

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

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<https://doi.org/10.71659/icsoba2025-br014>

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.

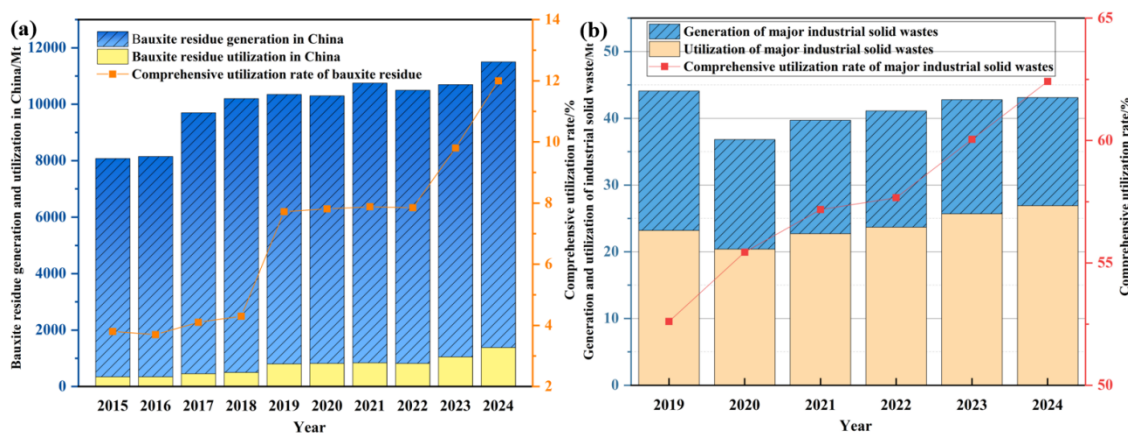


Figure 1: (a) Bauxite residue generation and utilization in China over the past decade, (b) Generation and utilization of major industrial solid wastes in China over the past six years.

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; geopolymetric 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

development of high-calcium and low-calcium systems. Xiaoming Liu [9, 10] et al. were the first to propose the concept of medium-calcium component cementitious materials, where the material contains moderate calcium content and the $(\text{CaO}+\text{MgO})/(\text{SiO}_2+\text{Al}_2\text{O}_3)$ ratio lies between 0.6 and 1.5. Research and practical applications over several years have shown that when industrial solid byproducts such as bauxite residue are used in large quantities to prepare cementitious materials, a green, low-carbon, high-performance medium-calcium cementitious material system can be developed when the Ca/Si ratio is between 0.6 and 1.5.

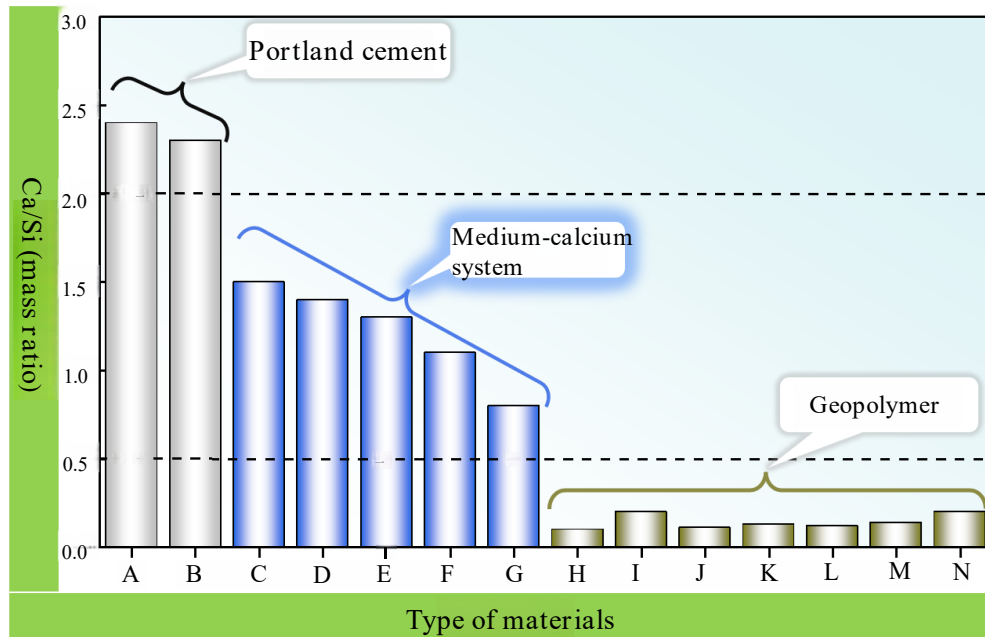


Figure 2: Relationship between cementitious material type and Ca/Si (mass ratio).

Xiaoming Liu et al. [11, 12] discovered that the main hydration products of medium-calcium cementitious materials are C-(N)-S-H gel, ettringite ($\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12}\cdot 26\text{H}_2\text{O}$), $\text{Ca}(\text{OH})_2$, and minerals like orthorhombic calcium zeolite ($\text{CaAl}_2\text{Si}_2\text{O}_8\cdot 4\text{H}_2\text{O}$), along with poorly crystalline silico-aluminate gel substances, which play a key role in the mechanical properties of cementitious materials. Jiaolong Chen et al. [13, 14], using SEM-EDS techniques, found that in medium-calcium cementitious materials, C-S-H gel and needle-like or rod-like ettringite can be observed within just one day of hydration, with hexagonal $\text{Ca}(\text{OH})_2$ crystals also distributed in local areas. These different-shaped ettringites generally distribute in the voids and pits, densifying the slurry structure. A fibrous C-S-H gel covers the unreacted particles, linking the previously dispersed particles, and the bond between the hydration products and unhydrated particles is also strong. As hydration progresses, the fibrous C-S-H gel interweaves to form an amorphous network structure. Ettringite grows along the pore walls and interweaves with one another, filling the voids and making the medium-calcium cementitious material structure more compact. Thus, the combination of C-S-H gel, ettringite, and the material matrix ensures the mechanical properties of the cementitious material. As shown in Figure 3a, Liu et al. [9] found that when solid wastes such as municipal solid waste incineration fly ash, coal fly ash, and blast furnace slag are co-used to prepare cementitious materials, the compressive strength of the cementitious material first increases and then decreases as the Ca/Si ratio increases. The maximum compressive strength of the cementitious material occurs when Ca/Si is 0.88. As shown in Figure 3b, Xu et al. [15] found that when bauxite residue, fly ash, and desulphurization gypsum are used to prepare non-fired bricks, the compressive strength first increases and then decreases as the Ca/Si ratio increases. The maximum compressive strength of the non-fired brick occurs when Ca/Si is 1.23. As shown in Figure 3c, Zhang et al. [12] found that when bauxite residue, electrolytic manganese slag, and

fly ash are used to prepare road base materials, the compressive strength first increases and then decreases as the Ca/Si ratio increases. The maximum compressive strength of the non-fired brick occurs when Ca/Si is 0.95. The introduction of the medium-calcium component design theory provides a practical and feasible path for the co-utilization of bauxite residue and other industrial solid byproducts at a large scale.

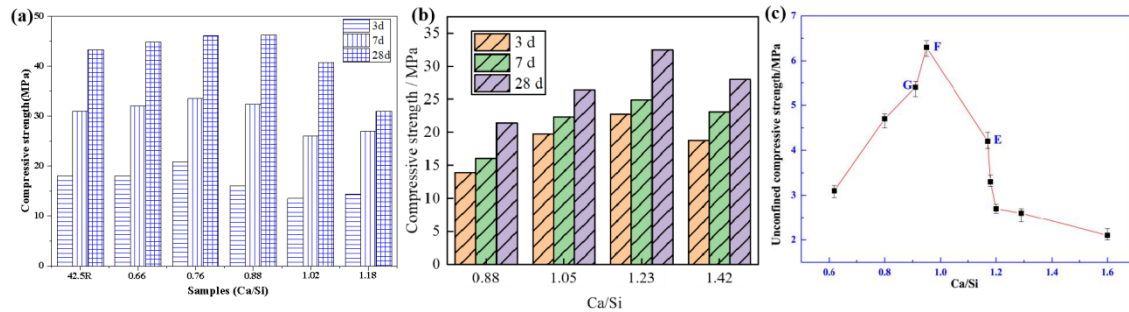


Figure 3: Relationship between medium-calcium component cementitious materials Ca/Si and compressive strength: (a) Cementitious materials, (b) Non-fired bricks, (c) Road base materials.

2.2 Multi-Polymerization Degree Matching Design

The essential process by which pozzolanic active components in industrial solid byproducts participate in cement hydration is a transformation of $[\text{Si}(\text{Al})\text{O}_4]$ tetrahedra from polymerized to isolated states and then back to a polymerized state. The degree of polymerization can be used to evaluate the ease with which raw materials participate in hydration reactions and the extent of hydration in cementitious materials. Changes in the number of bridging oxygens in the silicon-oxygen tetrahedra can reflect the relative degree of polymerization or depolymerization reactions occurring in the system. Therefore, variations in the Relative Bridging Oxygen number (RBO) can be used to characterize the degree of polymerization, and the RBO can be calculated as shown in Equation (1):

$$RBO = \frac{1}{4} \left(1 \times \frac{Q^1}{\sum Q^n} + 2 \times \frac{Q^2}{\sum Q^n} + 3 \times \frac{Q^3}{\sum Q^n} + 4 \times \frac{Q^4}{\sum Q^n} \right) = \frac{1}{4} \times \frac{\sum n \times Q^n}{\sum Q^n} \quad (1)$$

As shown in Figure 4a, Yaguang Wang et al. [16] found that different industrial solid wastes possess different silicate structures, structural units, and degrees of polymerization; the lower the polymerization degree of silicon–aluminium structures in the waste, the higher their pozzolanic reactivity. Based on the coordination structures of silicon and aluminium in different wastes, their corresponding degrees of polymerization can be calculated. Through multi-polymerization degree matching design, low-polymerization solid wastes (Table 1) can be converted through hydration reactions into highly polymerized hydration products (Figure 4b). The higher the degree of polymerization in the hydration product, the higher the reaction extent and the better the material performance.

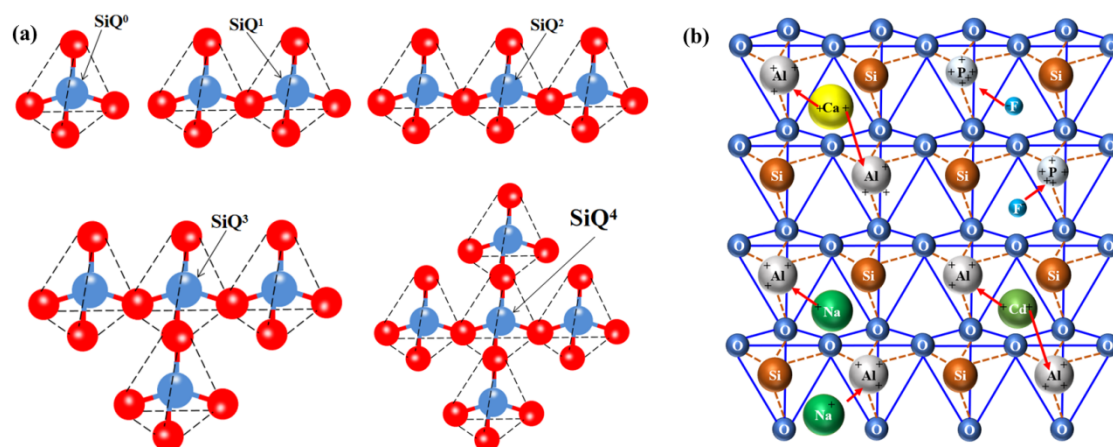


Figure 4. Multi-polymerization degree matching structure design: (a) Forms of silicon-oxygen tetrahedral spatial structures in bauxite residue and other solid wastes, (b) RBO of hydration products in bauxite residue-based cementitious materials.

Table 1. Chemical composition and structural units of multi-polymerization degree materials (wt.%).

Material	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	Na ₂ O	Structural Units
Bauxite residue	24.81	27.46	19.03	10.59	1.15	10.89	SiQ ⁰ , SiQ ¹
Coal gangue	49.41	21.32	2.52	6.02	1.56	1.44	SiQ ² , SiQ ⁴
Blast furnace slag	33.59	14.37	38.32	1.11	8.43	0.18	SiQ ⁰ , SiQ ¹ , SiQ ³
Cement clinker	21.94	5.27	66.09	2.96	0.88	0.30	SiQ ⁰

2.3 Isomorphic Substitution Effect of Silicon-Aluminium Coordination

During the depolymerization, migration, and repolymerization processes of silicon-oxygen tetrahedra, trivalent or pentavalent ions can enter the silicon-oxygen tetrahedral network and form tetrahedra with four oxygens, connecting with silicon-oxygen tetrahedra at the corners. Meanwhile, reactive monovalent or divalent cations or anions are captured into the network's voids for charge balance and stabilization. This phenomenon, where polymerization of silicon-oxygen tetrahedra promotes the formation of tetrahedral structures with four oxygens for trivalent or pentavalent ions, and simultaneously stabilizes large quantities of reactive monovalent or divalent ions, is referred to as the "isomorphic substitution effect of silicon tetrahedral coordination." As shown in Figure 5, Mukiza et al. [17] found that the coordination isomorphism of silicon with aluminium can effectively immobilize cations such as Cr, Hg, Pb, and Na. This is because after the dissolution of aluminosilicate minerals, Si in the [SiO₄] tetrahedra is substituted by Al under certain conditions, forming [AlO₄] tetrahedra. The [SiO₄] and [AlO₄] tetrahedra then bond via bridging oxygen to form a three-dimensional network structure. In this structure, the substitution of Si by Al in [AlO₄] tetrahedra introduces negative charges, which immobilize harmful cations via charge balance mechanisms. As the proportion of silico-aluminate solid wastes in Portland cement increases, the Al content also rises, and the primary product C-S-H gel can transition to C-A-S-H gel. As Al increases, the replacement of Si by Al in C-S-H gel to form C-A-S-H gel results in enhanced immobilization capacity for cations of concern. In recent years, leveraging advances in modern analytical instrumentation and coordination chemistry theories, Yaguang Wang et al. [18] used solid-state nuclear magnetic resonance (MAS NMR) to study hydration products of bauxite residue-based cementitious materials. Using NUTS software to simulate peak deconvolution of ²⁷Al MAS NMR and ²⁹Si MAS NMR spectra of hydration

products at different curing ages for silico-aluminate cementitious materials, they calculated the relative content of coordinated Al and the RBO values of Si. This confirmed the presence of the four-coordination isomorphic substitution effect of Si for Al with prolonged hydration age in multi-industrial solid waste-based cementitious materials. This reveals the structural mechanism of hydration products in immobilizing harmful ions within multi-industrial solid waste-based cementitious matrices.

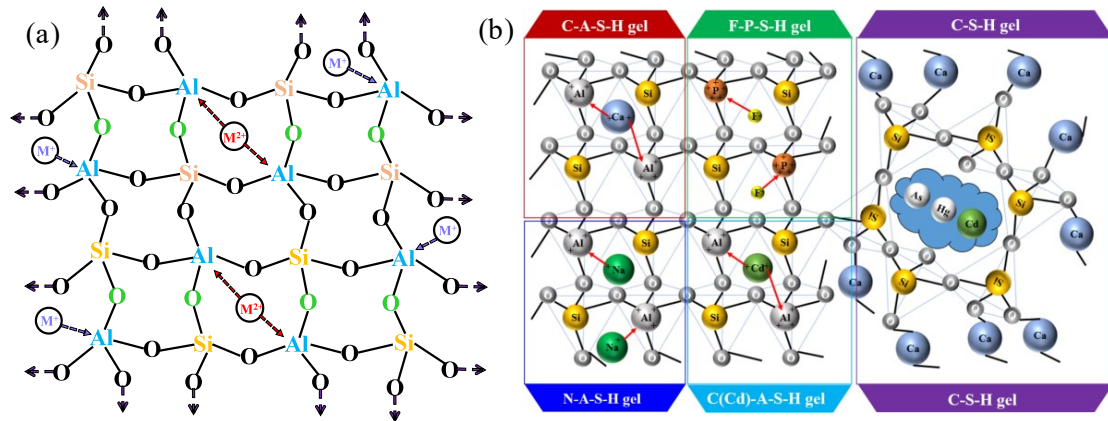


Figure 5. (a) Isomorphic substitution effect of silicon-aluminium coordination, (b) Immobilization model of harmful ions in bauxite residue-based cementitious materials.

2.4 Synergistic Effect of Multi-Solid Waste Blending

Studies have shown that alkaline reagents and sulphate reagents can effectively enhance the reactivity of silicon-aluminium components in aluminosilicate solid wastes, providing a scientific basis for the synergistic utilization of alkaline, sulphate-based, and aluminosilicate solid wastes. Alkalis have an activating effect on the latent reactivity of aluminosilicate solid wastes. Under alkaline conditions, the crystalline and glassy structures of aluminosilicate phases in solid wastes are dissolved and disrupted, leading to structural transformation and improved reactivity. During alkali-activated cementitious reactions, silicon-aluminium components undergo processes such as monomer dissolution, monomer reconstruction, polycondensation, and polymerization under the action of alkaline activators, ultimately forming a three-dimensional polymeric network. Sulphate activation of silicon-aluminium materials in aluminosilicate solid wastes occurs primarily through reactions of SO_4^{2-} with gel products and AlO_2^- in the presence of Ca^{2+} to form ettringite [19]. Meanwhile, under alkaline conditions, some SiO_4^{4-} in the gel products is replaced by SO_4^{2-} , and the displaced SiO_4^{4-} reacts with other Ca^{2+} to form more gel products, thereby continuing the activation of aluminosilicate minerals [20, 21]. The mechanism of sulphate activation lies in the ionization of SO_4^{2-} upon dissolution, which promotes the breaking of Si–O and Al–O bonds at reactive sites, and under the action of Ca^{2+} , reacts with dissolved Al_2O_3 in the liquid phase to form ettringite [22, 23]. Therefore, the combined use of alkaline and sulphate solid wastes can significantly enhance the cementitious activity of aluminosilicate solid wastes during hydration, promoting hydration product formation and improving mechanical performance of the matrix. The alkali–aluminosilicate–sulphate solid waste synergistic utilization technology, developed based on the synergistic effects of multiple solid wastes, has been applied to the resource utilization of bauxite residue, metallurgical slag, fly ash, flue gas desulphurization gypsum, municipal solid waste incineration fly ash, coal gangue, and tailings [10, 17, 22, 24, 25], achieving notable economic and social benefits.

3. Full-Component Utilization Practice of Bauxite Residue and Other Multi-Solid Waste-Based Cementitious Materials

3.1 Eco-Cementitious Materials

Eco-cementitious materials are environmentally friendly construction materials composed of cement clinker, bauxite residue, fly ash, and other solid waste raw materials. Compared to traditional binders, eco-cementitious materials offer better environmental performance and durability, effectively reducing the energy consumption and cost of construction materials. Numerous studies have confirmed that bauxite residue is a promising raw material for producing calcium-rich cementitious materials. Research shows [26] that medium-calcium binders prepared from bauxite residue and coal gangue solid wastes can achieve physical properties that meet the P•O42.5 cement standard. As the Ca/Si ratio of the cementitious material increases, the content of $\text{Ca}(\text{OH})_2$ phases also increases, and with prolonged hydration age, more hydration products are formed, enhancing mechanical strength accordingly. Similarly, bauxite residue, fly ash, flue gas desulphurization (FGD) gypsum can be used to prepare high-performance medium-calcium cementitious materials [23]. As shown in Figure 6a, under the synergistic effect of these three industrial solid wastes, the mechanical strength of the bauxite residue–fly ash–FGD gypsum based cementitious material is significantly improved. When the total content of the three solid wastes reaches 70 %, the 28-day compressive strength of the bauxite residue-based binder reaches 50.6 MPa, and the mechanical properties at all curing ages exceed the P•O42.5 cement standard. As shown in Figure 6b, microstructural analysis indicates that the hydration products of the bauxite residue-based cementitious material mainly include ettringite, C-S-H gel, and C(N)-A-S-H gel; under the combined action of alkali and sulphate, reactive silicon and aluminium species from bauxite residue and fly ash rapidly participate in reactions, driving hydration toward higher degrees of polymerization. A large amount of gel and ettringite intergrow densely, reducing the porosity of the bauxite residue-based matrix and forming a compact structure, thereby enhancing mechanical strength. Meanwhile, as shown by the leaching results in Table 2, the prepared medium-calcium binder exhibits excellent immobilization of Na^+ , meeting the limits for Class III groundwater, mainly due to the effective stabilization of harmful ions like Na^+ through the silicon-aluminium coordination isomorphous substitution effect.

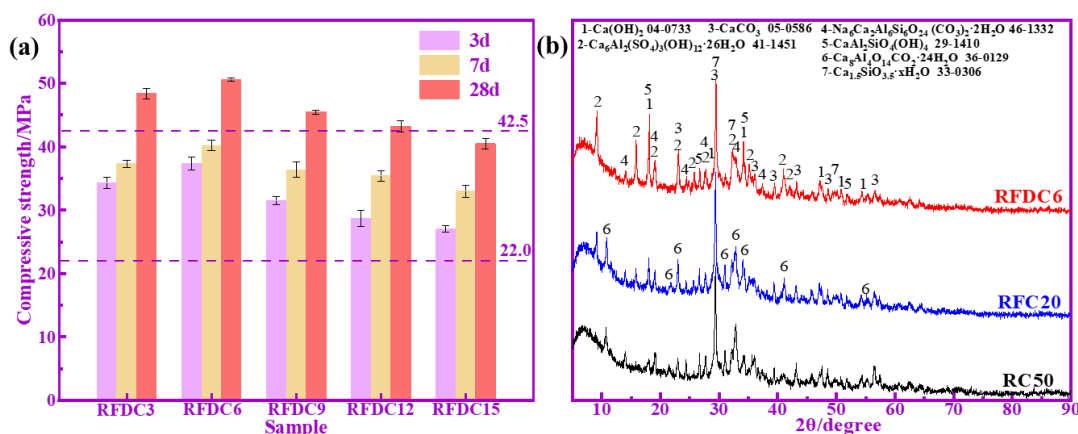


Figure 6. Compressive strength and hydration products of bauxite residue-based medium-calcium cementitious materials.

Cementitious materials prepared with steel slag often exhibit low early strength and poor volume stability. Studies by Hao et al. [24] demonstrated that the addition of bauxite residue and desulphurised gypsum can significantly enhance the early strength of steel slag-based binders, while fly ash can effectively improve their volume stability. Under the synergistic effect of multi-

solid waste blending, binders with a Ca/Si mass ratio between 1.2 and 1.3 show favourable cementitious and environmental performance. When 30 % steel slag is used with bauxite residue and fly ash, and the Ca/Si mass ratio is 1.25, the compressive strength of the binder reaches 18.5 MPa at 3 days and 53.4 MPa at 28 days, meeting the strength standard of P•O42.5 cement, and its setting time and volume stability also meet national standards. To address the issue of high soluble phosphorus content in phosphogypsum, Wei et al. [27] utilized the alkali in bauxite residue to convert soluble phosphorus into hydration products, preparing a medium-calcium binder using bauxite residue and phosphogypsum, in which bauxite residue and phosphogypsum can replace up to 90 % of cement. The mechanical properties of the binder also meet the national standard for P•O42.5 cement, with a phosphorus solidification rate of 97 %, and initial and final setting times of 221 min and 362 min, respectively, meeting the requirements for ordinary Portland cement.

Table 2. Na⁺ leaching results of bauxite residue-based cementitious materials with different mix ratios using various leaching methods.

Leaching Method	Sample Name	Curing Age			Na ⁺ Limit for Class III Groundwater (mg/L)
		3 d	7 d	28 d	
HJ 557-2009	RFDC-1.52	158.05	114.24	56.14	200.00
	RFDC-1.68	89.47	67.92	27.33	
	RFDC-1.80	122.11	86.35	48.42	
HJ/T 300-2007	RFDC-1.52	193.26	174.71	146.47	
	RFDC-1.68	95.08	82.41	65.16	
	RFDC-1.80	172.33	151.56	130.03	
Deionized Water Soaking	RFDC-1.52	30.40	25.05	10.13	
	RFDC-1.68	15.58	10.25	5.60	
	RFDC-1.80	24.14	11.20	8.41	
Acetate Buffer Solution Soaking	RFDC-1.52	52.86	32.52	16.49	
	RFDC-1.68	18.06	15.01	7.27	
	RFDC-1.80	49.19	31.45	13.35	

3.2 Non-Sintered Block Materials

Non-sintered blocks are a new type of brick material produced without firing, using metallurgical slag, coal fly ash, tailings, and other industrial solid wastes as the main raw materials, supplemented with cement, gypsum, and lime as binders, and processed through mixing, pressing, and curing. Compared with traditional fired bricks, non-sintered blocks offer advantages such as lower cost, energy saving, environmental friendliness, and effective solid waste utilization, and are thus rapidly replacing sintered bricks. Various industrial solid wastes (such as bauxite residue, electrolytic manganese slag, etc.) contain hydraulic cementitious components that can exhibit hydraulicity and cementitious properties under suitable conditions, making them fully suitable for the production of non-sintered blocks. Figure 7 shows non-sintered block products and their applications prepared by the synergistic use of bauxite residue and other solid wastes.

In addition, using different types of industrial solid wastes together can produce a composite synergistic effect; for example, alkaline components in bauxite residue can activate the cementitious activity of aluminosilicate solid wastes such as fly ash and slag, generating more hydration products. Sulphate-containing industrial wastes like gypsum can also promote the formation of more ettringite in the cementitious system by utilizing their sulphur content. Furthermore, industrial wastes differ in physical characteristics. For instance, fly ash particles are mostly spherical with high specific surface area, which can exert "micro-aggregate effect" and "morphology effect" in the non-sintered brick system, making the microstructure denser and thereby improving the mechanical and durability performance of the non-sintered bricks. Relevant studies have shown [15, 31, 32] that non-sintered bricks can be prepared using bauxite residue, fly ash, desulphurised gypsum, and cement combined with other aggregates. By following the medium-calcium design concept and adjusting parameters such as Ca/Si, MU15 to MU30 grade non-sintered blocks were successfully developed. Table 3 presents the compressive strength results of bauxite residue-based multi-solid waste non-sintered bricks with different bauxite residue dosages. It can be seen that the designed bauxite residue-based non-sintered bricks achieved a maximum compressive strength of 25.68 MPa, meeting the MU25 grade requirement in the Solid Concrete Brick standard (GB/T 21144-2007).



Figure 7. Non-sintered bricks and applications prepared from bauxite residue and other industrial solid wastes.

Table 3. Compressive strength (MPa) of bauxite residue-based multi-solid waste non-sintered bricks with varying bauxite residue contents.

Compressive Strength	3d	7d	28d
R1	7.32	11.84	22.21
R2	9.26	14.98	23.14
R3	9.25	14.89	25.68

R4	8.69	13.99	24.15
R5	8.35	12.69	24.01

3.3 Pavement Base Materials

As shown in Figures 8a and 8b, the pavement base is a layered structure constructed by placing single or mixed materials over the subgrade (soil base) bedding layer according to specific technical procedures. The base layer serves as the primary load-bearing component of the road and is generally composed of high-strength, high-performance, and low-pollution materials. Pavement base materials must possess excellent mechanical and durability properties while ensuring they do not contaminate groundwater or other resources. As shown in Figure 8c and 8d, pavement base materials were prepared using bauxite residue, coal gangue, and fly ash as the main raw materials. Results showed that when Ca/Si = 0.88, the unconfined compressive strength at 7 days reached 5.49 MPa, meeting the mechanical requirements for base layers of expressways and first-class highways in China’s national highway standards, and the relevant test sections have been operating stably for over five years in Yangquan, Shanxi and other regions [28]. In studies on using bauxite residue and circulating fluidized bed (CFB) coal fly ash to prepare subgrade materials, it was found that the alkali in bauxite residue can accelerate the silicification of f-CaO in CFB fly ash, overcoming the issue of material expansion caused by f-CaO in CFB fly ash. Meanwhile, the unstable component SO₃ in CFB fly ash participates in hydration reactions to form ettringite, thereby improving the early strength of pavement base materials [29].

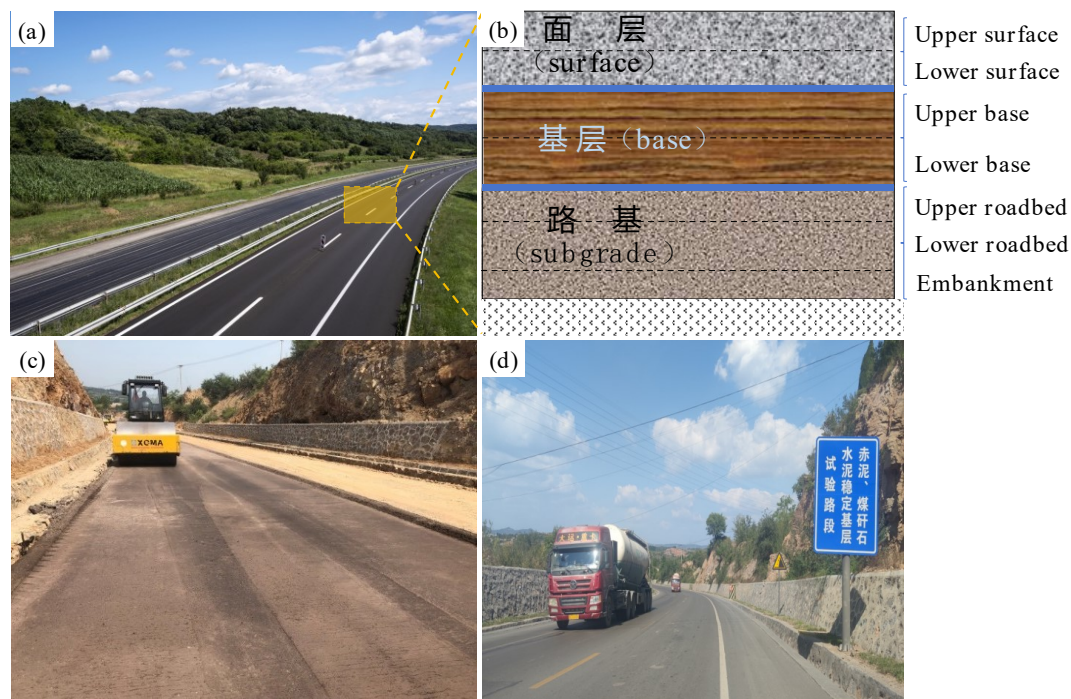


Figure 8. Schematic of road structure and construction/application of bauxite residue-based pavement base materials.

As shown in Figure 9, core samples showed a 7-day unconfined compressive strength of 7.36 MPa, a 90-day compressive strength of 11.5 MPa, and a splitting tensile strength of 1.65 MPa. After five freeze-thaw cycles, the residual strength of the base remained above 90 %, which exceeds the national standard requirement (70 %). Due to the isomorphous substitution effect in Si-Al coordination, heavy metal ions in bauxite residue were effectively stabilized, with solidification rates of 96.5 % for As and 91.4 % for Hg. The concentrations of various heavy metal ions in the leachate complied with national standard limits. In another study based on

medium-calcium component design, pavement base materials were prepared using electrolytic manganese slag and bauxite residue as industrial solid wastes [30]. The results showed that when $\text{Ca}/\text{Si} = 0.95$, the 7-day unconfined compressive strength of the pavement base material reached 6.1 MPa, meeting relevant national standards. Leaching test results indicated that the prepared pavement base material exhibited excellent environmental performance. Meanwhile, effective solidification of residual Mn^{2+} in the manganese slag was also achieved. The main hydration products of bauxite residue-based pavement base materials are C-A-S-H gel and ettringite, both of which play a positive role in strength development and manganese ion immobilization.

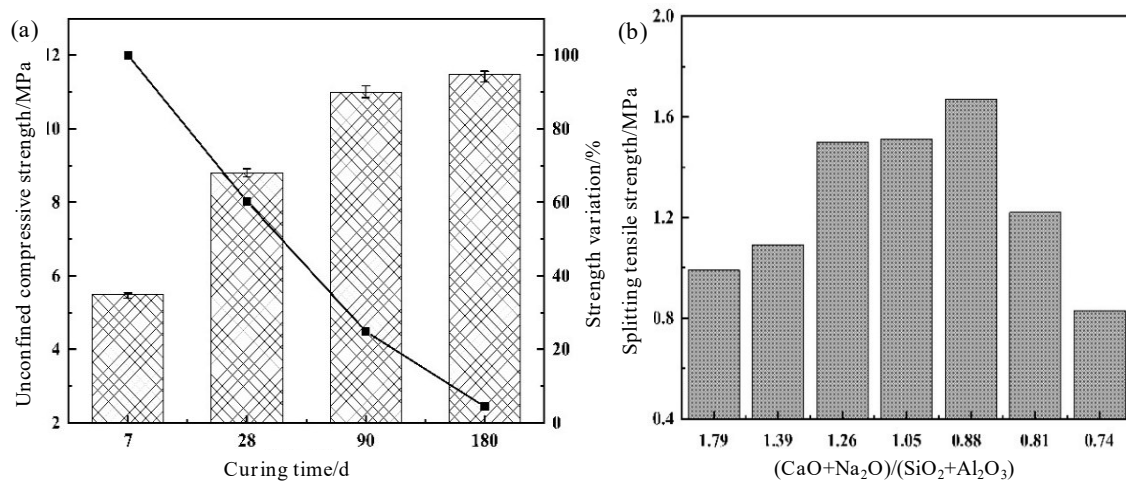


Figure 9. Bauxite residue–CFB fly ash pavement base materials: (a) variation in unconfined compressive strength over curing time, (b) splitting tensile strength of the pavement base material.

3.4 Mine Filling/Backfilling Materials

During the extraction and use of bauxite and coal, not only is a large amount of industrial solid waste generated, but also considerable areas of mining tunnels and open-pit mine pits. If these mining sites are not effectively restored and treated, they can lead to surface subsidence and environmental pollution, creating significant safety hazards and ecological risks. With the development of backfilling technology, the use of industrial solid byproducts with potential pozzolanic activity (such as bauxite residue, slag, fly ash, and steel slag) to prepare backfilling cementitious materials has become a mainstream choice in this field, constrained by cost and carbon emissions. This technology can promote the green and cyclical development of underground and surface mines, reduce backfilling material costs, innovate backfilling technologies, improve economic benefits for enterprises, and encourage large-scale utilization of bauxite residue and coal-based solid wastes.

As shown in Figures 10a–10c, Xiaoming Liu's team from Beijing University of Science and Technology [13] prepared bauxite residue-based expansive paste-like backfilling materials using bauxite residue, coal gangue, coal fly ash, and desulphurization gypsum. When the cement content was 3 %, the compressive strength of the filling material reached 2 MPa at 1 day, over 5 MPa at 7 days, and around 8 MPa at 28 days, meeting the strength requirements for mine backfilling. The slump of the filling material was between 20 cm and 23 cm, indicating good flowability that meets the pumping requirements for mining backfilling. Additionally, as shown in Figures 10d and 10e, Xiaoming Liu's team also successfully prepared bauxite residue-based composite surface backfilling materials, using bauxite residue, circulating fluidized bed coal fly ash, and desulphurization ash, for the large demand of surface backfilling and land reclamation in Tangshan Caofeidian. The preparation was based on medium-calcium component design and

multi-waste composite synergistic effect theories. As shown in Figure 11, when no cement was added and the bauxite residue content was 45 %, after rational formulation and optimization, the backfilling material’s 7-day unconfined compressive strength reached 7.3 MPa. After five freeze-thaw cycles, the strength retention was still above 90 %, and after 20 wet-dry cycles, the unconfined compressive strength remained greater than 4 MPa. Leaching analysis indicated that the Na⁺ leaching met the requirements for groundwater Category IV water standards. Microscopic analysis showed that bauxite residue could provide alkaline components for the backfilling material’s reactive system, increasing the alkalinity of the hydration environment, promoting the hydrolysis of active aluminosilicate substances in solid wastes, generating more SiO₄⁴⁻ and AlO₂²⁻, and reacting with Ca²⁺ and SO₄²⁻ released from sulphate solid wastes to form hydration products such as ettringite, C-S-H, and C(N)-A-S-H. These hydration products continuously fill pores and interlock to form a dense network structure, promoting the development of the backfilling material’s mechanical properties.

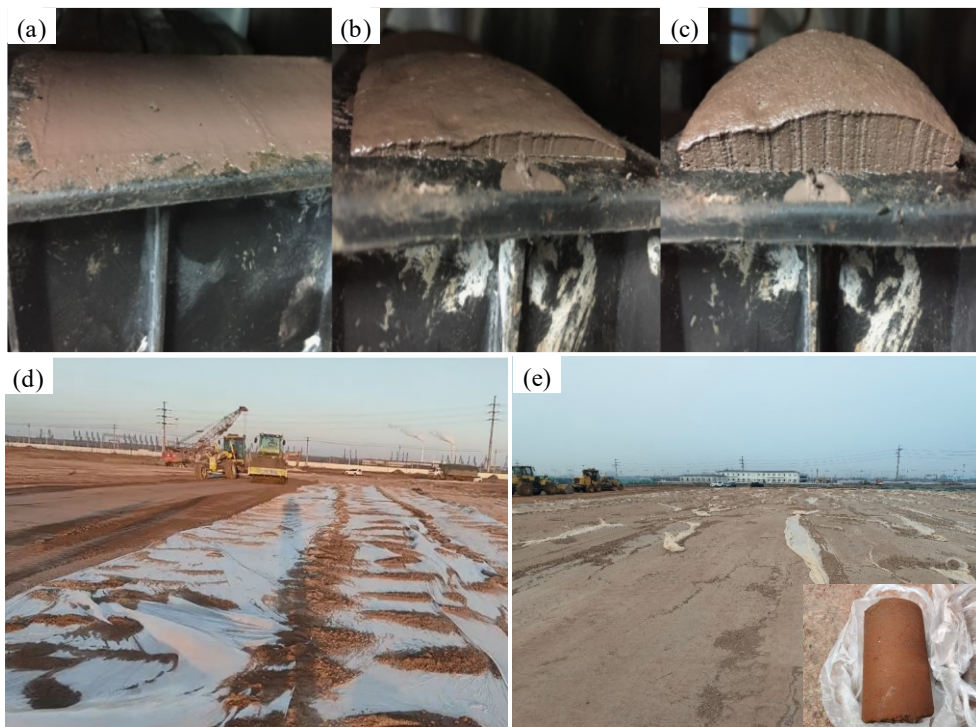


Figure 10. Bauxite residue-based underground backfilling materials and surface backfilling materials: (a, b, c) underground backfilling materials, (d, e) surface backfilling materials.

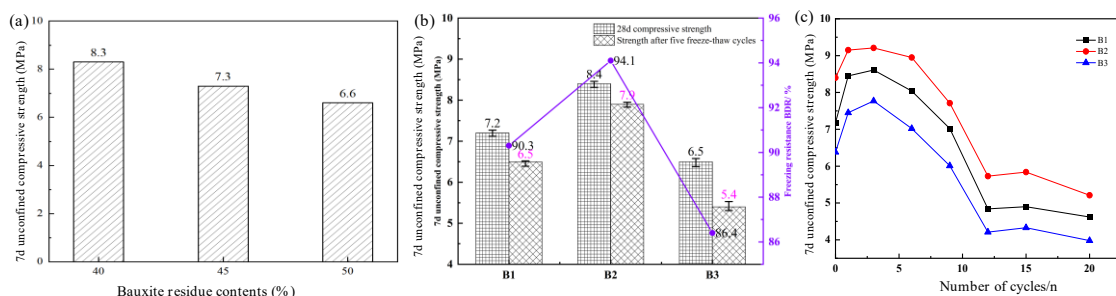


Figure 11. Mechanical and durability performance of bauxite residue-based surface backfilling materials: (a) 7-day unconfined compressive strength, (b) freeze-thaw cycle performance, (c) wet-dry cycle performance.

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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