Review of the Co-Utilization of Bauxite Residue with Other Solid Wastes for Cementitious Material Applications

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Abstract

Bauxite residue is an alkaline industrial by-product, and its large-scale safe utilization is crucial for the green development of the aluminium industry. This paper reviews the mechanisms and technological progress of the co-utilization of alkaline byproducts (such as bauxite residue), silico-aluminate byproducts (such as coal fly ash), and sulphate byproducts (such as industrial gypsum). It outlines the theoretical framework of medium-calcium cementitious material, the tetrahedral coordination isomerism effect of silicon, and the composite synergistic effect of multiple solid wastes. The study reveals that through combined synergistic effects such as alkaline activation and sulphate activation between various solid wastes, silicon and aluminium components in silico-aluminates are activated to form a gel system dominated by C-(N)-S-H gel and ettringite. The paper elaborates on the efficient solidification mechanism of Na^+ and heavy metal ions by the silicon-aluminium oxygen tetrahedral network and innovatively proposes the synergistic utilization pathway for potentially harmful ions through "alkali control, salt encapsulation, and transformation." Based on this, a multi-product system is formed, including bauxite residue-based cementitious materials, road base materials, non-fired blocks, and mining backfill materials, all of which meet Chinese national standards for mechanical properties, durability, and environmental performance. This paper summarizes the current research progress and key issues in the co-utilization of bauxite residue and other solid wastes and suggests future research directions.

Keywords: Bauxite residue, Co-utilization, medium-calcium cementitious materials, Composite synergistic effect.

1. Introduction

Bauxite residue is a strongly alkaline industrial solid byproduct generated during the production of alumina, and its large-scale safe utilization is crucial for the green development of the aluminium industry. Figure 1a shows the generation and utilization of bauxite residue in China over the past decade. By 2024, the cumulative storage of bauxite residue in China has exceeded 1.5 billion tonnes and continues to grow rapidly at an annual rate of about 100 million tonnes [1]. Bauxite residue is characterized by strong alkalinity and complex composition, making resource utilization challenging. The comprehensive utilization rate of bauxite residue in China is less than 15 % [2, 3], and landfilling remains the most common disposal method. Large-scale storage of bauxite residue burdens the surrounding environment and may pose major safety risks, such as potential dam failures in cases of wet storage. Meanwhile, with the rapid development of industries such as metallurgy, mining, and chemicals in China, the discharge of industrial solid byproducts from other sectors is also increasing. These mainly include various smelting slags (e.g., blast furnace slag, steel slag), coal-based solid wastes (e.g., coal fly ash, coal gangue), industrial by-product gypsum (e.g., desulphurization gypsum, phosphogypsum), and various tailings. Figure 1b shows the generation and utilization of major industrial solid byproducts in

China over the past six years. In 2024, the total discharge of major industrial solid byproducts in China reached 4.31 billion tonnes, with a comprehensive utilization amount of 2.69 billion tonnes, giving a utilization rate of about 63 %. The historical cumulative storage has exceeded 60 billion tonnes, occupying land, wasting resources, and posing environmental and health risks [4, 5]. Therefore, promoting the large-scale utilization of difficult-to-handle solid byproducts such as bauxite residue and improving the utilization rate of major industrial solid byproducts has become an important part of promoting the green transformation of traditional industries.

This paper classifies industrial solid byproducts into three categories based on their physical and chemical properties: alkaline solids (such as bauxite residue, carbide slag), sulphate solids (such as industrial gypsum and electrolytic manganese slag), and silico-aluminate solids (such as coal fly ash and coal gangue). To address the bottleneck problem of industrial solid waste generation, it is essential to perform "complementary advantages" based on the physical and chemical characteristics of different solid waste types; fully exploit the composite synergistic effects between multiple solid wastes; and simultaneously enhance material properties. This approach will turn solid byproducts into resources and fundamentally solve the ecological and environmental issues caused by their landfilling [6-8]. Based on this, this paper systematically reviews the mechanisms and technological advancements of the co-utilization of alkaline solids (such as bauxite residue), silico-aluminate solids (such as coal fly ash), and sulphate solids (such as desulphurization gypsum). It outlines the theoretical framework of medium-calcium cementitious materials, tetrahedral coordination isomerism of silicon, and the composite synergistic effect of multiple solid wastes. Finally, the paper summarizes the current research progress and key issues in bauxite residue-based ecological cementitious materials, road base materials, non-fired bricks, mining backfill materials, and other multi-products, while providing future perspectives.

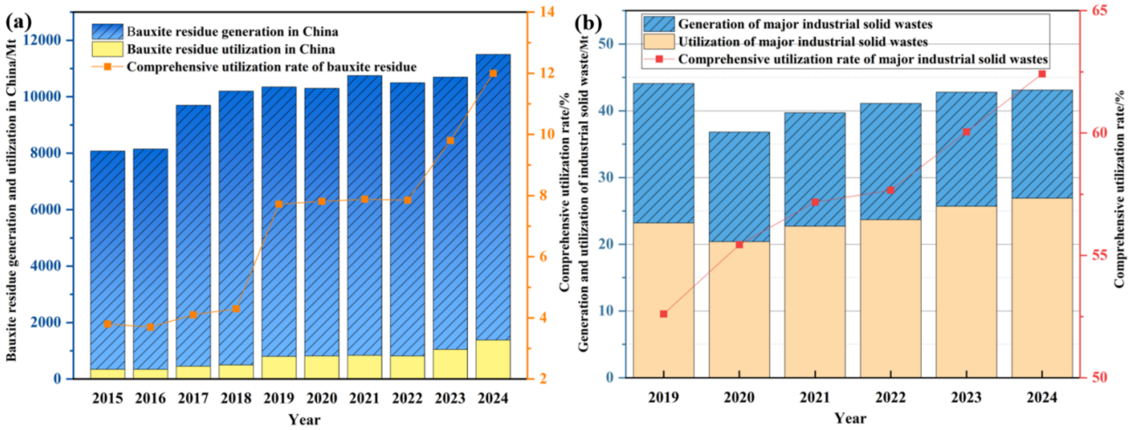

Figure 1: (a) Bauxite residue generation and utilization in China over the past decade, (b) Generation and utilization of major industrial solid wastes in China over the past six years.

2. Mechanism of Co-utilization of Bauxite Residue and Other Solid Wastes

2.1 Medium-Calcium Component Design

As shown in Figure 2, based on the Ca/Si (Calcium to Silica mass ratio) in cementitious materials, they can be classified into three systems: high-calcium, medium-calcium, and low-calcium systems. Portland cement belongs to the high-calcium cementitious material system, where Ca/Si is generally greater than 2; geopolymeric cementitious materials belong to the low-calcium system, with Ca/Si typically less than 0.5. Between high-calcium and low-calcium cementitious materials, there exists a transition of medium-calcium cementitious materials, bridging the

3.5 Conclusions and Outlook

This paper systematically reviews the latest research progress and engineering applications of the synergistic utilization of bauxite residue with various industrial solid wastes such as coal fly ash, metallurgical slag, and desulphurization gypsum. First, it elaborated the theoretical framework of synergistic utilization of solid wastes, including medium-calcium component design, multi-polymerization degree matching design, Si-Al coordination isomorphism effect, and multi-solid waste composite synergistic effects. Then, it summarized the reaction mechanisms of bauxite residue-based medium-calcium cementitious materials, the structural characteristics of hydration products, and the efficient immobilization mechanisms for harmful ions such as Na^+. Based on this, various application products are introduced, including bauxite residue-based eco-cementitious materials, pavement base materials, non-fired blocks, and mine backfilling materials, providing a feasible path and theoretical support for the "reduction, harmlessness, and resource utilization" of industrial solid wastes such as bauxite residue.

Although remarkable progress has been made in the synergistic utilization of bauxite residue and other solid wastes, many challenges remain in advancing the engineering application of these materials. Firstly, the significant compositional variation in solid waste raw materials leads to instability and limited control of product performance, necessitating the establishment of efficient raw material regulation and standardized evaluation systems; secondly, some solid wastes still contain heavy metals and other pollutants, and the long-term environmental safety assessment and monitoring mechanisms are not yet complete. Additionally, the industrial-scale development of bauxite residue and other solid waste resource utilization is still constrained by factors such as economic feasibility, policies and regulations, and social acceptance.

Future research and application should focus on the following directions: (1) strengthening multi-scale studies on the synergistic utilization patterns, reaction mechanisms, and microstructures of multiple solid wastes to enable precise design of high-performance bauxite residue-based cementitious material systems; (2) introducing advanced artificial intelligence methods such as machine learning to assist in raw material ratio and reaction condition optimization, performance prediction, and pattern analysis for synergistic solid waste products, thereby improving R&D efficiency; (3) accelerating policy guidance and standards development to promote the transition of bauxite residue and other solid waste utilization technologies from the laboratory to engineering, large-scale, and market-oriented applications.

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