

Review

Modification of Steel Slag Aggregate in Road Engineering: Key Technologies, Performance Enhancements, and Sustainable Prospects

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Abstract

The growing demand for natural aggregates and continued stockpiling of steel slag have increased interest in using steel slag aggregate (SSA) in road engineering. However, delayed hydration of free calcium oxide (f-CaO) and free magnesium oxide (f-MgO), porous and rough surfaces, and the potential release of hazardous elements constrain its long-term application. This review compares aging treatment, surface modification, direct carbonation, microbially induced calcium carbonate precipitation (MICP), and combined treatments from a raw-material heterogeneity and defect-oriented perspective. Their effectiveness is strongly condition-dependent. Aging treatment can control volume expansion, but reaction depth and treatment uniformity remain limited. Surface modification can reduce water absorption and improve interfacial performance but cannot eliminate internal expansive phases. Direct carbonation and MICP can stabilize reactive phases, refine pore structures, and reduce the mobility of some elements, but are limited by mass transfer and equipment requirements, and by mineralization uniformity and ammonium by-product management, respectively. Combined treatments can address multiple defects but increase process complexity, resource consumption, and quality-control requirements. Because material properties and evaluation methods vary among studies, reported performance gains should not be directly used for technology ranking. Instead, technology selection should follow the framework of “raw-material characteristics–dominant defects–preferred technology–engineering boundaries”. From a life-cycle perspective, sustainability depends on balancing resource and environmental benefits against additional treatment burdens. Near-term implementation should integrate raw-material classification, process monitoring, long-term durability and dynamic leaching verification, and the progressive incorporation of key performance and environmental indicators into road-material specifications and engineering acceptance criteria.



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Keywords: steel slag aggregate; volume stability; heavy metal leaching; surface modification; direct carbonation; microbially induced calcium carbonate precipitation

1. Introduction

As global industrialization and urbanization continue to advance, the demand for the renewal and maintenance of existing infrastructure and building structures is also increasing [1,2]. Consequently, the consumption of natural aggregates in transportation, building

construction, and municipal engineering continues to rise, placing growing pressure on natural resources and the environment [3]. As the world's largest crude steel producer, China's crude steel production scale has remained high for a long time [4]. According to statistics from the World Steel Association, global crude steel production reached 1849.4 million tonnes (Mt) in 2025. China produced 960.8 Mt, accounting for 52.0% of the global total [5]. Figure 1a shows the spatial distribution of the top 10 crude steel-producing countries, while Figure 1b presents the regional shares of global crude steel production. Steel slag is the main solid by-product produced during the steel smelting process, and its production is usually about 10% to 15% of crude steel production [6]. Based on this estimate, China's steel slag production in 2025 is about 96.1–144.1 Mt. However, the comprehensive utilization rate of steel slag in China is still relatively low, with the cumulative stockpile amount reaching approximately 1.1 billion tonnes, and the pressure for resource consumption is outstanding [7].

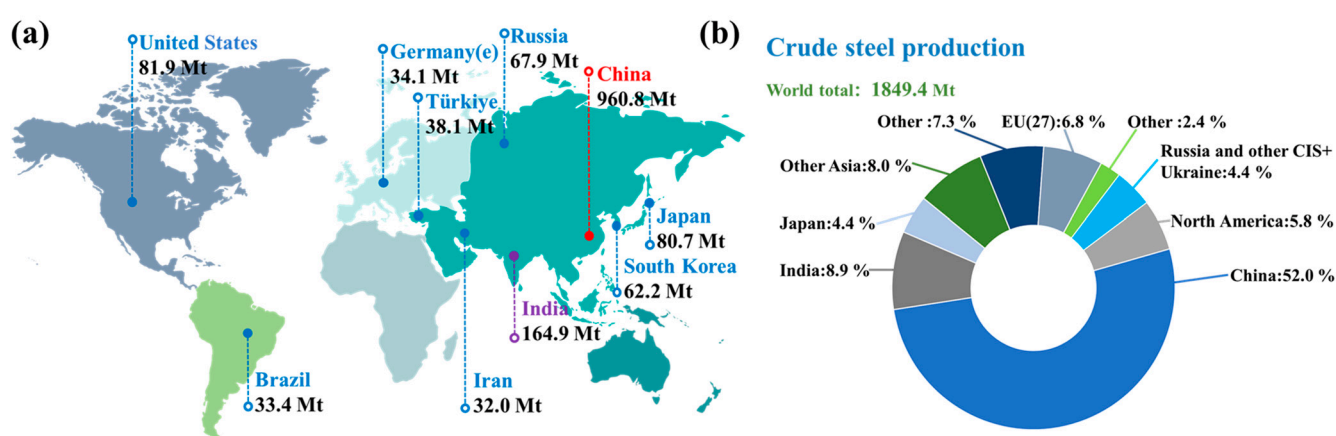


Figure 1. Global crude steel production in 2025: leading producing countries and regional shares [5]. (a) Spatial distribution of the top 10 crude steel-producing countries in 2025 (unit: Mt); (b) regional shares of global crude steel production, with a total global output of 1849.4 Mt. Data source: World Steel Association, 2026. Note: The ranking in panel (a) is based on year-to-date crude steel production. Some regional values in panel (b) include estimates.

Steel slag aggregate (SSA) can be obtained by crushing, screening and classifying steel slag [8]. SSA usually has high hardness, good wear resistance and anti-fragmentation properties, as well as prominent particle angularity and surface texture, which can provide better skeleton load-bearing, particle interlocking and anti-skid properties for road materials [9,10]. Therefore, using SSA for road engineering can not only reduce the mining of natural aggregates, but also promote the resource utilization of bulk solid steel waste. However, these mechanical advantages do not directly guarantee its long-term engineering suitability. The slow hydration of free calcium oxide (f-CaO) and free magnesium oxide (f-MgO) may cause volume expansion [11]; although the porous rough surface is conducive to mechanical interlocking, it may increase water absorption and binder requirements, and weaken long-term interface water stability [12]; trace elements such as Cr, V, Ni and Cd may also migrate under specific occurrence states and long-term environmental effects [13]. These issues respectively involve the active phase inside the particles, the interface between surface pores and materials, and long-term environmental safety, and have different formation mechanisms and action scales. Therefore, SSA modification should not preset a unified treatment plan, but should identify dominant defects based on material characteristics, and select a technical path that matches the target, treatment depth, and engineering conditions.

In response to the above problems, existing research has formed main technical routes such as aging treatment, surface modification, direct carbonation and microbially induced

calcium carbonate precipitation (MICP). The aging treatment controls expansion by promoting hydration of the active calcium and magnesium components in advance, and has a mature process and a basis for batch processing. The natural aging cycle is long, and although hydrothermal or steam intensification can shorten the processing time, it will increase the demand for water supply, heating or pressure; different methods may be limited by the reaction depth and processing uniformity [14]. Surface modification can improve surface properties through active reactions, pore filling, hydrophobic film formation or interface bridging [15]. It is flexible and can deal with water absorption and interface problems directly, but it is difficult to eliminate the expansion source inside the particles. Direct carbonation converts active calcium- and magnesium-bearing minerals into stable carbonates, thereby improving the volume stability and pore structure of SSA. It also offers potential for CO₂ mineral sequestration, although its effectiveness is constrained by mass-transfer conditions, reaction depth, equipment requirements, and resource inputs [16]. MICP can induce carbonate deposition under relatively mild conditions and provide a biomineralization path for active phase stabilization and pore repair, but it still faces problems such as mineralization uniformity, by-product management, treatment cost, and long-term durability [17]. When multiple types of defects exist at the same time, combined treatment can use the complementary functions of different technologies to expand the scope of improvement, but it will also increase the complexity of the process and the difficulty of quality control [18].

Existing reviews generally fall into two categories. Some provide broad overviews of steel slag utilization in road engineering and its effects on pavement performance [1,19,20], whereas others focus on specific issues or treatment technologies, such as volume stability and carbonation [21–23]. However, existing reviews rarely conduct comprehensive comparisons of multiple types of modification technologies under the same analytical framework based on differences in raw materials and dominant defects. At the same time, existing research has large differences in material basis, processing conditions and evaluation systems, making the performance improvement of similar technologies obviously condition-dependent; comprehensive evidence on long-term service, environmental safety and engineering amplification is still relatively insufficient. Therefore, this review adopts a raw-material heterogeneity and defect-oriented perspective to systematically examine the relationships among SSA characteristics, dominant defects, and modification mechanisms. It further compares the applicable conditions, representative performance evidence, and engineering boundaries of aging treatment, surface modification, direct carbonation, MICP, and combined treatments. On this basis, this review proposes a technology-matching framework tailored to different material characteristics and dominant defects. It also examines the trade-offs between performance improvements and the additional resource use and environmental burdens associated with modification from long-term service and life-cycle perspectives, and identifies key research priorities in process control, durability assessment, and large-scale application.

The rest of this article is organized as follows: Section 2 introduces the literature search and screening methods; Section 3 analyzes the source, basic performance and inherent defects of SSA; Section 4 reviews the mechanism of action, performance improvement effects and application limitations of the main modification technologies; Section 5 conducts a multi-dimensional technology comparison and discusses targeted modification paths, life cycle trade-offs and future research directions; Section 6 summarizes the main conclusions. This article aims to provide scientific reference for the rational selection, comprehensive evaluation and engineering amplification of SSA modification technology for roads.

2. Literature Search and Screening Methods

This review selects Web of Science Core Collection as the main data source. The database has a strict source selection mechanism, standardized bibliographic information and a complete citation index, and extensively covers high-quality journals in the fields of materials, environment and civil engineering [24,25]. It has been widely used for systematic reviews and bibliometric research.

The index selections are Science Citation Index Expanded (SCI-EXPANDED) and Social Sciences Citation Index (SSCI). Author J.M. conducted the preliminary search, and two other authors, J.L. and Y.L., verified the final search string. The search formula was $TS = ((\text{steel slag}^* \text{ OR steel slag aggregate}^* \text{ OR slag aggregate}^*) \text{ AND } (\text{road}^* \text{ OR pavement}^* \text{ OR highway}^* \text{ OR asphalt}^* \text{ OR infrastructure}^* \text{ OR "civil engineering"})) \text{ AND } (\text{stabiliz}^* \text{ OR modification}^* \text{ OR treatment}^* \text{ OR aging}^* \text{ OR surface}^* \text{ OR carbonat}^* \text{ OR MICP OR combined}^* \text{ OR synergistic}^*)$). The search covered January 2008 to June 2026, with the final search performed on 30 June 2026. Only Articles and Review Articles published in English were considered. After repeated record checking, a total of 886 journal papers were obtained (including 815 journal papers and 71 review papers). The retrieved papers were then screened. The specific screening process is shown in Figure 2, and the inclusion and exclusion criteria are shown in Table 1. As shown in Figure 2, the literature screening includes title and abstract screening and full-text eligibility assessment in sequence. In the title and abstract screening stage, a preliminary judgment was made based on the correlation between the research object, application scenario and research content and SSA material characteristics, road engineering applications and modification treatments. A total of 187 documents were retained for full-text assessment, and 699 documents with obviously irrelevant topics were excluded. The full-text assessment further examined the eligibility and extractability of study subjects, treatment methods, evaluation indicators, experimental information, and reported results. A total of 73 articles were excluded. Among them, 35 were outside the scope of this review, 35 did not meet the eligibility criteria for treatment methods or reported outcomes, and 3 lacked full-text access or essential methodological information. Consequently, 114 studies were included in the qualitative synthesis and constituted the main evidence base of this review. Additional references were used only for methodological descriptions, background information, or supplementary mechanistic context and were not counted among the included studies.

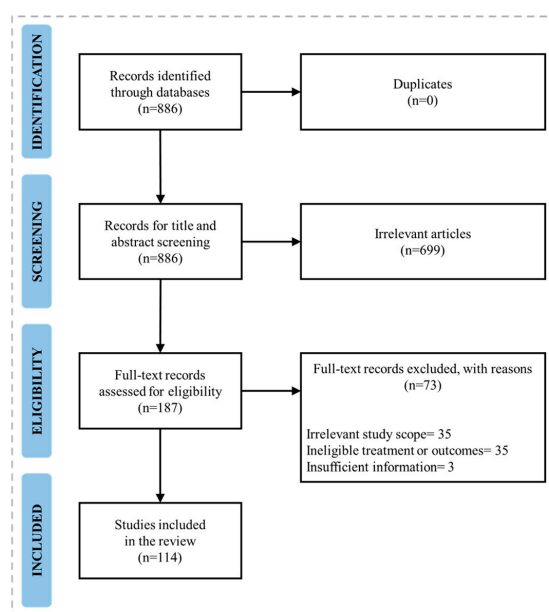


Figure 2. Literature search and screening process [26].

Table 1. Inclusion and exclusion criteria for full-text literature screening.

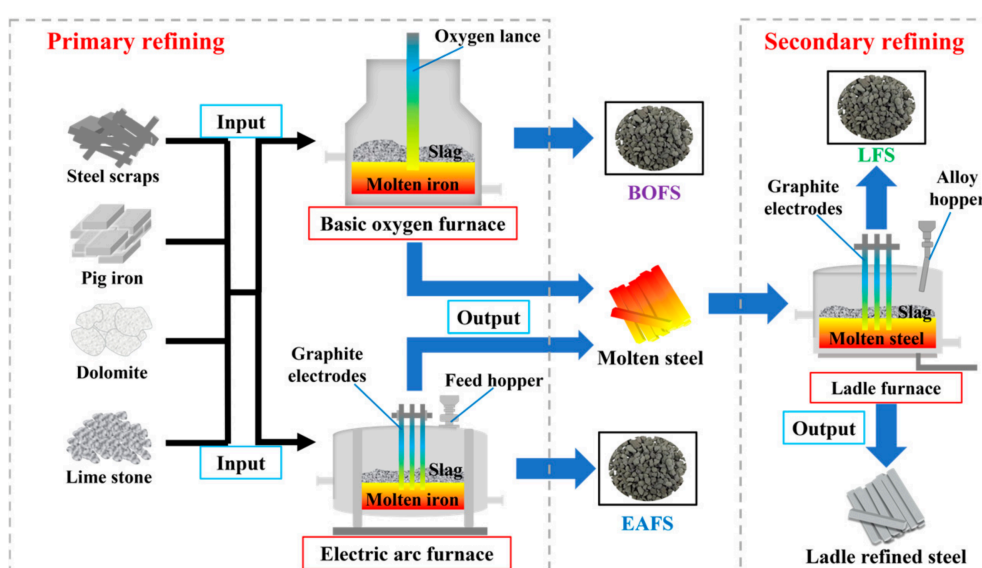
Criterion	Inclusion Criteria	Exclusion Criteria
Study subject	SSA, steel slag aggregate, or road materials containing SSA	Non-steel-slag materials or studies unrelated to road aggregates
Research content	Material characteristics, intrinsic defects, or road performance	Studies limited to unrelated applications or general compositional analysis
Modification techniques	Aging, surface modification, carbonation, MICP, or combined treatment	Non-target treatments or studies modifying only the asphalt binder or cementitious matrix
Reported outcomes	Mechanisms, process parameters, performance indicators, or environmental data	Irrelevant indicators or no extractable results
Powder-based studies	Studies supporting the analysis of aggregate carbonation, mineral transformation, pore structure, or leaching behavior	Studies focusing only on cementitious activity, with findings not transferable to aggregate applications
Full-text availability	Full text available, with adequately reported methods and complete data	Full text unavailable, methods unclear, or data sources unidentified

(Note: Reviews directly related to the research topic are used for technical classification and mechanism induction, while qualitative synthesis gives priority to original research data).

3. Sources, Properties, and Inherent Defects of Steel Slag Aggregates

3.1. Classification and Sources of Steel Slag

According to the production method, steel slag mainly includes converter slag (BOFS), electric arc furnace slag (EAFS) and ladle slag (LFS) [27]. Figure 3 schematically illustrates the generation process of BOFS, EAFS and LFS. The smelting process, steel type, raw material components and slag treatment methods will all affect the chemical composition and mineral structure of steel slag. Different types of steel slag usually have their own characteristics. Table 2 summarizes the main chemical components of BOFS, EAFS and LFS reported in different studies and classifies them according to their origin. The main chemical components of the three types of steel slag include calcium oxide (CaO), magnesium oxide (MgO), silicon dioxide (SiO₂) and aluminum oxide (Al₂O₃). The difference is mainly reflected in the content of CaO, Al₂O₃ and iron(II)/iron(III) oxide (FeO/Fe₂O₃).

**Figure 3.** Schematic diagram of the steelmaking process and the generation of BOFS, EAFS, and LFS.

As shown in Table 2 and Figure 3, BOFS is generated during the primary converter refining of molten iron. It accounts for approximately 80% of the total steel slag generated [28]. Compared with other types of steel slag, BOFS generally contains higher proportions of CaO, FeO/Fe₂O₃, and silicate minerals. Affected by the degree of slagging reaction and cooling process, its structure is dense and accompanied by certain pore development, and usually contains more unstable substances such as f-CaO and f-MgO [29]. EAFS is mainly produced in the electric arc furnace smelting process using scrap steel as raw material. Its composition is greatly affected by the scrap source, smelting steel type, redox conditions and slagging parameters. Compared with BOFS, EAFS usually has lower alkalinity and a relatively higher proportion of RO phase. The RO phase is mainly a solid solution formed by divalent metal oxides such as FeO, MgO, MnO and CaO [30]. Due to large fluctuations in raw material sources and process conditions, there may be significant differences in the composition and particle properties of different batches of EAFS. LFS is formed in the secondary refining stage of the ladle. In order to achieve desulfurization, deoxidation and inclusion adsorption, more calcareous and aluminum slagging materials are usually added during the refining process, so LFS often shows higher CaO and Al₂O₃ content and lower FeO/Fe₂O₃ content [31]. This compositional feature gives LFS strong potential gelling activity and hydration reaction ability. However, it may pulverize after cooling, and the particle morphological stability is usually weaker than BOFS and EAFS.

To sum up, the main chemical components of different types of steel slag are roughly the same, but the content and mineral structure of each chemical component are obviously different, resulting in different characteristics. These compositions and structural characteristics together form the material basis for the physical and mechanical properties and particle morphology of SSA.

Table 2. Major chemical compositions of BOFS, EAFS, and LFS from different countries/regions (mass fraction, %).

Steel Slag Type	CaO	MgO	SiO ₂	Al ₂ O ₃	FeO/Fe ₂ O ₃	Place of Origin
BOFS [32–35]	46.28	5.49	16.75	2.29	22.17	China
	39.40	9.69	11.97	2.16	30.23	USA
	40.3	7.78	14.1	2.04	26.7	Europe
	44.2	3.0	15.6	1.6	19.0	Japan
EAFS [36–39]	35.9	4.7	21.9	6.8	23.1	China
	32.1	4.3	19.4	8.6	26.4	USA
	26.8	2.8	16.3	10.5	35.4	Europe
	22.8	4.8	12.1	6.8	29.5	Japan
LFS [37,40–42]	54.86	3.41	16.33	21.46	0.62	China
	56.5	3.8	26.7	4.7	1.2	USA
	44.2	7.9	19.4	8.5	10.7	Europe
	55.1	7.3	18.8	16.5	0.3	Japan

3.2. Basic Mechanical Properties of Steel Slag Aggregates

SSA usually has higher hardness, good resistance to breakage and wear, and also exhibits prominent particle angularity and surface texture [43]. The high hardness components of SSA, such as olivine, silicate and iron minerals, and their relatively dense mineral skeleton together give the SSA good load-bearing capacity and anti-fragmentation properties [44]. The crushing values of SSA reported in existing studies are generally 12% to 16%, which are generally lower than those of limestone and similar to some basalt and granite aggregates [45,46]. In addition, the relative density of SSA is usually 3.1 to 3.5,

which is higher than that of commonly used limestone and basalt aggregates, facilitating the formation of a stable aggregate skeleton [47,48]. Meanwhile, the high hardness endows SSA with excellent wear resistance and impact resistance. Relevant reviews indicate that the SSA Los Angeles abrasion value is mostly between 11% and 26%, typically lower than that of limestone and close to that of high-quality basalt [1]. Diaz-Piloneta et al. [49] found that BOFS showed favorable performance in the Los Angeles abrasion and polishing tests. The crushed SSA usually has sharp edges and rough surface textures, which is conducive to the interlocking between particles and the anti-skid performance of the road surface. Wang et al. [50] confirmed through comparative experiments that the angularity and surface roughness of SSA are 30% to 50% higher than those of granite and limestone. After Zhang et al. [51] incorporated SSA into an asphalt wearing course and observed improved skid resistance and wear resistance of the mixture. The correlation coefficients between skid resistance and the surface texture index, measured both before and after abrasion, were greater than 0.9.

The above-mentioned mechanical and morphological advantages form the performance basis for SSA road utilization, but its engineering applicability is still restricted by the migration of active components, porous rough surfaces and risk elements. The next section will further analyze the intrinsic correlation between these material characteristics and volume stability, water absorption and interfacial properties, and environmental risks.

3.3. The Intrinsic Relationship Between Material Characteristics and Performance Defects

The engineering performance of SSA is mainly affected by the active mineral composition, porous rough surface and trace element occurrence form. f-CaO and f-MgO are the main active substances that affect the volume stability of SSA. When the two are hydrated to form $\text{Ca}(\text{OH})_2$ and $\text{Mg}(\text{OH})_2$, the molar volume increases by approximately 98% and 148% respectively [52]. Among them, f-CaO hydrates quickly, which mainly affects early stability; f-MgO reacts more slowly and may continue to expand during long-term service [53]. The local expansion stress caused by hydration can cause aggregate cracking, interface debonding, and further induce diseases such as pavement cracking, arching, or loose base layers [54].

The pores, cracks and pits formed during the cooling process of SSA give it a high specific surface area and adsorption capacity [55]. Although a rough surface is conducive to mechanical interlocking and initial interface adhesion, excessive open pores will absorb water and light components of asphalt, making the effective asphalt film thinner and increasing the amount of asphalt [56]. In cement-stabilized materials, pores may also absorb mixing water and partial hydration products, interfering with the gelling reaction. Long-term water intrusion and freezing and thawing can further expand pores and weaken interface stability [57,58]. Therefore, the interfacial performance of SSA depends on the balance between the beneficial interlocking caused by surface roughness and the adverse effects caused by pore adsorption.

Trace elements such as Cr, V, Ni and Cd are mainly found in silicates, oxides and other mineral phases, and their migration and release are affected by the valence state, occurrence form and environmental conditions of the elements [13]. Under long-term acid leaching, saline-wet environment, or damaged pavement structure, some heavy metal-containing mineral phases may dissolve and release movable ions, increasing the risk of soil and water pollution [59,60]. Therefore, the environmental safety of SSA cannot be judged only based on the total amount of elements, but also needs to be evaluated in combination with the occurrence form and long-term service environment. The above material characteristics, action processes and corresponding performance defects are shown

in Table 3. Clarifying the intrinsic relationship between the three is the basis for selecting targeted modification technology.

Table 3. Correspondence between SSA material characteristics and performance defects.

Material Characteristics	Main Action Process	Performance Flaws	Modification Target
f-CaO, f-MgO	Delayed hydration expansion	Insufficient volume stability	Digest or stabilize active phase
Porous rough surface	Competition between water absorption, adsorption and interlocking	High water absorption, increased binder demand, and unstable interface	Fill pores and optimize interface adaptability
Heavy metal occurrence phase	Acid solubility and ion migration	Potential leaching risk	Cure elements, reduce migration

4. Major Modification Technologies for Steel Slag Aggregate

In view of the engineering defects caused by the aforementioned three types of material characteristics, existing research has mainly formed four types of single technologies: aging treatment, surface modification, direct carbonation and MICP modification, as well as combined treatment methods. This section will analyze the mechanism of action, improvement effects, technical advantages and application limitations of various technologies in turn.

4.1. Aging Treatment

4.1.1. Aging Method and Mechanism of Action

Aging treatment refers to storing SSA for a certain period of time under suitable temperature and humidity conditions so that active materials such as f-CaO and f-MgO can be hydrated in advance before engineering application. The basic reaction equation is as shown in (1) to (2) [15]:



According to the processing medium and temperature and pressure conditions, it can be divided into natural aging, hydrothermal aging, normal pressure steam aging and high pressure steam aging. Natural aging relies on precipitation, air humidity and atmospheric CO₂. In addition to the hydration of active oxides, it is also accompanied by calcium silicate dissolution and partial carbonation, and the treatment cycle is longer [20]. Compared with natural aging, hydrothermal aging accelerates the hydration reaction rate of active substances inside SSA through heating and continuous water supply [61]; in water On the basis of thermal aging, atmospheric pressure steam aging uses high-temperature saturated steam to further increase the aging speed and shorten the aging time. However, if the pile is too thick, it can easily lead to uneven hydration [62]. The researchers then proposed high-pressure steam aging, which uses temperature and pressure to further shorten the processing time and mitigate uneven hydration of SSA [63].

4.1.2. Modification Effect of Aging Treatment

Aging treatment is one of the core technical means to improve the volume stability of SSA and reduce its expansion risk. Huang et al. [64] used a semi-quantitative analysis method and found that after 12 months of natural aging, the f-CaO and f-MgO contents in SSA decreased by 57.89% and 24.32% respectively, but the digestion efficiency showed a steady decreasing trend with time. Increasing temperature and pressure can improve aging efficiency. Research shows that under the conditions of 162 °C and 0.6 MPa saturated

steam, the aging reaction can be completed within 3 h, which greatly shortens the aging time [65].

In addition to volume stability, aging also changes the pore structure and particle mechanical properties of SSA. After hydrothermal aging at 90 °C for two days, the crushing value, abrasion value and water absorption of SSA decreased by 13.85%, 15.89% and 3.83% respectively [65]; however, after natural aging for 12 months, the crushing value and abrasion value of SSA increased from 17.4% to 19.2% and from 12.0% to 13.0% respectively [64], indicating that pore filling and local deterioration of particles may occur at the same time. Aging causes SSA's elemental leaching mechanisms to change over time. In the early stages of aging, the hydration and dissolution of f-CaO and dicalcium silicate will release Ca, Si, and V. Fine particles show higher leaching levels due to their larger specific surface area. As the surface Ca-Si-H modified layer and CaCO₃ are deposited, the leaching process gradually turns to diffusion control. The long-term release rate of V can be reduced by about an order of magnitude, but particle breakage may re-expose the internal active phase [66].

4.1.3. Technical Advantages and Application Limitations of Aging Treatment

The main advantages of aging treatment are mature technology and relatively simple operation. Natural aging equipment has low investment and is suitable for scenarios with sufficient processing cycles and storage conditions; hydrothermal and steam aging can shorten the processing cycle from months to days or hours, and improve the controllability and production efficiency of the processing process. The characteristics and applicable scenarios of the four aging methods are summarized in Table 4. The main limitation of aging treatment is insufficient depth and uniformity of reaction. Research shows that the f-CaO content of SSA particles aged for more than 1 year still fluctuates greatly, and the average f-CaO content of aged particles in random sampling is even higher than that of fresh particles [67]; this is because the aging reaction is mainly concentrated on the surface of the aggregate, and the f-CaO enriched area inside the particles still remains after aging. The impact of aging on SSA environment and interface properties is obviously conditional. In the early stages of treatment, especially for fine-grained SSA, the dissolution of f-CaO and silicate minerals may lead to higher releases of Ca, Si, and V. Therefore, the leachate and hydrothermal treatment wastewater generated by natural aging need to be properly collected and disposed of [66]. At the same time, although aging can reduce the risk of swelling by promoting hydration of active components, the hydration products generated may also change the surface chemistry and interfacial adhesion of SSA. Zhang et al. [68] found that after hydration, the adhesion work between SSA and asphalt decreased by 2.0%, and the peeling work increased by 33.5%; after boiling for 10 min, its mass loss rate and peeling rate were 1.3 times and 2.2 times that of unhydrated SSA, respectively. This shows that the improvement in volume stability is not necessarily accompanied by a simultaneous improvement in interfacial water stability, which still needs to be evaluated separately.

In summary, existing research shows that aging treatment has a clear application basis in terms of active component digestion and volume expansion control, but its modification effect is limited by particle size, reaction depth and treatment uniformity, and insufficiently reacted active phases may still remain inside the particles. In contrast, aging is not stable in improving high water absorption, interfacial water damage, and long-term element leaching behavior, and may even affect the interfacial adhesion between SSA and asphalt due to changes in surface chemical characteristics of hydration products. Therefore, the aging effect should not only be evaluated by f-CaO content or expansion rate, but should also be comprehensively judged in conjunction with indicators such as particle physical properties, interfacial water stability, and element leaching.

Table 4. Characteristics and applicable scenarios of the four aging methods.

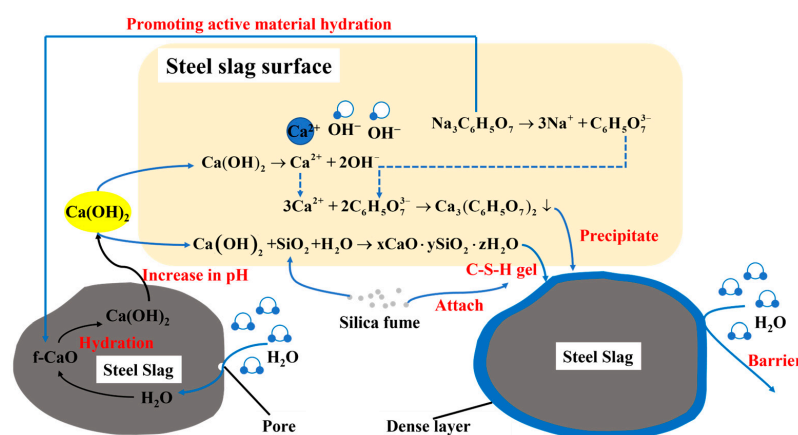
Aging Method	Typical Cycle	Main Advantages	Main Limitations	Applicable Scenarios
Natural aging [69]	6~12 months	Low cost and easy to implement	Long cycle and large fluctuations	Large-scale stockpiling
Hydrothermal aging [70]	2~7 d	Reaction is sufficient	Use more water and heat	Centralized preprocessing
Atmospheric pressure steam aging [62]	8~12 h	Shorter cycle	Limited deep reactions	Continuous processing
High pressure steam aging [63]	3 h	Deep response and high efficiency	Equipment energy consumption is high	High stability requirements

4.2. Surface Modification

4.2.1. Surface Modification Mode and Action Mechanism

Surface modification can be divided into inorganic, organic and composite surface modification according to the modified materials and mechanism of action. Inorganic modification mainly uses materials such as silica fume [71], fly ash [72], slag powder [73] and cement slurry [74]. Through the reaction of microfiller effect and pozzolanic reaction, a dense protective layer is formed on the surface of SSA, blocking the contact between expansion components such as f-CaO and moisture. Organic modification can be further divided into two categories: organic acid treatment and resin coating. Organic acids (such as acetic acid [75], oxalic acid [76], citric acid [77], etc.) form stable salts by reacting with active substances such as f-CaO and their hydration products, which are mainly used to digest surface swelling sources. Polyurethane [78], silicone resin [79], and epoxy materials close the pores through film formation and hydrophobicity, reduce the water absorption and moisture sensitivity of SSA, and limit the migration of light components of asphalt into the interior of the particles.

Composite surface modification achieves the synergy of multiple action mechanisms by combining inorganic active materials, organic acids, resins or coupling agents [14,80]. For example, in the silica fume (SiO_2) and sodium citrate ($\text{Na}_3\text{C}_6\text{H}_5\text{O}_7$) system, $\text{Na}_3\text{C}_6\text{H}_5\text{O}_7$ promotes the hydration of active substances such as f-CaO. The citrate radical ($\text{C}_6\text{H}_5\text{O}_7^{3-}$) dissociated from $\text{Na}_3\text{C}_6\text{H}_5\text{O}_7$ promotes the adsorption of metal ions in steel slag and the hydration products generated by chemical reactions on the surface of SSA. Part of the hydration product $\text{Ca}(\text{OH})_2$ is consumed by $\text{C}_6\text{H}_5\text{O}_7^{3-}$ to form $\text{Ca}_3(\text{C}_6\text{H}_5\text{O}_7)_2$ precipitation, and the other part reacts with activated SiO_2 to form calcium silicate (C-S-H) gel. Nano- SiO_2 connects the C-S-H gel to form a dense layered structure on the surface of SSA, preventing moisture from intruding into the interior of the aggregate [53]. The synergistic modification mechanism is illustrated in Figure 4.

**Figure 4.** Mechanism of SSA modified by silica fume and sodium citrate composite treatment.

4.2.2. Modification Effect of Surface Modification

The representative materials, processing conditions and performance improvement range of surface modification are shown in Table 5. In general, both inorganic fine additives and organic acid treatment can improve the volume stability of SSA, among which the mineral fine additives show a better comprehensive stabilization effect [81]. In addition to reducing the content of active components in the surface layer, organic acid treatment can also change the mineral composition and microstructure of SSA. Taking oxalic acid treatment as an example, the XRD results show (Figure 5a) that after treatment, the CaO diffraction peak disappears, some C₂S and C₃S diffraction peaks weaken, and the characteristic peaks of calcium oxalate and Ca(OH)₂ appear. SEM images further show that calcium oxalate crystals are deposited on the surface and pores of SSA, filling the original loose network structure and improving surface density (Figure 5b–e), which provides a microscopic basis for the improvement of volume stability, wear resistance and crush resistance.

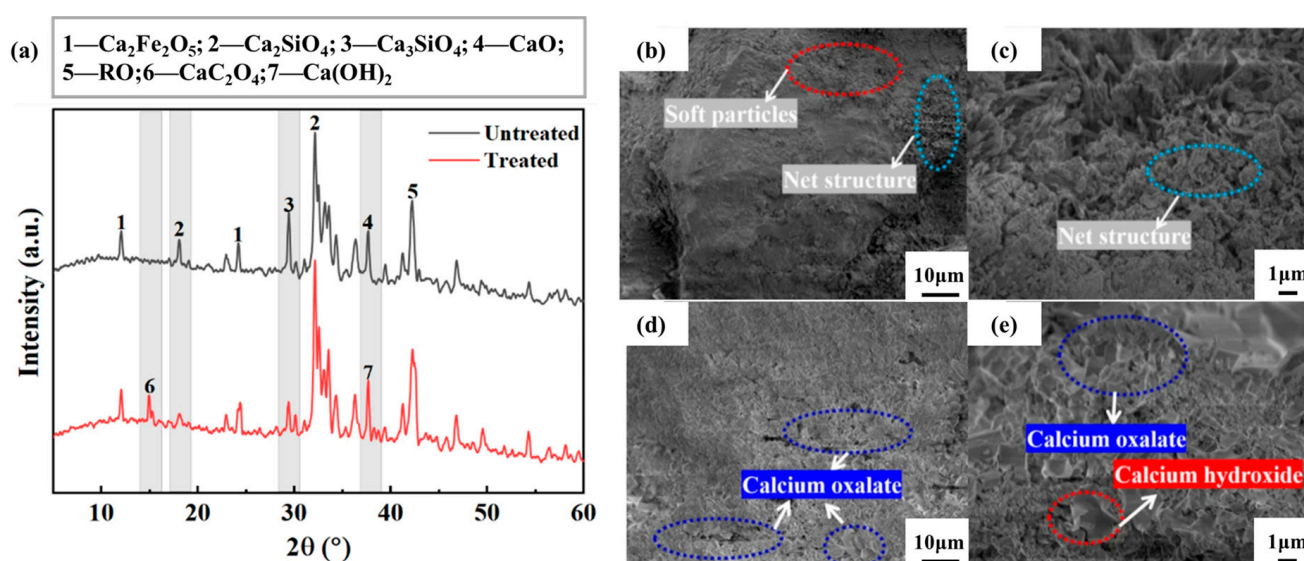


Figure 5. Mineralogical and microstructural changes in SSA before and after oxalic acid treatment [82]. (a) XRD patterns; (b,c) SEM images of untreated SSA; (d,e) SEM images of treated SSA.

For the problems of high porosity, high water absorption and interfacial water damage, resin coating and composite surface modification can generally reduce water absorption and binder requirements, and improve the interfacial and water stability properties of the mixture. When silica powder and a silane coupling agent are compounded, the former mainly fills surface pores, while the latter forms an interface bridge between inorganic aggregate and organic asphalt. Epoxy acrylic silicone resin (EAOR) can form a continuous protective film on the SSA surface, sealing pores and limiting moisture intrusion. Surface coating can also reduce the mobility of some heavy metals through pore closure and physical barrier. The continuous film layer formed by silicone resin can reduce the leaching concentration of Cd, Cr and other elements [83]. However, the existing environmental evidence mainly comes from short-term leaching tests, and its long-term service effect still needs further verification.

Table 5. Surface modification materials, treatment conditions, and representative performance improvements for SSA.

Modification Category	Modifier	Treatment Conditions	Representative Performance Improvements
Inorganic modification	Silica fume [64]	1. Dosage of 4.8% 2. 10-day immersion test	1. Expansion rate decreased by approximately 87%.
	Ground granulated blast-furnace slag, fly ash, and silica fume [84]	1. Total dosage of 10% 2. Mass ratio of 1:1:2 3. 10-day water-bath cycling at 90 ± 3 °C	1. Expansion rate decreased by approximately 96.5%.
Organic modification	Oxalic acid [82]	1. Concentration of 0.4 mol/L 2. Liquid-to-solid ratio of 5:1 3. Immersion at 25 °C for 84 h	1. f-CaO content decreased by 51.1%; 2. Expansion rate decreased by 53%; 3. Abrasion loss and crushing value decreased by 27.7% and 7.9%, respectively.
	Silicone resin [83]	1. Dosage of 25 mL/kg 2. Curing at 60 °C for 12 h	1. Water absorption decreased by 62.3%.
Combined surface modification	Silane coupling agent–epoxy resin composite gel (HC-1) [85]	1. Immersion at 20 °C for 24 h 2. Curing at 25 °C for 24 h	1. Water contact angle increased by 32.2%; 2. Marshall stability increased by 15.4%; 3. Optimum asphalt content decreased by 0.21 percentage points.
	Isocyanate–hydroxyl acrylic resin composite modifier (NOCM) [86]	1. Dosage of 4%; NCO/OH ratio of 1.25 2. Curing for 24 h followed by drying at 60 °C for 10 h	1. Asphalt stripping rate decreased by 54.97%; 2. Residual Marshall stability and freeze–thaw splitting strength ratio (TSR) increased by 8.72% and 6.69%, respectively; 3. 7-day expansion rate decreased by 50.85%.
	Nano-silica–silane coupling agent (KH-550) [87]	1. Combination of 3% nano-silica solution and 15% silane coupling agent 2. Immersion for 6 h 3. Optimum modified SSA content of 10%	1. TSR increased by 3.4%–5.4%; 2. Low-temperature cracking resistance increased by 5.4%–27.2%.
	EAOR [74]	1. EAOR dosage of 4% 2. EAOR-to-xylene mass ratio of 2:1 3. Treatment at 160 °C for 30 min	1. Water absorption decreased by 64.9%; 2. Crushing value decreased by approximately 8.3%; 3. Asphalt-to-aggregate ratio decreased by 0.4 percentage points; 4. Dynamic stability increased by 7.7%.

(Note: The reported results were obtained under different SSA sources, particle sizes, initial conditions, mixture compositions, and evaluation methods. Therefore, the data are intended to illustrate representative improvements and should not be used for direct comparison or ranking of the modification methods).

4.2.3. Technical Advantages and Application Limitations of Surface Modification

The main advantage of inorganic surface modification lies in the wide range of material sources and the ability to improve the volume stability and surface density of SSA through pore filling and surface active component reactions. However, the hydrophobic capacity of inorganic modified layers is usually limited, and overfilling may also reduce the surface

roughness of SSA and weaken the mechanical interlocking effect between aggregates and cementing materials [88]. Organic acid treatment is characterized by a relatively short reaction time and direct consumption of surface-active components. However, its effectiveness is sensitive to acid concentration and treatment duration, and improved volume stability may be accompanied by deterioration in pore structure or interfacial properties. After soaking in 0.034 mol/L citric acid for 72 h, the expansion rate of SSA decreased by approximately 42.9%, but the water absorption rate increased by 36.43% [89], indicating that the digestion of active components may simultaneously expand surface pores. When this type of SSA is used for cement-based materials, the actual water–cement ratio needs to be controlled through prewetting or water consumption correction. Oxalic acid treatment may weaken the asphalt-aggregate adhesion due to the leaching of alkaline components on the surface; after treatment with 0.4 mol/L oxalic acid for 84 h, the asphalt peeling rate of SSA increased by 8%–34% [82]. In addition, this process also involves neutralization of acidic waste liquid, cleaning of aggregates and subsequent drying, etc., which increases the resource consumption and environmental burden of the treatment process. Resin coating and composite surface modification have obvious advantages in reducing water absorption rate, binder adsorption and water damage, and can be connected with the aggregate processing flow through spraying or impregnation. However, an overly dense film layer may cover the original rough texture of the aggregate and weaken the mechanical interlocking effect. Although EAOR treatment significantly reduced the water absorption rate of SSA and the oil-to-stone ratio of the mixture, its adhesion grade dropped from grade 5 to grade 4 [74], indicating that the dosage of the modifier and the thickness of the film layer are not necessarily the greater the better. A balance needs to be struck among pore sealing, hydrophobic performance and interfacial adhesion.

The common limitation of surface modification lies in the limited depth of action. Even if the surface pores are sealed, f-CaO and f-MgO may still remain inside the particles and continue to undergo delayed hydration after the film layer is damaged or water has invaded for a long time. In addition, the integrity and stability of the modified layer under high-temperature mixing, transportation compaction, freeze–thaw cycles, and long-term traffic loads still lack systematic verification. Therefore, surface modification is more suitable for addressing surface issues such as high water absorption, high binder adsorption, and insufficient interfacial water stability, but it cannot replace the stabilization treatment of the active components inside the particles.

4.3. Direct Carbonation

Accelerated carbonation of steel slag can be carried out in two main ways: direct carbonation and indirect carbonation [90,91]. These two carbonation paths are shown in Figure 6a. Direct carbonation refers to the direct contact reaction between steel slag and CO₂ under controlled conditions. Indirect carbonation first uses chemical extraction agents to leach calcium and magnesium ions from steel slag, and then carbonates and precipitates them [92,93]. The former can better retain the shape of aggregate particles and is more in line with the requirements of SSA stabilization treatment for roads; the latter route is primarily intended for efficient CO₂ sequestration and the production of high-value carbonate products. It generally involves grinding, leaching, solid–liquid separation, and product purification, which differ from the engineering objectives of modifying aggregates for road use. Therefore, this section focuses on the modification mechanism and effect of direct carbonation on SSA.

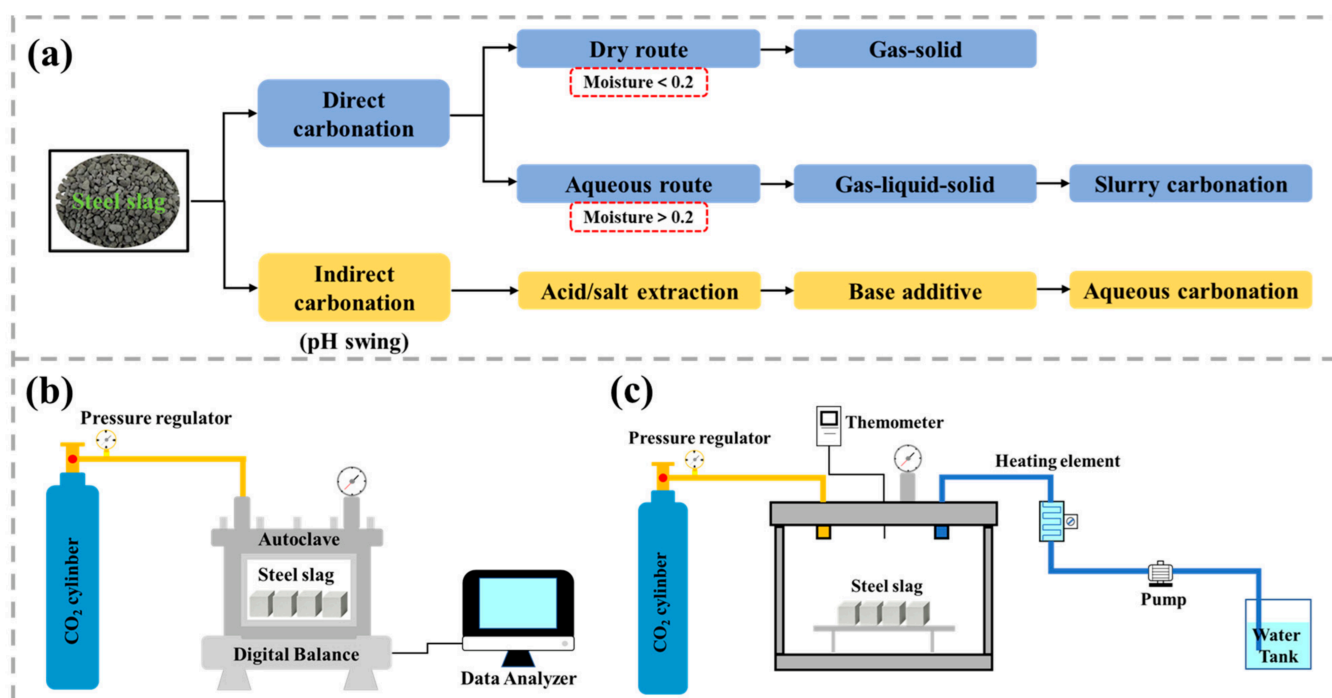
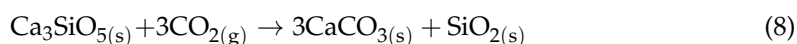
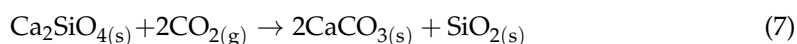
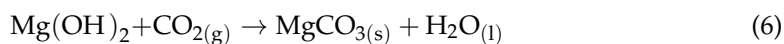
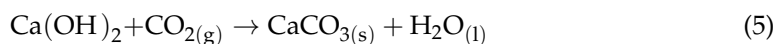
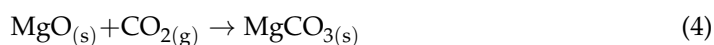
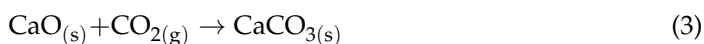


Figure 6. Pathways of accelerated carbonation and two direct carbonation devices. (a) Two main pathways of accelerated carbonation of steel slag; (b) Schematic diagram of dry carbonation apparatus; (c) Schematic diagram of wet carbonation apparatus.

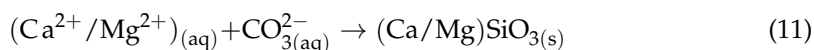
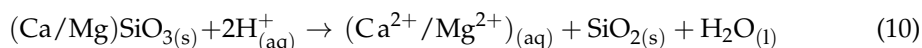
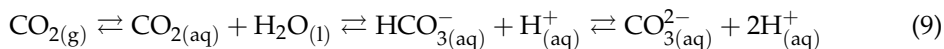
4.3.1. Direct Carbonation Method and Mechanism of Action

As shown in Figure 6a, according to the operation moisture of the reaction system, direct carbonation can be divided into dry carbonation (moisture < 0.2) and wet carbonation (moisture > 0.2) [94,95]. From the perspective of the reaction system, dry carbonation is a gas–solid two-phase reaction [96]. The schematic diagram of the device is shown in Figure 6b. As shown in the figure, the reaction mechanism of this process is as follows: CO₂ gas directly diffuses into the interior of SSA and reacts with f-CaO, f-MgO, Ca(OH)₂, Mg(OH)₂, C₂S, and C₃S in SSA to generate stable carbonate. The specific reaction process is shown in Equations (3)–(8) [97,98].



Wet carbonation uses water as the reaction medium and involves a gas–liquid–solid reaction system [99]. Figure 6c shows a schematic diagram of the wet carbonation apparatus. CO₂ is continuously supplied to the reactor, while water is circulated and preheated to promote contact between the gas phase and SSA under controlled temperature and pressure. The basic reaction process can be described as follows [100,101]: CO₂ first dissolves in water and participates in a series of acid–base equilibria involving H₂CO₃, HCO₃[−], and CO₃^{2−} (Equation (9)). The relative distribution of these dissolved carbon species is closely related to the pH of the aqueous phase [101]. The resulting H⁺ promotes the dis-

solution of Ca- and Mg-bearing phases in SSA and releases Ca^{2+} and Mg^{2+} into solution (Equation (10)). When the ionic product of Ca^{2+} and CO_3^{2-} exceeds the solubility product of CaCO_3 , carbonate precipitation becomes thermodynamically favorable. Ca^{2+} and Mg^{2+} can subsequently react with CO_3^{2-} to form the corresponding carbonate precipitates (Equation (11)), thereby stabilizing reactive Ca/Mg-bearing phases in SSA.



4.3.2. Modification Effect of Direct Carbonation

Direct carbonation usually improves the volume stability and water absorption properties of SSA by stabilizing active minerals and reconstructing the pore structure, and changes its element leaching behavior. The modification effect is affected by factors such as steel slag type, active mineral components [102], particle size and pore structure [103], as well as CO_2 concentration [104], temperature and pressure conditions [100,105], water content and treatment time [106]. The difference is mainly reflected in the depth of carbonation and the uniformity of reactions inside and outside the particles.

In the existing carbonation research on SSA for road use, volume stability improvement is the evaluation direction that receives the most attention and the evidence is relatively concentrated. Gao et al. [107] conducted a carbonation test on steel slag fine aggregate and found that after 8 h of carbonation, the f-CaO content dropped from 3.17% to 0.93%. However, under ambient temperature and pressure, CO_2 diffusion into the interior of coarse aggregates is limited. As a result, carbonation may be concentrated near the surface, leaving active components unreacted within the particles. In recent years, some scholars have studied the carbonation effect of pressurized hydrothermal carbonation treatment on steel slag coarse aggregate. At an initial CO_2 pressure of 1.0 MPa, increasing the temperature promotes RO-phase decomposition and the migration of Ca^{2+} , Fe^{2+} , and Mn^{2+} ions. After carbonation at 90 °C for 3 h, the reaction penetrates into 4.75–9.5 mm particles. When the temperature is raised to 180 °C for the same duration, f-CaO is nearly completely consumed, and the autoclave pulverization rate decreases by 56.24% [18]. This shows that appropriately increasing the temperature and pressure can help improve the internal carbonation degree of coarse-grained SSA. The CaCO_3 generated by carbonation has multiple contributions to material properties. On the one hand, CaCO_3 can fill the surface pores of SSA, reducing pore connectivity to a certain extent and improving the water stability of road materials. The study found that after 24 h of treatment at a solid–liquid ratio of 100% and a carbonation pressure of 0.3 MPa, the connected pore sealing rate of SSA exceeded 90%, and the water absorption rate dropped from 1.91% to 1.08%. The residual stability and TSR of asphalt concrete prepared using this carbonated SSA reached 91.3% and 91.0%, respectively [108], indicating that carbonation treatment can help improve the water stability of the mixture. On the other hand, it can serve as nucleation sites to promote cement hydration. Liu et al. [109] found that CaCO_3 formed on the surface of carbonated SSA provides nucleation sites and growth surfaces within the interfacial transition zone, thereby promoting cement hydration. Consequently, the 28-day compressive strength of the MM10SS group was 37% higher than that of the natural-sand control group. Zhang et al. [110] further found that carbonation products can promote the growth of C–S–H gel, making the cubic compressive strength of carbonated SSA engineered cement-based composites increase by 2.1% to 8.4% compared with the non-carbonated group. The effect of carbonation on the leaching behavior of chemical elements in SSA

also deserves attention. Relevant studies have shown that carbonate precipitation, surface adsorption and pore sealing can reduce the mobility of some metals such as Ni and Pb [111]; however, the pH drop and mineral phase changes caused by carbonation may also increase the release of elements such as V, which need to be controlled in process design.

4.3.3. Technical Advantages and Application Limitations of Direct Carbonation

There are obvious differences in reaction efficiency, resource investment, reaction depth and process complexity between different direct carbonation methods. Their technical advantages and application limitations are shown in Table 6. Dry carbonation process is simple, consumes little water, does not require solid–liquid separation and subsequent drying, and is beneficial to maintaining the particle shape of coarse aggregates. However, this process is affected by the diffusion rate of CO₂ and the passivation of the carbonate product layer, and unreacted active components are likely to remain inside coarse-grained SSA. Wet carbonation uses the water phase to promote the dissolution of CO₂ and the migration of Ca²⁺ and Mg²⁺, and usually has a higher reaction rate and degree of carbonation. However, this method will increase the steps of solid–liquid separation, aggregate cleaning, drying and waste liquid treatment, and bring high water consumption and post-processing burden. Pressurized hydrothermal carbonation uses temperature, pressure and water phase to jointly strengthen the migration of reaction medium into the particles, which can increase the carbonation depth of coarse-grained SSA and shorten the treatment cycle. Its main limitation is that it requires high pressure-resistant equipment and energy supply, and the equipment investment, operating energy consumption and safety management burden also increase accordingly.

Table 6. Comparison of process characteristics and technologies for different direct carbonation methods.

Carbonation Method	Main Processing Features	Main Advantages	Main Limitations	Maturity
Dry carbonation	Maintain granular form	Simple process and low water consumption	Insufficient internal response	Pilot stage
Wet carbonation	Aqueous phase enhanced mass transfer	Fast response and high efficiency	Water consumption and post-processing are difficult	Laboratory stage
Pressurized hydrothermal carbonation	Strengthen internal responses	Deep response, short cycle	Equipment energy consumption is high	Laboratory to pilot test
Wet and dry cycle	Periodic pre-moisturizing and hydrating	More efficient and less water consumption	Uniformity to be verified	Preliminary research

In order to take into account the low water consumption of the dry process and the high reaction efficiency of the wet process, Wang et al. [112] proposed a dry-wet cycle carbonation method. This method improves gas–liquid–solid mass transfer through static prewetting and periodic water replenishment, achieving a CO₂ absorption of 33.37 g/kg under normal temperature and pressure, which is 114.8% higher than the pure dry method. At the same time, the pressure steaming and powdering rate is reduced to less than 5.9%, and the crushing index meets the requirements of Class I sand. Compared with the traditional wet method, its water consumption is reduced by more than 50%, showing better reaction efficiency and water saving advantages. However, the water replenishment system, gas distribution and batch processing uniformity of this method still need to be further verified through pilot and engineering tests.

4.4. Microbially Induced Calcium Carbonate Precipitation Modification

4.4.1. Principle of Steel Slag Aggregates Modified by Microbially Induced Calcium Carbonate Precipitation

The core of MICP-modified SSA lies in the synergistic effect of microbial metabolism and calcium carbonate precipitation. The reaction process mainly includes four key steps: microbial metabolism, urease-catalyzed hydrolysis, local pH increase, and carbonate precipitation. Figure 7 is a schematic diagram of the mechanism of MICP modified SSA, which shows the process of microorganisms inducing carbonate precipitation to encapsulate SSA. Certain microorganisms involved in MICP can produce urease or carbonic anhydrase through microbial metabolism. Ureolytic microorganisms such as *Sporosarcina pasteurii* produce urease, which catalyzes urea hydrolysis and promotes the formation of NH_3 and inorganic carbon species. The dissolved NH_3 subsequently reacts with water to form NH_4^+ and OH^- , thereby increasing the local pH at the SSA interface [113]. Carbonic anhydrase can further facilitate carbonate formation by accelerating the reversible hydration of CO_2 and the formation of HCO_3^- [114]. Under alkaline conditions, HCO_3^- is further converted to CO_3^{2-} , which reacts with Ca^{2+} and Mg^{2+} released from SSA to precipitate carbonate minerals. These precipitates accumulate on the particle surface and within accessible pores, contributing to pore filling and the stabilization of reactive phases in SSA [115].

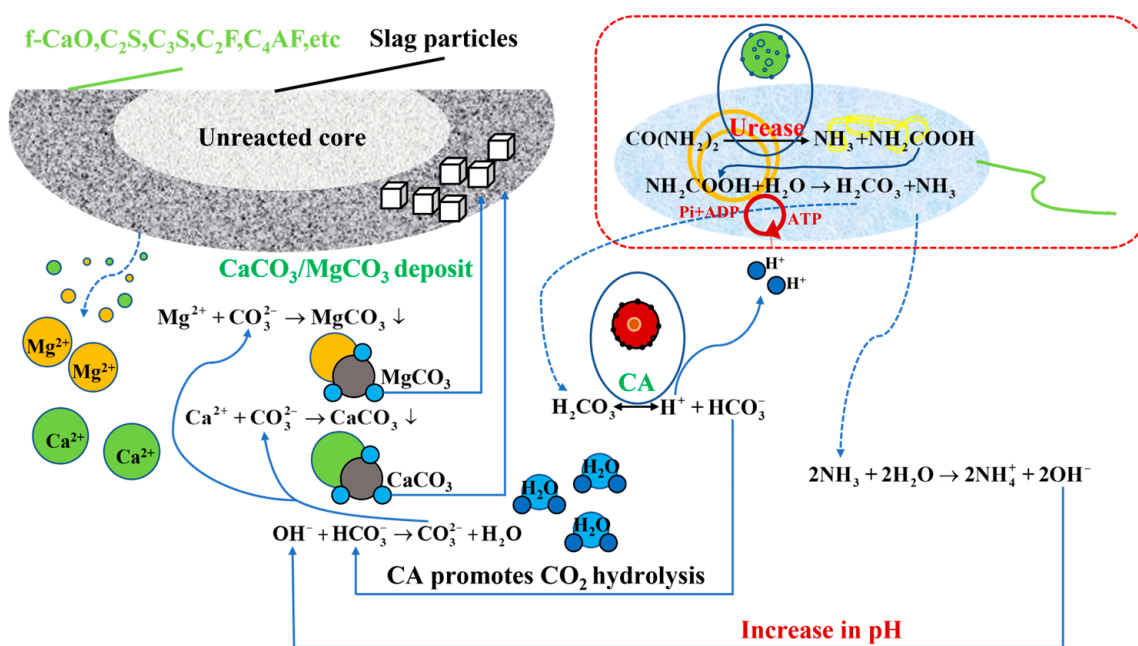


Figure 7. Schematic diagram of microbe-promoted carbonation of SSA.

4.4.2. Modification Effect of Microbially Induced Calcium Carbonate Precipitation

Existing studies indicate that MICP promotes carbonate precipitation on SSA surfaces and within pores, while reducing the content of active calcium-bearing components and improving the particle structure [116,117]. These changes enhance the volume stability, physical and mechanical properties, and environmental compatibility of SSA. The modification effect is affected by factors such as strain type, urease activity, reactant concentration, temperature, pH, treatment time, and reaction solution input method [113,118,119]. These factors mainly control the production amount, deposition location and spatial distribution uniformity of carbonate.

In terms of volume stability, MICP can promote the conversion of active materials such as f-CaO into stable carbonates. In one study, when the microbial dosage was 60% of the mass of SSA, the urea concentration was 2 mol/L, and the treatment temperature was

(20 ± 2) °C, the f-CaO content dropped to 2.98% after 72 h of reaction [120]. Another study used a mixture of *Sporosarcina pasteurii*, yeast and carbonic anhydrase bacteria in a ratio of 5:2:3, and controlled the microbial dosage to 60%. This multi-microbial system achieved good modification effects through the synergy of different bacterial species, reducing the f-CaO content of the treated SSA to 1.85% [121]. In addition to consuming active materials, carbonate deposition also fills pores and micro-cracks and enhances particle structure. Studies have found that the water absorption rate of SSA is significantly reduced after MICP treatment, its wear value is 41% lower than that of diabase, and its crushing value is 35% lower, indicating that the particle strength and wear resistance are improved [122]. Compared with atomized spraying, vacuum impregnation can promote the reaction liquid to enter the connected pores, reduce the water absorption rate of fine aggregates by 62.7%, and reduce the crushing value of coarse aggregates by up to 75.5% [123]. The above results show that the modification effect of MICP not only depends on the total amount of carbonate produced, but also depends on whether the mineralized products can enter the interior of the particles uniformly instead of being concentrated on the surface or pores. In terms of environmental safety, the generated carbonate can reduce the mobility of some metal elements through surface adsorption, co-precipitation, and lattice substitution [124]. In related studies, the leaching rates of each tested element in MICP-treated steel slag sand were less than 0.5%, showing a certain potential for heavy metal stabilization [125].

4.4.3. Technical Advantages and Application Limitations of Microbially Induced Calcium Carbonate Precipitation Modification

The main advantage of MICP is that the reaction conditions are relatively mild. Compared with pressurized hydrothermal carbonation or strong acid treatment, MICP can usually be performed at normal temperature and pressure [126]. In addition, the use of low-cost culture media and industrial and agricultural by-products to replace laboratory-grade nutrient sources can help reduce the cost of bacterial solution preparation. For example, Omoregie et al. [127] used food-grade yeast extract to cultivate *Sporosarcina pasteurii*. Under the conditions of a medium concentration of 15 g/L, an initial pH of 8.5, and a urea content of 4%, they obtained higher bacterial concentration and urease activity, and reduced the culture cost by 99.80%. In addition, urease-type MICP produces NH_4^+ by-product during urea hydrolysis. Relevant meter-scale biosolidification sand soil experiments have shown that NH_4^+ may remain in the pore fluid and particle surface [128]. Large-scale application requires supporting flushing and waste liquid treatment measures, thereby increasing water consumption and post-processing costs.

MICP still faces strong process sensitivity when used in road SSA. The high alkaline environment of SSA may inhibit microbial metabolism and urease activity, making the mineralization effect affected by strain type, temperature, pH and reactant concentration [129]. Relevant microscale studies have shown that low temperatures suppress bacterial growth and attachment and reduce the rate of CaCO_3 precipitation. In contrast, exposure to 50 °C markedly decreases urease activity, suggesting that temperature fluctuations may compromise both mineralization efficiency and deposition uniformity [130]. At the same time, carbonate may preferentially precipitate on particle surfaces or at pore openings, thereby restricting the further transport of bacterial suspensions and reactants into the particle interior [131,132]. This can produce a non-uniform modification pattern, characterized by a dense outer layer and insufficient internal treatment, particularly in coarse-grained SSA.

The long-term stability of mineralized products also lacks sufficient verification. Related research on MICP cured materials shows that acidic environments will aggravate CaCO_3 corrosion and material strength loss [133]. Although increasing the degree of carbonate cementation can delay deterioration, it is difficult to completely avoid acidic erosion. Wet-dry cycles, freeze–thaw effects and traffic loads may also cause cracking, detachment

or local failure of the mineralized layer [134]. For asphalt mixtures, it is also necessary to evaluate the integrity of the mineralized layer during high-temperature mixing, transportation and compaction, as well as its impact on the asphalt-aggregate interface bonding and long-term water stability [135]. At present, the application of MICP in SSA modification is still mainly based on laboratory research and small-scale verification. Mineralization uniformity, by-product management, treatment cost and long-term durability still need to be addressed during the engineering scale-up process.

4.5. Combined Treatment

In order to further improve the performance of SSA, researchers combined multiple methods to process SSA and achieved significant results. For coarse-grained SSA used in asphalt pavements, direct carbonation and silane coupling can play a role in internal stabilization and surface interface improvement respectively. Wang et al. [136] first consumed active Ca and Mg species and reduced the risk of swelling through carbonation, and then used silane to form a hydrophobic bridging layer on the surface of the carbonated product. After the combined treatment, the water absorption of SSA decreased from 1.85% to 1.61%, while the pull-out failure mode shifted from interfacial adhesion failure to cohesive failure. This change indicates that silane treatment can mitigate the adverse effect of the hydrophilic carbonated surface on asphalt–aggregate bonding. Other combined treatment strategies have also been investigated, with promising improvements reported. Wang et al. [18] first performed 100 h of boiling water pretreatment, and then implemented 12 h of microbial mineralization. Single boiling water pretreatment reduced the contents of f-CaO and f-MgO by 54.73% and 39.83% respectively; after subsequent MICP treatment, the two contents were further reduced to 0.16% and 0.12%, and the corresponding conversion rates reached 91.82% and 87.43%. The synergistic effect is that boiling water pretreatment promotes the hydration of f-CaO and f-MgO and releases Ca^{2+} and Mg^{2+} , providing reactants for subsequent microbial mineralization. The researchers further studied the combined treatment of SSA by MICP and wet carbonation. Studies have shown that carbonic anhydrase produced by *Bacillus alkalophilus* promotes CO_2 dissolution and carbonate nucleation. Compared with conventional wet carbonation, this process increased the carbonation weight gain by 57%–236% and limited the 10-day water-immersion expansion of SSA to 1.74% [137].

Figure 8 is a comparison of scanning electron microscopy (SEM) results on the surface of SSA, which further reveals the improvement mechanism of microbial synergistic carbonation on the microstructure of SSA. As shown in Figure 8a, the surface of untreated SSA is relatively loose and has many open pores. After microbial collaborative carbonation treatment, obvious mineralized sediments are formed on the surface of SSA and around the pores in Figure 8b. Some pores are filled or covered, bridges appear between local particles, and the overall structure tends to be dense. These microstructural changes indicate that microbial activity promotes carbonate nucleation and deposition while restricting water migration through pore filling and surface coverage. They also provide microstructural evidence for the increased carbonation weight gain and reduced water-immersion expansion. In summary, combined treatments can broaden defect coverage through the complementary functions of different technologies, particularly when multiple defects coexist. However, they do not necessarily outperform single treatments because additional processing steps may increase resource inputs, process interactions, and quality-control requirements.

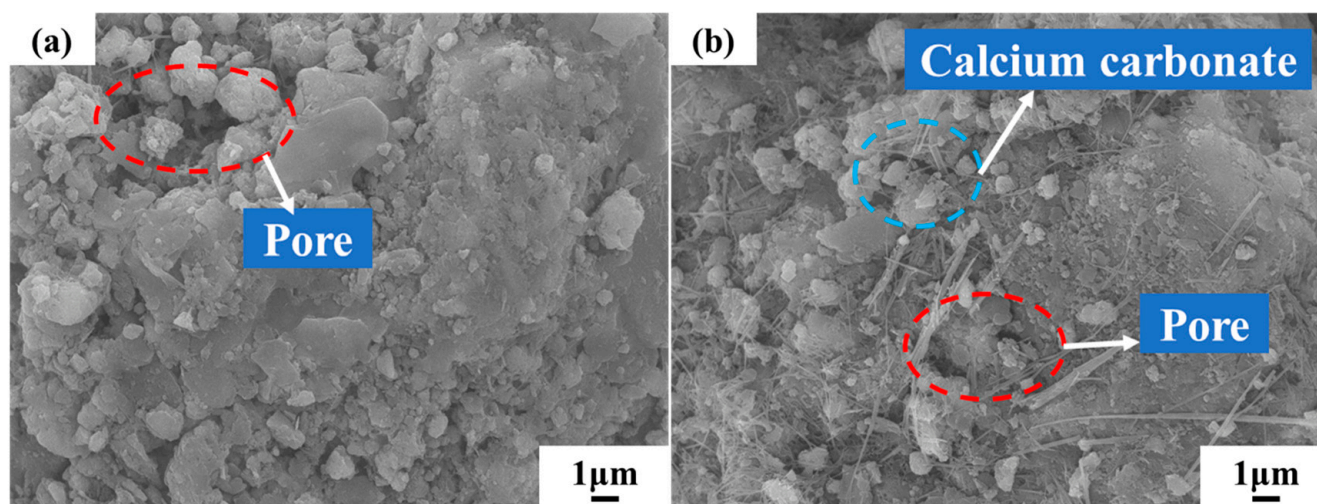


Figure 8. SEM images of microbial-assisted carbonated SSA. (a) Untreated; (b) treated.

5. Discussion

5.1. Multidimensional Comparison of Steel Slag Aggregates Modification Technologies

Section 4 summarizes the mechanisms, modification effects, and application limitations of aging treatment, surface modification, direct carbonation, MICP, and combined treatments. To provide a multidimensional comparison of these technologies, this section considers two aspects: representative quantitative evidence and key technical characteristics. Table 7 summarizes representative indicators and reported performance changes from individual studies, whereas Table 8 compares the technologies in terms of dominant defects, treatment duration, key characteristics, major limitations, and level of evidence.

Table 7. Representative quantitative evidence for different SSA modification technologies.

Modification Technology	Representative Evaluation Indicators	Representative Quantitative Evidence
Aging treatment [64,65]	1. f-CaO/f-MgO content 2. Crushing value 3. Abrasion value 4. Water absorption	1. After 12 months of natural aging, the f-CaO and f-MgO contents decreased by 57.89% and 24.32%, respectively; 2. After hydrothermal aging at 90 °C for 2 d, the crushing value, abrasion value, and water absorption decreased by 13.85%, 15.89%, and 3.83%, respectively.
Surface modification [79,86]	1. Contact angle 2. Asphalt stripping ratio 3. Expansion rate 4. TSR	1. Silicone resin treatment increased the contact angle by 45.90° and reduced the asphalt stripping ratio by 83.9%; 2. NOCM reduced the 7 d expansion rate by 50.85% and increased TSR by 6.69%.
Direct carbonation [70,107]	1. f-CaO content 2. Expansion rate 3. Residual stability 4. TSR	1. The f-CaO content could be reduced from 3.17% to 0.93%; 2. Carbonation treatment reduced the 10 d immersion expansion rate to 0.76%, while the residual stability and TSR reached 92.07% and 88.67%, respectively.

Table 7. Cont.

Modification Technology	Representative Evaluation Indicators	Representative Quantitative Evidence
MICP modification [120,123]	1. f-CaO content 2. Water absorption 3. Crushing value	1. After modification with <i>Sporosarcina pasteurii</i>, the f-CaO content decreased to 2.98%; 2. Vacuum impregnation reduced the water absorption of fine aggregates by 62.7% and the crushing value of coarse aggregates by up to 75.5%.
Combined treatment [18,137]	1. f-CaO/f-MgO content 2. Carbonation weight gain	1. Boiling-water pretreatment combined with MICP reduced the f-CaO and f-MgO contents to 0.16% and 0.12%, respectively; 2. Microbial-assisted carbonation increased the carbonation weight gain by 57%–236%.

(Note: The data in this table were extracted from different studies with variations in steel slag source, particle size, initial composition, treatment conditions, and evaluation methods. They are intended to indicate representative improvement ranges rather than provide a direct ranking of different technologies.).

Table 8. Comprehensive comparison of different SSA modification technologies.

Modification Technology	Targeted Deficiency	Treatment Duration	Key Advantage	Key Limitation	Level of Evidence
Aging treatment [69]	Control of volume expansion	Hours to months	Mature process	Limited reaction depth and uniformity	Relatively extensive engineering evidence
Surface modification [14]	Improvement of pore structure and interfacial performance	Hours to days	Flexible processing	Limited treatment depth	Substantial experimental evidence
Direct carbonation [70]	Stabilization of reactive phases and pore filling	Hours to days	Stabilization, pore filling, and CO ₂ sequestration	Mass-transfer and equipment constraints	Experimental and pilot-scale evidence
MICP modification [138,139]	Mineralization and pore repair	Typically 48–72 h	Mild treatment conditions	Non-uniform mineralization and by-product generation	Mainly laboratory evidence
Combined treatment [136]	Integrated improvement of multiple defects	Depends on the combination	Complementary functions	Complex process control	Preliminary validation

(Note: MICP treatment time usually refers to the mineralization reaction stage, and does not necessarily include bacterial culture, repeated liquid supply and post-processing time; the level of evidence is mainly based on engineering applications, pilot scale and the completeness of long-term service data for qualitative judgment).

Comprehensive analysis shows that there are obvious differences among various technologies in terms of defect coverage, uniformity of effect and engineering investment. Aging treatment based on the digestion of active components is more conducive to volume stability control. Previous studies have provided more evidence on the reduction and expansion inhibition of f-CaO/f-MgO, but the internal reaction of coarse-grained SSA may be insufficient; surface modification based on surface sealing and interface regulation is more conducive to reducing water absorption, improving hydrophobicity and enhancing interfacial adhesion. However, it is difficult to eliminate the internal expansion source, and excessive coating may also weaken the surface texture and mechanical interlocking; direct carbonation and MICP modification are centered on carbonate formation or mineralization deposition. These processes can regulate reactive phases, pore structure, and the migration

of some elements to a certain extent, thereby showing multi-target improvement potential in volume stability, pore repair, and environmental risk control. However, both are limited by internal mass transfer and reaction uniformity. The former also involves equipment, energy consumption, and water consumption, while the latter faces problems with microbial activity, by-product management, and long-term stability. Combined treatment can improve multiple types of defects through complementary functions, but it will also increase process complexity, resource investment and quality control difficulty [140,141].

The quantitative results in Table 7 should be interpreted as representative evidence of the types and magnitudes of performance changes reported under specific experimental conditions, rather than as directly comparable measures of technological superiority. The reported improvements vary with steel slag type, particle size, initial reactive-phase content, treatment conditions, mixture composition, and evaluation method. Accordingly, Table 8 complements the quantitative evidence by summarizing the principal treatment targets, process characteristics, limitations, and level of evidence of each technology. The results of Tables 7 and 8 therefore provide a basis for subsequent defect diagnosis and technology matching rather than a fixed ranking of modification methods.

5.2. Targeted Modification and Engineering Applicability Based on Raw Material Heterogeneity

Based on the aforementioned comparison, the choice of SSA modification technology should be determined by both raw material characteristics and dominant defects. The type of steel slag generally reflects its smelting source and typical chemical composition. However, even similar SSA may differ substantially in reactive calcium and magnesium components, pore structure, interfacial characteristics, and the occurrence state of risk elements because of variations in raw material composition, cooling regime, and aging degree [4,23]. Therefore, technology selection should not only be based on steel slag type or single performance index, but should be comprehensively judged based on material defect diagnosis results, road material system, processing scale and equipment conditions.

When insufficient volume stability is identified as the dominant defect, the f-CaO and f-MgO contents, expansion rate, and particle integrity should be jointly considered when selecting among aging treatment, direct carbonation, and MICP. Aging treatment has a good basis for batch processing and is suitable for SSA with sufficient treatment cycles; direct carbonation can take into account both the stabilization of active components and pore control, but is limited by CO₂ sources, mass transfer conditions and equipment investment; MICP reaction conditions are mild, but it is currently more suitable for small-scale scenarios that can control reaction liquid transportation, mineralization uniformity and by-product disposal. When high water absorption, excessive adsorption of binders or insufficient interfacial water stability dominate, inorganic filling, resin coating or coupling agent treatment can be used. If there is still a significant risk of swelling inside the particles, priority should be given to stabilizing the internal active components before surface control is implemented. For SSA with a high risk of potential element leaching, direct carbonation, MICP or surface coating can be selected based on the occurrence state of the target element and environmental response. These technologies can reduce the mobility of some elements through precipitation, adsorption, co-precipitation or physical blocking, but the responses of different elements are not consistent. For example, carbonation may reduce the mobility of Ni and Pb, but increase the risk of V release. Therefore, environmental safety still needs to be evaluated over the long term in combination with service conditions and dynamic leaching behavior. When volume expansion, high water absorption, and interface defects coexist, combined treatment can be used to bring into play the complementary functions of different technologies, but the processing sequence, process compatibility, reaction uniformity, resource investment, and new costs need to be evaluated simultaneously. Based

on the above analysis, the priority modification paths corresponding to different material characteristics and their engineering boundaries are shown in Table 9.

Table 9. Prioritized modification paths and engineering boundaries based on SSA material characteristics.

Material Characteristics	Targeted Deficiency	Preferred Modification Routes	Applicable Conditions	Key Limitations
High levels of reactive Ca/Mg phases	Volume instability	Aging/direct carbonation/MICP	Selected according to treatment scale and equipment availability	Variable treatment depth and technological maturity
Porous and rough surface	High water absorption and interfacial instability	Surface modification	Surface-dominated defects	Internal expansion must be controlled first
High elemental mobility	Potential leaching risk	Carbonation/MICP/surface coating	Environmentally sensitive applications	Element-specific evaluation is required
Coexisting multiple defects	Constrained overall performance	Combined treatment	High-performance material systems	Process compatibility and additional costs

(Note: The technologies in the table are priority choices, and the specific solutions still need to be determined based on actual material measurement results and engineering conditions).

5.3. Environmental Sustainability and Trade-Offs from a Life Cycle Perspective

SSA road utilization can reduce natural aggregate mining and steel slag stockpiling, but material substitution does not necessarily produce significant life cycle environmental benefits. Its environmental performance is affected by factors such as transportation distance, modifier input, energy and water consumption, pollution control, and service life [142,143]. Therefore, SSA modification technology should not be evaluated solely based on the carbon emissions or carbon sequestration per unit mass of materials, but should be comprehensively judged in combination with equivalent road performance and design service life.

There are significant differences in economic performance among different treatment methods. Natural aging usually does not need additional modifiers and special reaction equipment, so the cost of direct treatment is low, while surface modification increases the input of modified materials, coating and curing. The related evaluation shows that when natural aging SSA is used in AC-10C and AC-16C mixture, the construction cost is 14.6% and 12.7% lower than that of the basalt scheme, while the surface modified SSA scheme increases 1.71% and 1.67% respectively [61]. This shows that the treatment process and material input are the key factors affecting the initial economy. From the perspective of environmental impact, surface modification can produce potential environmental benefits by reducing water absorption and binder requirements, but additional processes such as modifier production, coating, and curing will also increase energy consumption and emissions. Taking 1000 m³ AC-13 mixture as the functional unit, the silicone-modified acrylic acid treatment SSA scheme reduces energy consumption by approximately 2.92×10^4 MJ and 2.4×10^3 kg CO₂-eq compared with the diabase scheme [144]. This result indicates that under the setting of this study, the benefits brought by natural aggregate substitution and binder saving can offset the new load of the modification process. Although a certain amount of CO₂ can be fixed in the direct carbonation process, emissions from heating, pressurization and gas supply may offset part of the carbon sequestration benefits. Taking 1 km of road surface as the functional unit, the carbon emissions of the carbonated SSA scheme during the raw material acquisition and construction phases are 34.38 t CO₂-eq/km, which is higher than the 29.97 t CO₂-eq/km of the basalt scheme. After considering avoiding steel slag landfills, its carbon emissions are still 10% higher [136]. Compared with direct carbonation and other treatment methods that require heating or pressure, MICP temperature and pressure conditions are relatively mild, but bacterial culture, urea,

flush water and NH_4^+ treatment will also cause new loads. In addition, the increased process and material inputs of combined treatment may also partially offset its performance improvement benefits.

Generally speaking, existing assessments mainly focus on raw material acquisition, modification processes, and construction. Maintenance and repair, degradation of modification effectiveness, long-term heavy-metal migration, and end-of-life stages remain insufficiently considered. There is also a lack of consistency in functional units, transportation distances and energy structures of different studies. Therefore, it is not yet possible to absolutely rank the life cycle environmental benefits of various SSA modification technologies at this stage. Only when the comprehensive benefits of resource substitution, landfill avoidance, binder saving, CO_2 fixation, and life extension can offset the new load in the modification process can SSA modification be substantially sustainable.

5.4. Research Deficiencies and Future Research Directions

Existing research has made progress in controlling the volume expansion of SSA, improving pore and interface properties, and reducing the mobility of some elements. However, most results still rely on single source materials, short-term performance evaluation and laboratory-scale processing, and have not yet formed a complete evidence chain from material identification, mechanism elucidation to long-term verification and engineering applications. Future research should focus on the following aspects.

- (1) Raw material heterogeneity, defect diagnosis and targeted design. A multi-source SSA database should be established to systematically record key physicochemical characteristics, pore and interfacial parameters, and environmental risk indicators. This database should be supported by composition analysis, phase identification, pore characterization, interfacial testing, and dynamic leaching tests. On this basis, defect diagnosis methods should be developed for volume instability, high water absorption, interfacial water damage, and element leaching. A targeted design framework linking “raw material characteristics–dominant defects–modification mechanisms–process parameters–target performance” should then be constructed to guide technology selection and parameter optimization.
- (2) Multi-scale modification mechanism and process control. Multi-scale characterization techniques, such as X-ray CT, AFM, TEM, and in situ characterization, should be used to reveal reaction front advancement, product layer formation, pore connectivity evolution, and interfacial chemical interactions. For aging, carbonation, surface modification, and MICP, particular attention should be paid to the spatial distribution of reaction products on particle surfaces, within pores, and around internal defects. Furthermore, a “reaction–mass transfer–damage” model should be developed to quantitatively describe the relationships among moisture, CO_2 or reaction-fluid migration, reactive phase consumption, product deposition and pore blocking, and performance degradation. Such a model would provide a theoretical basis for process control in SSA modification.
- (3) Green low-cost composite modification and process synergy. Efficient and low-cost composite modification systems should be further developed to address multiple coupled defects. Representative strategies include aging treatment combined with MICP, accelerated carbonation combined with surface modification, and inorganic filling combined with organic coating. These approaches are expected to promote synergistic improvements in reactive phase stabilization, pore regulation, interfacial enhancement, and element immobilization. Meanwhile, bio-based modifiers and industrial solid-waste-derived modifiers deserve further exploration to reduce treatment costs and additional environmental burdens. More attention should also be given to the

- synergistic and antagonistic effects among different treatment processes, as well as the optimization of treatment sequence, reaction conditions, and process compatibility.
- (4) Long-term service performance, environmental safety and life prediction. Long-term performance evaluation should move beyond short-term expansion, water absorption, water stability, and freeze–thaw indicators. Multi-factor coupling tests, accelerated aging tests, and long-term field exposure tests are needed to evaluate the damage evolution of SSA particles, modified layers, and interfacial zones under high-temperature mixing, traffic abrasion, freeze–thaw cycles, wet–dry cycles, and corrosive media. Prediction methods for modification-effect attenuation, failure thresholds, and service life should also be established. In addition, environmental safety assessment should be extended from short-term batch leaching to dynamic leaching and element migration under material damage and long-term service conditions.
 - (5) Low carbon engineering applications, quality control and standardization. For engineering application, continuous treatment systems should be developed in coordination with steel slag crushing, screening, storage, mixing, and construction processes. Raw material testing, process monitoring, product acceptance, and quality traceability should also be incorporated into the production chain. Life cycle assessment and life cycle cost analysis are necessary to quantify carbon emissions, energy consumption, long-term leaching risks, and the benefits associated with service-life extension. In terms of standardization, unified performance and environmental safety evaluation methods should be established for different particle size ranges and road material systems. Relevant indicators should also be incorporated into road material specifications, construction guidelines, and engineering acceptance systems.

Overall, the core value of SSA modification research should not be limited to the improvement of individual performance indicators. Greater emphasis should be placed on the systematic integration of material defect diagnosis, modification route selection, long-term service assurance, and engineering standardization. By establishing a complete technical chain from raw material identification to process control, performance evaluation, and standardized application, modified SSA can be further transformed into a stable, low-impact, and scalable road material. This would support both bulk solid-waste utilization and the low-carbon transition of road engineering.

6. Conclusions

The comprehensive analysis shows that the engineering applicability of SSA in road construction is jointly governed by its internal reactive phases, pore structure, interfacial characteristics, and the occurrence forms of potentially hazardous elements. These properties vary significantly with the steel slag source, steelmaking and cooling processes, and initial aging condition. Therefore, there is no universally applicable optimal modification technology. Raw-material characterization and dominant-defect identification should precede treatment design and guide the selection of treatment targets, treatment depth, and performance objectives.

The improvement effects of different modification technologies have obvious condition dependence. Aging treatment and surface modification respectively focus on the digestion of active components and the control of surface pores and interfaces; direct carbonation and MICP have multi-target improvement potential, but are limited by mass transfer and reaction uniformity. Combined treatments can broaden defect coverage but increase process-integration complexity, resource inputs, and quality-control requirements. Due to the large differences in material conditions and evaluation methods among existing studies, representative performance increases are not suitable for direct use in technology ranking. Based on this, this article summarizes the matching idea of “raw material characteristics–

dominant defects–priority technology–engineering boundaries” to provide a structured basis for the comparison and selection of modification schemes.

The sustainability of SSA modification depends on the net balance between resource and environmental benefits and the new load of the modification process. The life cycle assessment should be based on equivalent road performance and design service life, and cannot be judged solely on the solid waste replacement rate or carbon sequestration amount. In the near future, industrial applications should focus on solving problems such as raw material fluctuations, batch processing uniformity, insufficient evidence of long-term durability and dynamic leaching, and lack of standards. Raw-material classification, process monitoring, quality traceability, and demonstration validation systems should also be established, while key performance and environmental indicators should be progressively incorporated into road-material specifications and engineering acceptance criteria. Cooperating with green procurement, solid waste resource identification and carbon emission reduction accounting, we can further promote the connection between SSA modification technology and carbon neutrality and solid waste management goals.

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