Strategies for Fixation of Leachable Ions from Bauxite Residue for use in Cementitious Materials

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Abstract

Driven by sustainability goals, the major players of the aluminum industry aim to eliminate new permanent storage of bauxite residue (BR) by 2050. Complete BR use is feasible through large material streams, with construction materials – particularly as a supplementary cementitious material (SCM) – being one of the most promising approaches due to the high demand for cement. However, BR's high alkalinity and low reactivity pose challenges for cement chemistry, alongside environmental concerns regarding leachable elements such as sodium, which can cause irritation and corrosion in human tissue, chromium, and other toxic metals with carcinogenic potential. Two main strategies have been developed to mitigate the negative effects of BR: thermochemical activation, which involves energy-intensive processes like calcination and vitrification, and chemical fixation, which incorporates BR into ternary cementitious systems that react with SCMs. This study presents strategies to immobilize the main deleterious elements in BR prior to its application through chemical fixation with reactive materials (such as slags, pozzolans, and other materials). These strategies will enable BR to be used both in the production of a co-product that can be marketed as an SCM and in direct cementitious applications (concrete and mortar) without the need for energy-intensive processes. Pure solutions of the target deleterious elements were simulated based on their concentrations in raw BR. These solutions were mixed with the reactive materials in varying proportions, and the solubilized extract was analyzed to assess ion fixation efficiency. Effective reactive materials were then tested in BR solutions to validate their ability to immobilize these ions. The results demonstrate that ion fixation is achievable without high-energy processing, thereby supporting the large-scale use of BR as a safe byproduct in the cement industry.

Keywords: Bauxite residue, Leaching, Ion fixation, Supplementary cementitious material.

1. Introduction

The aluminum industry faces a significant environmental challenge related to the disposal of bauxite residue (BR) generated by the Bayer process. It typically exhibits high alkalinity and contains residual NaOH and trace elements that can leach into the environment if not properly immobilized [1–3]. Therefore, its chemical stabilization is a key step toward expanding its potential for safe and effective reuse. Full-scale utilization of BR requires high stream material flows enabled by competitive, economically viable, and large-scale solutions. In this context, the construction sector emerges as a promising pathway for BR reuse, particularly in cementitious formulations where it can act as a supplementary cementitious material (SCM) [2, 4].

However, to ensure the safe use of BR for both end-users and handling personnel, certain technical challenges must still be addressed, particularly the need to stabilize potentially leachable deleterious elements. Two main strategies have been adopted to safely incorporate BR into cementitious compositions. The first involves the thermochemical activation of the residue, employing thermal processes such as calcination and vitrification to stabilize BR, thereby reducing the leaching of harmful substances and improving its suitability for cement-based applications [5–7]. Nevertheless, these techniques are energy-intensive, leading to higher costs and environmental impacts, which hinder their large-scale feasibility. The second strategy focuses on direct chemical fixation, wherein BR is incorporated into ternary cementitious systems containing other supplementary cementitious materials. These systems promote reactions that immobilize leachable elements without requiring significant energy input [7–13].

Aiming to reduce the handling risks associated with BR without resorting to energy-intensive processes, this study evaluates the chemical fixation capacity of key deleterious elements in BR using reactive materials such as slags, pozzolans, and other compatible materials, before its application on cementitious materials. Once these ions are immobilized, BR can be used either in the production of a co-product marketable as an SCM or directly in cementitious applications such as concrete and mortars.

2. Materials and Methods

Three different Brazilian bauxite residues (BRs) were used in this study and were solubilized in water following the Brazilian standard procedure for obtaining solubilized extracts from solid waste (NBR 10006) [14]. This procedure consists of mixing the solid waste with deionized water at a 1:4 ratio, agitating for 5 minutes, letting it stand for 7 days, and then filtering the mixture through a 0.45-µm membrane filter to obtain the solubilized extract. The concentrations of various ions in the solubilized extract were determined using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP – OES), from Thermo Scientific, iCap 6300 Duo, and the results are presented in Table 1. Two ions are highlighted due to their potential risk to human health when BR is used in cementitious materials: sodium (Na) and chromium (Cr). Their immobilization is therefore necessary prior to application. The highest concentrations of Na and Cr among the three BRs were selected as reference values. Chromium remained insoluble in BR1, which is an important observation. The chemical composition of the primary oxides, present in each BR, as determined by X-ray fluorescence (XRF), is shown in Table 2.

Table 1. Solubilized ions of each BR sample.

Soluble ions (in mg/L)	BR1	BR2	BR3	LQ
Al^{3+}	58.2	136	123	0.05
As^{3-}	< LQ	< LQ	< LQ	0.01
Cd^{2+}	< LQ	< LQ	< LQ	0.003
Cr^{tot}	< LQ	1.17	1.79	0.02
Fe^{tot}	1.28	< LQ	< LQ	0.04
Na^{+}	2359	880	1590	0.05
Pb^{2+}	< LQ	< LQ	< LQ	0.02
SO_4^{2-}	21.3	1.0	18.1	0.03
Se^{tot}	< LQ	< LQ	< LQ	0.01
pH	10.7	12.2	12.0	-

LQ = Limit of Quantification of the equipment.

still high, a reduction in efficiency in BR3 suggests that competing ions or specific matrix characteristics can influence immobilization effectiveness.

Bentonite showed the most consistent results for Na immobilization, with moderate efficiency in both simulated and real solutions. Though the immobilization percentages in BR extracts were slightly lower than in the pure solution, it maintained a relatively stable behavior across different matrices, likely due to its ion exchange capacity.

The results indicate that while some mitigators perform well under controlled conditions, their effectiveness can be altered in real BR scenarios. Therefore, preliminary testing with real leachates is essential before implementing remediation strategies.

Further studies are needed to confirm the mechanisms that led each material to the immobilization of Cr and Na, particularly through analysis of the solid phases obtained after treatment. Additionally, although not required in the Brazilian standard, it would be relevant to quantify Cr in its different oxidation states, Cr(III) and Cr(VI), since only Cr(VI) poses significant risks to human health. This work focused on evaluating the chemical fixation capacity of deleterious elements in BR using accessible mitigators, showing the possibility of using BR safely without incorporating high amounts of energy. Studies will be continued to improve the understanding of physico-chemical fixation mechanisms, whether by chemical reaction, promoting crystal precipitation, or physical adsorption and ion exchange processes.

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6. References

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