses the potential of these methods to enhance mortar properties and promote circularity in construction, while also considering radiological implications, environmental safety, and economic factors. Key research gaps are identified, including the need for a comprehensive BR composition database, detailed radiological and leaching assessments, to guide future development and facilitate the large-scale, safe utilization of BR.

Keywords

Bauxite Residue, residue utilization, supplementary cementitious material, sustainable construction, environmental Impact

1 INTRODUCTION

The current accumulation of bauxite residue exceeds 4 billion tonnes, stored in landfills worldwide. The storage and disposal of bauxite residue present significant environmental challenges due to its high alkalinity (pH 10–13), the presence of heavy metals, and the potential presence of naturally occurring radionuclides.

The continuously increasing volume of this raw material has spurred growing interest in utilizing bauxite residue in various applications to minimize its environmental impact and promote resource recovery. However, the current utilization rate remains low, with only about 2–3% of the annually generated bauxite residue being effectively reused.

One promising avenue for bauxite residue utilization lies in its application as a supplementary cementitious material (SCM) in mortar production. SCMs are materials that partially replace cement in mortar mixtures, leading to several potential benefits, such as enhanced durability and mechanical properties, reduced CO_2 emissions associated with cement manufacturing, and lower costs. However, incorporating bauxite residue into mortar also presents challenges that require careful consideration.

This comprehensive review aims to explore the utilization of bauxite residue as an SCM in mortar production, focusing on its potential benefits, challenges, and radiological implications. The review will cover the following key aspects: history of bauxite residue, bauxite residue generation, properties and composition of bauxite residue, current research directions in BR utilization, bauxite residue as a supplementary cementitious material, radiological assessment, environmental and safety considerations, environmental and economic implications, and challenges and future directions for research and development.

By addressing these aspects, this review seeks to contribute to a better understanding of the potential for bauxite residue utilization in sustainable construction practices, specifically in mortar applications.

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2 HISTORICAL EVOLUTION AND CURRENT CONTEXT OF BAUXITE RESIDUE

History of bauxite residue

In 1885, Karl Josef Bayer moved from Brno to St. Petersburg, where he worked with pure aluminium hydroxide $Al(OH)_3$, which was a rare and expensive raw material at the time, at the Tentelev Chemical Plant [1]. By 1888, he had discovered the precipitation method for obtaining crystalline aluminium hydroxide from a cold sodium aluminate ($NaAl(OH)_4$) solution using a seed of aluminium hydroxide. Later, in 1892, Bayer found that the required $NaAl(OH)_4$ solution could be dissolved selectively, from bauxite containing alumina, by heating it with a solution of sodium hydroxide (NaOH) under pressure in an autoclave [2]. He patented both inventions, now known as the Bayer's process, involving both pressure leaching and controlled precipitation.

The Bayer process, providing alumina as feedstock for the newly invented process for manufacturing aluminium metal, was immediately put into practice. By 1892, Bayer plants had been established in England, France, Italy, and Germany for this purpose. Between 1893 and 1910, two further Bayer plants were built in France and in the USA. In the ensuing 30 years, more plants were built in the USA, Germany, Great Britain, Japan, and the Soviet Union. Of these early plants, only the plant at Gardanne (France) is still operating today [1].

Bayer's alumina plants use practically the same process as it was when discovered one hundred and thirty-three years ago. The process underwent major technological advancements, resulting in lower energy consumption and, therefore, cost.

Historical timeline of bauxite residue:

- 1821: Bauxite discovered by P. Berthier.
- 1825: Aluminum isolated by Hans Christian Oersted.
- 1854: Sainte-Claire Deville process to produce aluminium chloride and its reduction to the metal by metallic sodium invented.
- 1855: Louis Le Châtelier process to produce aluminium invented.
- 1856: 25 kg of aluminium produced in a small plant at Glacière near Paris.
- 1886: Hall–Héroult process replaces Sainte-Claire Deville's process. This method is based on the electrolytic reduction of Al_2O_3 dissolved in fused cryolite (Na_3AlF_6).
- 1892: Bayer process patented.
- 1892: Alumina plants established in England, France, Italy, and Germany.
- 1980: Bauxite residue generation recognized as an environmental issue.

Bauxite residue generation

The alumina made by the Bayer process produces for every tonne of alumina extracted, approximately 1 to 1,5 tonnes (Mt) of bauxite tailings [3]. The aluminium industry grew rapidly from the early beginning. From 6800 tonnes in 1900, the global production rate of aluminium metal reached 1 Mt per annum in 1940. The global inventory of bauxite residue at that time can be estimated to have been approximately 22 Mt. The total volume of produced alumina per annum in 2023 grew to 146 million tonnes worldwide generating approximately 170 million tonnes of BR. Currently itis estimated that there is more than 4 Gt of bauxite residue stored in landfill globally. The demand by the metallurgical industry is still rapidly growing [4].

Properties and composition of bauxite residue

The composition of bauxite residue varies significantly depending on the source of bauxite and the specific processing methods employed in its extraction. Chemical and mineralogical properties can differ markedly across different geographical locations and processing facilities.

A comprehensive analysis of bauxite tailings from various locations reveals that the chemical composition typically includes significant amounts of iron oxides (Fe_2O_3), aluminium oxides (Al_2O_3), silicon dioxide (SiO_2), sodium oxide (Na_2O), calcium oxide (CaO), and titanium dioxide (TiO_2). For instance, studies indicate that the iron content in bauxite residue can range from 20% to 60% by weight, while aluminum content varies

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from 10% to 30% [5]. Additionally, the presence of silica can range from 2% to 20%, and other oxides also contribute to the overall composition [6].

Some residues have been noted for their high concentration of iron oxyhydroxides, while residues from other locations have shown the potential for recovering rare earth elements. Common properties of BR are high alkalinity, leaching of heavy metals, and the content of naturally occurring radionuclides, which must be individually assessed before each application of the raw material.

The chemical composition of studied BRs is scattered across many theses, journals, conference proceedings, etc., without an available library or review of the collected information up to date.

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Current research directions in bauxite residue utilization

Current research on bauxite residue utilization highlights its multifaceted potential in environmental remediation, construction, and resource recovery. Bauxite tailings utilization research began in the early 1980s. The ongoing exploration of innovative methods to manage and repurpose this byproduct is essential for sustainable practices in the alumina industry and beyond.

The most promising avenues in bauxite residue recycling can be categorized as follows [7]:

- Recovering valuable metals and rare earth elements such as iron, titanium, aluminium, sodium, and scandium [8], [9].
- Using it as a main component in the production of other products, e.g. cement [10].
- Using it as an additive in the production of building materials such as concrete, bricks, or tiles [11].
- Applying it for specific purposes, e.g. soil remediation or landfill capping [11].
- Converting red mud into a useful material by modifying the present compounds, e.g. the Virotec process [12].

Bauxite residue in cementitious systems

Cement production has been identified by the International Aluminium Institute as the most promising target market for the large-scale application of bauxite residue [13]. Global cement production in 2020 reached 4,100 million tonnes, with the EU accounting for an estimated 176 million tonnes, or 4.3% of the global total. Given that the realistic substitution level of cement by bauxite residue as a supplementary cementitious material (SCM) could be 20–30% by weight, the entire annual production of BR could potentially be absorbed by the cement industry at both the European and global levels.

Due to differences in chemical composition, not all bauxite tailings are reactive in cementitious materials. Different ways to improve the reactivity of the raw meal have been studied, e.g. alkalinity reduction, co-calcination and vitrification, which will be described in the following paragraph.

The reactivity of raw bauxite residue in cementitious applications is primarily attributed to its substantial content of reactive silica and iron oxides, which together enhance its pozzolanic properties. This reactivity not only improves the performance of concrete but also facilitates the cement hydration process through the iron oxides present in the bauxite residue. These iron oxides contribute to the formation of ettringite and other hydration products that bolster the mechanical properties of concrete. However, it is essential to manage the alkaline nature of the residue to address potential durability issues.

This work provides an overview of viable options for utilizing bauxite residue in cementitious systems (specifically in blended cements and as raw material for clinker), evaluated using indicators like incorporation amount, industrial-scale feasibility, and compressive strength requirements for structural applications.

Bauxite residue as a raw material

Bauxite tailings can be used without additional treatment, either in blended cement with Ordinary Portland Cement (OPC) or as a raw material for meal for clinker meal, which is then fired in a kiln and subsequently mixed with gypsum after cooling.

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Studies show that mortars containing blended cement made with raw bauxite residue as an SCM and OPC exhibit low compressive strength, making them suitable for non-structural applications like plastering, allowing for a BR substitution of up to 35% [14, 15].

Furthermore, other three main directions exist for using raw red mud in cement production: preparation of clinkers, production of composite cements, and development of alkali-activated cements [16]. Clinkers produced via the first route are suitable for large-scale applications.

Bauxite residue can be used as raw material in a mix containing limestone, shale and fine coal, which is then fired in a kiln to produce clinker. The clinker is cooled, and gypsum is added into it to obtain OPC. A study by Mishra et al. [17] incorporated 3,5% of red mud into Ordinary Portland Cement while maintaining a 28–day compressive strength of produced mortar at 60,8 MPa, meeting the EN 197-1 requirement of >42,5MPa for 42,5N strength class .

Vangelatos et al. [18] demonstrated the successful incorporation of up to 5% bauxite residue in a meal with limestone and sandstone to produce OPC clinker. Mortars made from this cement maintained a 28–day compressive strength of 58.4 MPa.

For structural applications, consumption of bauxite residue of up to 5% is feasible. To achieve higher volume incorporation of the material, further processing aimed at increasing the reactivity of BR is needed.

Alkali reduced bauxite residue

Another viable approach to utilize bauxite residue is its alkalinity (pH) reduction. The lower pH of Bauxite residue has a positive impact on the long-term strength development, minimizing alkali-aggregate reactions (AAR), increasing clinker replacement and also assisting to avoid the classification of BR as hazardous material.

Danner et al. [19] proposed washing BR with diluted acetic acid to produce a low-alkali SCM with the potential for industrial-scale implementation. Alkali-reduced bauxite residue was shown to supplement cement up to 20%, reaching the required 28–day compressive strength of 42.5 MPa (in line with EN 197–1 for class 42.5 N) in a reference mortar containing CEM I 42.5 N.

Co-calcined bauxite residue

Treating raw bauxite meal by co-calcination is a very effective way to increase the reactivity of the material. The method is simple: 70 wt% of BR is mixed with 30 wt% kaolinite and co-calcined at a low temperature below 800°C. The produced SCM can supplement OPC up to 30% in mortar. These settings were evaluated in an experiment, where 30 wt% of CEM I 52.5 N was substituted with the co-calcined SCM in casted mortars according to EN 196–1. However, the workability of these mortars must be improved with plasticizers. The strengths of the mortar samples fall within the 42.5 R strength class defined in EN 197–1 [20].

The method is suitable for large-scale application and was patented in the USA in 2024 [21].

Vitrified bauxite residue

The process of vitrification is another option to obtain reactive SCM. A blend containing finely milled bauxite residue with additives is quenched at high temperatures between 1200–1300°C to produce a glass-like material, also called vitrified bauxite residue (VBR) [22]. VBR was already manufactured at pilot scale at the time of the study. Mortar prisms produced according to EN 196–1 contained a ternary blend cement composed of ground VBR, up to 50 wt% of binder, OPC 52.5N, and limestone. The proposed systems classified as 42.5N according to EN 197–1.

3 DISCUSSION

Due to the high production of aluminium for the construction industry and the high consumption of cement, bauxite residue has the potential to support sustainable construction and the circular economy. Upcycling the annual production of bauxite residue in blended cements is feasible if developed processes for reactivity enhancement allow the substitution of ordinary Portland cement by SCMs containing bauxite tailings at a level of at least 20%. Another criterion to be met is the possibility of industrial-scale production. All presented methods of BR treatment, alkali reduction, co–calcination with kaolinite, and vitrification, meet these requirements. Alkali–reduced bauxite

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residue can supplement 20 wt% of cement in the binder. Up to 30 wt% of OPC in the binder can be substituted by co–calcined BR. Vitrified bauxite residue facilitates the highest replacement of cement in the binder, up to 50 wt%. These supplementary cementitious materials have been proven to be applicable in structural applications on a large scale. The use of untreated bauxite residue in cementitious applications at a rate above 20% is possible in non-structural applications, e.g. plastering.

4 CONCLUSION

Understanding the historical evolution of the bauxite industry is crucial for contextualizing current practices and identifying future research needs. The Bayer process, developed in the late 19th century, has remained largely unchanged, leading to the continuous generation of bauxite residue (BR) as a significant by-product. As the global inventory of bauxite residue exceeds 4 billion tonnes, the environmental challenges associated with its storage and disposal have become increasingly pressing. Key findings from this review highlight the multifaceted potential of bauxite residue, particularly in its application as a supplementary cementitious material (SCM). However, to fully realize this potential, further investigation is necessary in several areas:

Composition database: Establishing a comprehensive database of the chemical and mineralogical composition of bauxite residue from various sources is essential. This would facilitate a better understanding of its properties and reactivity, as variations can significantly impact its usability in different applications.

Radiological assessment: The presence of naturally occurring radionuclides in bauxite residue necessitates thorough radiological assessments to ensure safety in its reuse. Understanding the radiological implications will help mitigate health risks associated with its application in construction and other sectors.

Leaching studies: Investigating the leaching behaviour of heavy metals and rare earth elements from bauxite residue is critical for evaluating its environmental impact and potential for resource recovery. This research can inform about strategies for safe disposal and utilization.

By addressing these research gaps, we can enhance our understanding of bauxite residue and develop effective strategies for its management and utilization. The findings from this review not only contribute to the existing body of knowledge but also lay the groundwork for future studies aimed at promoting sustainable practices in the alumina industry and beyond.

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