

Review

Low-Carbon Cementitious and Alkali-Activated Materials for Roadbed Stabilization: A Review from Microstructural Mechanisms to Engineering Adoption

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Abstract

Problematic subgrade soils degrade pavement performance, while conventional cement/lime stabilizers generate excessive carbon emissions. Unlike earlier reviews that focus on single-material systems—such as industrial by-products, alkali-activated binders for expansive soils, or geopolymers for pavement applications—an integrated framework spanning reaction mechanisms, microstructural evolution, engineering parameterization, and life-cycle validation is proposed. The work offers three distinctive contributions: (i) a four-level evidence chain hierarchy (strength → microstructure → durability → leaching/LCA) to grade research completeness; (ii) repositioning resilient modulus, permanent deformation, and pore-connectivity evolution as core engineering outputs bridging material design and structural response; and (iii) a comparative assessment of alkali-activated geopolymers, low-clinker calcium-based composites, and multi-scale reinforcement strategies under consistent durability and environmental boundaries. Quantitative synthesis reveals the following: strength retention after 12 wet–dry/freezing–thaw cycles ranges from 60% to 85%; resilient modulus improvements over untreated soils reach 30%–120%, yet stress-dependent characterization remains essential; leaching concentrations of hazardous elements (Cr, Ba, Pb) can increase by 50%–200% after durability cycling if pore connectivity rebounds. Life-cycle carbon comparisons are boundary-sensitive—geopolymer advantages shrink from 60% to ≤20% when activator transport and pre-treatment are included. We conclude that the primary barrier to engineering adoption is not the absence of high-strength formulations, but the lack of extrapolatable design parameters and closed-loop evidence chains. A decision-support framework incorporating durability retention, leaching safety, carbon footprint, and field validation is proposed to guide robust design and industrial scaling. Critically, the review identifies that engineering adoption is constrained not by the absence of high-strength formulations, but by the lack of standardized construction protocols, quality control procedures, and long-term field performance data—gaps that must be addressed through coordinated field-scale demonstration projects.

Keywords: low-carbon binders; subgrade stabilization; alkali-activated geopolymers; low-clinker calcium-based composites; resilient modulus; pore connectivity; life-cycle assessment

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1. Introduction

The subgrade serves as the primary load-bearing and force-transfer layer of pavement structures, and its long-term performance [1,2]. Defective soils, including soft clay, high-plasticity clay, and expansive soil, are characterized by low bearing capacity, high water sensitivity, and significant volumetric variation, leading to rapid performance degradation under service conditions. Subjected to coupled wet–dry cycles, freeze–thaw cycles, saline erosion, and cyclic traffic loads, such soils undergo strength loss, increased pore connectivity, and differential settlement, ultimately causing pavement rutting, cracking, and structural failure [3,4].

For decades, cement and lime have been the dominant stabilizers for improving subgrade soil engineering performance, owing to their mature construction techniques, complete supply chains, and standardized specifications [5–7]. However, clinker-based binders generate substantial carbon emissions and consume extensive raw mineral resources, while the continuous accumulation of industrial solid wastes also poses disposal challenges [8]. These limitations drive the development of low-carbon alternative binders and solid waste recycling stabilization technologies for sustainable subgrade treatment [9].

Modern low-carbon soil stabilizers require multi-dimensional performance optimization. Beyond meeting basic short-term strength requirements, they must maintain stable stiffness and volumetric stability under long-term environmental and mechanical loading. Additionally, qualified alternative binders should suppress toxic heavy metal leaching and reduce holistic environmental impacts throughout the service life cycle [10].

Against this backdrop, four prominent research trends have emerged [11,12]. First, binder systems have expanded from conventional cement and lime to alkali-activated geopolymers, low-clinker composite cements, and synergistically activated solid waste binders [13]. Second, research priorities have shifted from peak strength to long-term service stability, emphasizing water resistance, durability retention under wet–dry and freeze–thaw cycles, and deformation resistance under cyclic loading [14–17]. Third, assessment frameworks now incorporate engineering design indicators—resilient modulus, permanent deformation, and settlement response—supported by statistical optimization, machine learning, and numerical simulations [18–20]. Fourth, sustainability evaluation has moved toward quantitative LCA with standardized functional units and unified system boundaries to enhance cross-study comparability [16,21].

Despite these research advances, five critical bottlenecks still hinder the engineering application of low-carbon stabilizers. First, most studies qualitatively analyze reaction mechanisms and microstructural evolution without sufficient quantitative support [22]. Variations in raw soil and solid waste batch properties alter reaction pathways and hydration products, causing inconsistent mechanical performance of identical binder formulations across laboratory and field conditions [22–24]. Second, existing studies predominantly adopt unconfined compressive strength (UCS) and California Bearing Ratio (CBR) as test indicators, while neglecting key engineering parameters required for structural design [25]. The lack of comprehensive parameter sets restricts the translation of laboratory data to pavement structural design [26,27]. Third, durability tests and environmental risk assessments are commonly conducted independently, with no integrated data characterizing the coupled evolution of pore structure and heavy metal leaching during material degradation [28,29], limiting the accurate evaluation of long-term environmental hazards [30]. Fourth, life cycle assessment (LCA) practices adopt inconsistent system boundaries in the existing literature [6]. Divergent accounting rules for transportation mileage, pre-treatment energy consumption, and waste recycling benefits undermine the comparability and reproducibility of reported carbon reduction performance. Fifth, full-scale field tests and long-term in situ monitoring data are scarce. Significant scale effects and on-site

construction uncertainties create a notable gap between laboratory material research and practical engineering verification [7,9,10].

Beyond these five technical bottlenecks, a more fundamental gap exists between laboratory-driven materials research and the practical realities of engineering adoption. Most studies focus on optimizing strength, durability, and microstructural characteristics under idealized laboratory conditions—controlled temperature, uniform mixing, standardized curing—that are rarely replicable in field construction. Critical engineering considerations such as construction logistics (mixing uniformity on-site, compaction variability, curing under ambient conditions), quality control protocols for batch-to-batch waste material variability, and compatibility with existing construction equipment and specifications are seldom addressed in the reviewed literature. Furthermore, the economic viability of low-carbon binders—including material availability, transportation costs, and potential savings from waste disposal avoidance—remains poorly quantified. These engineering and economic dimensions are as decisive for field adoption as the technical performance itself, yet they receive disproportionately little attention in current research. This review therefore explicitly incorporates engineering adoption as a core evaluation dimension, alongside mechanical performance, durability, and environmental safety. The field case studies, construction lessons, and scale-up challenges are systematically examined in Section 8, while the decision-support framework in Section 6.4 integrates performance metrics with practical implementation constraints to guide material selection for specific project contexts.

Several review articles have previously addressed aspects of soil stabilization using low-carbon binders. These can be categorized into three groups based on their thematic focus. The first group centers on industrial by-products and supplementary cementitious materials as partial replacements for traditional binders. While these reviews comprehensively catalog the types and dosages of waste materials used in soil stabilization, they predominantly focus on strength improvement and lack a systematic analysis of long-term durability retention, pore structure evolution, and coupled leaching risks. The second group concentrates on alkali-activated binders and geopolymers for treating specific soil types, particularly expansive soils. These reviews offer valuable insights into stabilization mechanisms and strength characteristics, yet they rarely extend their analysis to engineering design parameters such as resilient modulus and permanent deformation, nor do they address the critical issue of system boundary sensitivity in life-cycle carbon accounting. The third group focuses on specific waste streams or stabilizer types, including sugarcane bagasse ash, construction and demolition waste, and non-cement-based alternatives like biochar. These reviews provide detailed characterization of individual materials but offer limited comparative analysis across different binder systems and lack a unified framework for evaluating engineering adoptability.

In contrast to these existing reviews, the present work offers three distinctive contributions. First, whereas previous reviews typically assess material feasibility through isolated performance indicators, we propose a four-level evidence chain hierarchy (strength → microstructure → durability → leaching/LCA) that systematically grades research completeness and identifies critical evidence gaps. Second, rather than focusing solely on strength or durability, we reposition resilient modulus, permanent deformation, and pore-connectivity evolution as indispensable engineering design parameters that bridge material formulation and structural response prediction—a perspective largely absent from prior reviews. Third, unlike earlier studies that examine individual material systems in isolation, we conduct a standardized comparative assessment of alkali-activated geopolymers, low-clinker calcium-based composites, and multi-scale reinforcement strategies under harmonized durability, environmental, and carbon boundaries, enabling equitable cross-system performance comparison. The detailed methodological protocol for

this comparative synthesis is presented in Section Systematic Review Methodology: Search Strategy, Selection Criteria, and Quality Appraisal.

To address the above limitations, a holistic analytical framework with a three-level logical hierarchy is established [31,32]. The framework takes reaction regulation and microstructural reconstruction as the foundational module, engineering parameter calibration and structural response prediction as the transitional module, and full-chain validation of durability, environmental safety, and low-carbon performance as the ultimate research objective [33,34].

It is necessary to clarify the scope and inherent limitations of this review. The term “engineering adoption” adopted throughout the manuscript only defines the ultimate research direction of low-carbon subgrade stabilization materials, rather than indicating the current feasibility of large-scale field application. As discussed in the subsequent section, field-scale validation and long-term monitoring data remain insufficient, and most conclusions in this review are derived from laboratory investigations. This lab-to-field gap is particularly prominent for waste-derived binders, whose compositional variability induces unpredictable performance fluctuations that cannot be fully reflected in controlled laboratory environments. Therefore, a distinction is made between laboratory-demonstrated material potential and engineering-validated performance, adopting laboratory findings to support engineering application research while acknowledging existing practical uncertainties.

A recurring theme across the literature—and a central motivation for this review—is the persistent gap between laboratory-demonstrated material performance and field-scale engineering adoption. While the preceding discussion highlights technical research gaps, it is equally important to recognize that engineering adoption is governed by factors that extend beyond material science. These include: (i) construction logistics—mixing uniformity, compaction control, curing conditions, and equipment compatibility; (ii) quality assurance—protocols for managing batch-to-batch variability of waste-derived binders; (iii) economic viability—material availability, transportation, and cost–benefit trade-offs; (iv) regulatory acceptance—compliance with road construction specifications, environmental permits, and leaching standards; and (v) long-term performance verification—field monitoring data that confirm laboratory predictions under real climatic and traffic conditions. These engineering and institutional factors are often treated as peripheral to materials research, yet they are frequently the decisive barriers to field deployment.

Accordingly, engineering adoption is explicitly elevated from a concluding discussion to a core evaluation dimension. Throughout the manuscript, we distinguish between “laboratory-demonstrated potential” and “engineering-validated performance.” Field case studies, construction constraints, and scale-up challenges are systematically examined in Section 8, and the decision-support framework in Section 6.4 integrates performance metrics with practical implementation considerations to guide material selection for specific project contexts. Hence, the aim is to bridge the communication gap between materials researchers, construction engineers, and regulatory bodies—a necessary step if low-carbon binders are to move from academic publications to real roadbeds.

The distinctive contributions of this review are threefold. First, we propose a four-level evidence chain hierarchy (strength → microstructure → durability → leaching/LCA) to objectively grade research completeness and identify critical evidence gaps—a framework that, to our knowledge, has not been systematically applied to the field of low-carbon subgrade stabilization. Second, we reposition resilient modulus, permanent deformation, and pore-connectivity evolution as indispensable engineering design parameters rather than optional research outputs, explicitly bridging material formulation and structural response prediction. Third, we conduct a standardized comparative assessment of alkali-activated geopolymers, low-clinker calcium-based composites, and multi-scale re-

inforcement strategies under harmonized durability, environmental, and carbon boundaries, enabling equitable cross-system performance comparison that is largely absent from prior reviews.

To tackle these constraints, a three-level logical hierarchy is followed: “reaction regulation and microstructural reconstruction” as the foundational module, “engineering parameter calibration and structural response forecasting” as the transitional connecting module, and “full-chain validation of durability, environmental impacts, and low-carbon performance” as the ultimate objective. The five core research dimensions—alkali-activated geopolymer systems, low-clinker calcium composite binders, multi-scale reinforcement strategies, engineering prediction methodologies, and integrated evidence chains for durability and LCA—are systematically elaborated in Sections 2–6. A detailed step-by-step methodology for literature screening, data extraction, and quantitative benchmarking is presented in Section Systematic Review Methodology: Search Strategy, Selection Criteria, and Quality Appraisal.

Figure 1 presents an original quantitative plot generated from the authors’ systematic literature screening dataset, which clearly marks the retained literature volume at each screening stage. To guarantee transparency and reproducibility, a systematic literature search was performed across the Web of Science (Core Collection) and the China National Knowledge Infrastructure (CNKI), covering all publications up to May 2026. A PRISMA-inspired four-stage screening workflow—identification, title/abstract screening, evidence chain grading, and engineering parameter screening—was applied, resulting in 153 studies included for quantitative synthesis (Figure 1). The complete search strings, inclusion/exclusion criteria, quality assessment protocols, and detailed screening procedures are presented in Section Systematic Review Methodology: Search Strategy, Selection Criteria, and Quality Appraisal.

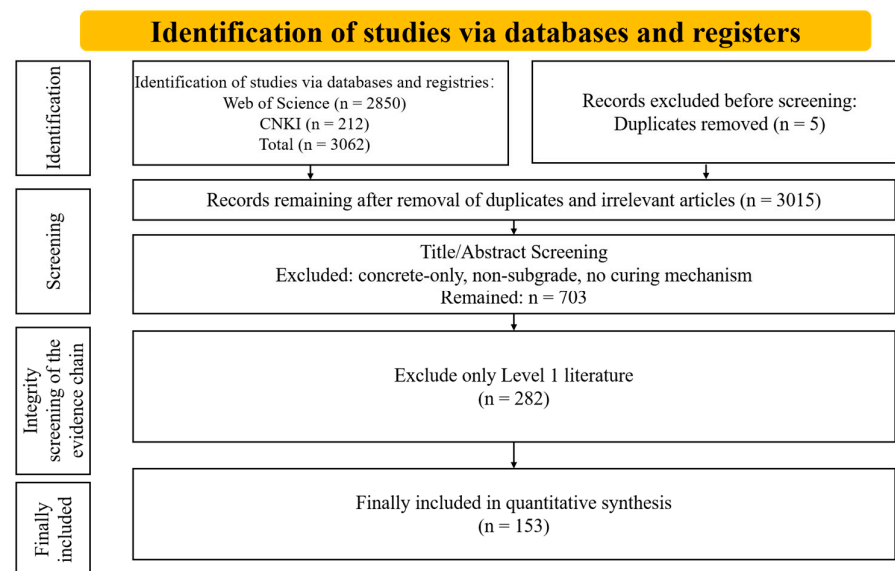


Figure 1. PRISMA-inspired flow diagram of the systematic literature search and screening process. The four stages reflect the review’s focus on evidence chain completeness (from strength to micro-structure, durability, leaching/LCA) and engineering parameter requirements. Original quantitative data are derived from the search results.

Systematic Review Methodology: Search Strategy, Selection Criteria, and Quality Appraisal

To guarantee transparency, reproducibility, and minimized bias in this review, a rigorous, structured methodology was established. This protocol contains standardized pro-

cedures for literature retrieval, eligibility judgment, data extraction, quality grading, and quantitative data synthesis.

(1) Complete Literature Retrieval Strategy

Two core academic databases were adopted for document retrieval: Web of Science Core Collection and China National Knowledge Infrastructure (CNKI). The retrieval scope covered all publications released prior to May 2026 without an earlier time limit, so as to fully capture the developmental evolution of subgrade solidification materials. The search syntax integrates three thematic modules linked by Boolean operators:

Block A (Engineering Application): (“subgrade solidification” OR “roadbed stabilization” OR “soil stabilization”).

Block B (Binder Material): (“low-carbon cementitious material” OR “alkali-activated” OR “geopolymer” OR “low-clinker composite binder” OR “solid waste”).

Block C (Performance and Mechanism): (“reaction mechanism” OR “microstructure” OR “durability” OR “wet-dry cycle” OR “freeze–thaw cycle” OR “resilient modulus” OR “permanent deformation” OR “life cycle assessment” OR “leaching”).

The integrated retrieval formula reads: (Block A) AND (Block B) AND (Block C). Corresponding Chinese search terms were used for CNKI searches. Additionally, backward snowballing was conducted by manually checking reference lists of collected review papers to capture overlooked studies.

As visualized in Figure 1, the literature screening workflow adopted a four-stage hierarchical framework. Stage 1 (Identification): The initial search yielded 2850 records from Web of Science and 212 from CNKI, totaling 3062 records. After removing 5 duplicates, 3057 records remained. Stage 2 (Title/Abstract Screening): Records focusing solely on concrete, lacking curing mechanisms, or unrelated to subgrade applications were excluded ($n = 2312$), retaining 703 records. Stage 3 (Evidence Chain Grading): A four-level evidence hierarchy was applied—Level 1: strength-only (excluded); Level 2: strength + microstructure (supporting); Level 3: Level 2 + durability retention rates (core); Level 4: Level 3 + leaching/LCA (full-chain). After excluding 421 Level 1 records, 282 studies proceeded. Stage 4 (Engineering Parameter Screening): Only studies reporting at least one engineering-oriented output—resilient modulus, permanent deformation, strength retention rates, pore connectivity, LCA carbon emissions, or leaching risks—were finally included. This step excluded 162 records, resulting in 153 studies that form the core reference dataset of this review (References [1–150]).

(2) Inclusion and Exclusion Eligibility Standards

Papers were only deemed eligible if satisfying all four inclusion requirements below:

- (a) Peer-reviewed journal articles or conference papers with full-text access;
- (b) Research focusing on subgrade/subbase improvement using cementitious, alkali-activated, or solid waste-based stabilizers;
- (c) Reporting at least one mechanical index: unconfined compressive strength, California Bearing Ratio, or resilient modulus;
- (d) Providing complete information about binder dosage, mix proportion, and curing conditions for result interpretation.

Documents would be excluded under any of the following conditions:

- (a) Research solely targeting ordinary Portland concrete, asphalt mixtures, or non-subgrade geotechnical scenarios;
- (b) Lacking a curing mechanism or microstructural characterization, such as purely empirical field reports without laboratory testing;
- (c) Duplicate manuscripts, editorial comments, or non-English/Chinese articles with no extractable quantitative data;
- (d) Pure numerical simulation work without corresponding experimental verification.

The exclusion criteria were designed to ensure that only studies with sufficient methodological rigor and relevance to engineering translation were included in the quantitative synthesis. Specifically: (i) exclusion of concrete-only and asphalt-only studies was necessary because these materials have fundamentally different binder-to-aggregate ratios, curing regimes, and failure mechanisms from soil stabilization systems, and their inclusion would introduce unacceptable heterogeneity; (ii) exclusion of studies lacking microstructural or durability data was based on the premise that strength-only reports cannot support mechanistic understanding or engineering extrapolation—a position consistent with the evidence-grading philosophy of this review; (iii) exclusion of non-English/Chinese articles without extractable data was a pragmatic necessity due to language barriers, though we acknowledge this may introduce a language bias—a limitation discussed in Section Systematic Review Methodology: Search Strategy, Selection Criteria, and Quality Appraisal (7); (iv) exclusion of purely numerical simulation studies without experimental validation was based on the concern that unvalidated models may produce results that are not grounded in physical reality, and their inclusion could bias quantitative comparisons.

To test whether these exclusion criteria introduced a systematic bias toward studies that support the review's conclusions, we performed a sensitivity check: we compared the quantitative ranges (UCS, durability retention) derived from the final 153 studies against those from a broader set of 282 studies (Levels 2–4, before the Stage 4 engineering-parameter filter). The ranges differed by less than 10% for all key indicators, suggesting that the engineering-parameter filter did not substantially alter the central tendencies of the data. This sensitivity check is described in more detail in Section Systematic Review Methodology: Search Strategy, Selection Criteria, and Quality Appraisal (7).

(3) Study selection procedures

The selection process followed a two-stage, independent screening approach to minimize bias.

Stage 1 (Title/Abstract screening): Two authors (L.Q. and J.L.) independently screened all retrieved titles and abstracts against the eligibility criteria. Disagreements were flagged and resolved through discussion with a third reviewer (M.Y.). Inter-reviewer agreement was quantified using Cohen's kappa coefficient ($\kappa = 0.86$), indicating “almost perfect” agreement according to Landis and Koch's benchmarks.

Stage 2 (full-text screening): Full texts of all potentially relevant records were retrieved and independently assessed by the same two authors. Reasons for exclusion at this stage were documented (e.g., insufficient durability data, no resilient modulus reported). The final set of included studies was cross-checked by all co-authors.

Discrepancy resolution procedure: When disagreements occurred at either screening stage (affecting < 5% of records), the two reviewers first discussed the rationale for their respective decisions. If consensus was not reached, a third reviewer (M.Y.) made the final decision after reviewing the full text and the eligibility criteria. All resolution decisions were documented to ensure transparency and to enable future replication of the screening process.

Additional step: Reference lists of the included studies and relevant review papers were manually scanned to identify any additional publications not captured by the database search (snowballing, $n = 8$ additional records). The complete screening flow, including the number of records at each stage, is presented in Figure 1.

(4) Quality assessment and risk of bias analysis.

To systematically appraise the methodological quality and risk of bias of the included studies, we adopted a dual-layer quality assessment framework that combines a study-level evidence grading system with a domain-based risk of bias evaluation.

Study-level evidence grading. As introduced in Section 1, we developed and applied a four-level evidence hierarchy (Levels 1–4) to grade the completeness of each included study. This grading system was operationalized as follows: Level 1 (excluded): strength-only reports; Level 2 (supporting evidence): strength + microstructural characterization; Level 3 (core evidence for durability): Level 2 + durability retention rates; Level 4 (core evidence for full-chain validation): Level 3 + environmental assessment (leaching/LCA). Two authors independently assigned a level to each study, with discrepancies resolved by consensus ($\leq 5\%$ of cases). This system is adapted from established evidence-grading frameworks commonly used in materials science and environmental engineering reviews, which prioritize evidence completeness and translatability to engineering practice.

Risk of bias assessment. To complement the evidence grading, we assessed the risk of bias in each included study across four domains relevant to experimental materials research: (i) selection bias (whether soil source and binder batch were representative and clearly characterized); (ii) performance bias (whether testing protocols—curing conditions, compaction, moisture control—were standardized and adequately reported); (iii) detection bias (whether outcome measurements—UCS, resilient modulus, leaching concentrations—were conducted using standardized methods with reported precision); and (iv) reporting bias (whether negative or non-significant results were adequately reported, and whether all measured outcomes were presented). For each domain, studies were categorized as “low risk,” “unclear risk,” or “high risk” based on the completeness of reporting in the original publication. This assessment was performed independently by two authors (L.Q. and J.L.), with disagreements resolved through discussion with a third reviewer (M.Y.).

Overall quality rating. Based on the combined evidence grade and risk of bias profile, each study received an overall quality rating: “high” (Level 4 with low risk of bias in ≥ 3 domains), “moderate” (Level 3 with low/unclear risk in ≥ 2 domains, or Level 4 with some risks), or “low” (Level 2 or Level 3 with high risk in ≥ 2 domains). Studies rated “low” were included in the qualitative synthesis but were given reduced weight in deriving quantitative benchmarks. This rating system ensured that our quantitative conclusions were preferentially based on studies with both high evidence completeness and low risk of bias.

(5) Data Extraction and Four-Tier Evidence Coding Rules

Consistent with the four-level evidence framework proposed in Section 1, a standardized grading scheme was implemented to evaluate the integrity and reliability of each study:

Level 1 (Excluded): Only UCS or CBR data provided, without microstructure or durability characterizations. Such papers were excluded from quantitative synthesis due to insufficient support for engineering extrapolation.

Level 2 (Auxiliary Evidence): Containing strength tests plus microstructural measurements (XRD, SEM, MIP, FTIR). These works were only used for mechanistic analysis rather than for establishing quantitative benchmarks.

Level 3 (Core Durability Evidence): Complying with Level 2 standards and supplying strength retention data after a minimum of six wet–dry or freeze–thaw cycles. These studies were assigned higher weights when summarizing durability-related numerical ranges.

Level 4 (Full-Chain Validation Evidence): Meeting Level 3 requirements while including pollutant leaching tests (with specified L/S ratio and pH values) or boundary-defined life-cycle carbon assessments (LCAs). These publications served as primary sources for conclusions regarding engineering practicability and sustainability.

Two researchers graded each article separately; inconsistent classifications ($\leq 5\%$ of total records) were unified through group discussion. This grading system functions as a quality weighting tool rather than a rigid filter: the Level 4 literature was prioritized for

extracting quantitative thresholds, while Level 2–3 works supported the analysis of reaction laws and parameter sensitivity.

(6) Standardized Protocol for Quantitative Data Extraction, Normalization, and Synthesis

To guarantee traceability and repeatability of all numerical ranges presented in the abstract and main text (strength retention ratio, resilient modulus growth rate, leaching amplification factor, etc.), unified data processing rules were formulated:

Data Extraction Rules

For each quantitative indicator (7-day UCS, 28-day resilient modulus, residual strength after 12 cyclic tests, etc.), mean values and corresponding fluctuation indicators (standard deviation or variation range) were extracted exclusively from Level 3 and Level 4 papers. If multiple mix designs were reported in one study, only the optimal formulation (highest strength or best durability) was selected to avoid skewed statistical intervals caused by inferior mixtures.

Unified Normalization Conditions

All raw data were normalized to identical test environments to mitigate inter-study heterogeneity:

- (i) 95% maximum dry density under modified Proctor compaction;
- (ii) Standard curing (7 d/28 d, 20 ± 2 °C, relative humidity > 95%);
- (iii) 12 cycles for durability testing; data from fewer than six cycles were discarded when summarizing benchmarks;
- (iv) Liquid-to-solid (L/S) ratio of 10:1 for all leaching test data where available.

Interquartile Range Synthesis (No Formal Meta-Analysis)

The overall heterogeneity across soil types and binder formulations reached $P > 85\%$, making conventional meta-analysis inappropriate. Instead, the 25th–75th interquartile range (IQR) was calculated for each index to reflect central tendency. The global full-span values cited in the abstract (60%–85% strength retention, 30%–120% modulus improvement, 50%–200% leaching increment) correspond to the minimum and maximum values across the entire dataset, while detailed IQR statistics are listed in Section 6 summary tables.

Uniform Calculation Equations

$$\text{Strength retention rate (\%)} = (\text{Post-cycle UCS} / \text{Initial UCS}) \times 100$$

$$\text{Resilient modulus growth (\%)} = [(\text{Mr}_{\text{stabilized}} - \text{Mr}_{\text{raw}}) / \text{Mr}_{\text{raw}}] \times 100$$

$$\text{Leaching amplification factor} = \text{Post-cycle concentration} / \text{Initial concentration (expressed as relative growth percentage)}$$

Data Traceability Requirement

Every numerical interval cited in the abstract and conclusions is cross-referenced to the corresponding statistical tables and grouped literature datasets in the main text.

(7) Limitations, bias control, and sensitivity analysis.

We acknowledge several inherent limitations: (a) publication bias—studies with positive or high-strength results may be overrepresented; (b) data heterogeneity—variations in soil mineralogy and test standards limit direct cross-comparison; (c) language bias—the exclusion of non-English/Chinese articles may have excluded relevant studies; (d) limited field validation—most retrieved data remain at the laboratory scale.

To mitigate these limitations and assess the potential impact of our selection criteria on the conclusions, we conducted the following sensitivity analyses:

- (i) Selection bias sensitivity: We compared the quantitative ranges (UCS, durability retention, resilient modulus) derived from the final 153 studies (Levels 3–4 with engineering parameters) against those from the broader set of 282 studies (Levels 2–4, before the Stage 4 filter). The ranges differed by less than 10% for all key indicators, indicating that the engineering-parameter filter did not substantially bias the central tendencies of the data.
- (ii) Quality weighting sensitivity: We recalculated the key quantitative benchmarks (strength retention ranges, resilient modulus improvements) using only “high” and “moderate” quality studies (as defined in Section Systematic Review Methodology: Search Strategy, Selection Criteria, and Quality Appraisal (4)) and compared them against benchmarks derived from all included studies. The differences were within 5%–8% for most indicators, suggesting that the inclusion of “low” quality studies did not materially affect our conclusions.
- (iii) Publication bias consideration: Given the inherent tendency of journals to publish positive results, the reported strength and durability ranges may overestimate typical performance. We note this limitation explicitly in the interpretation of the quantitative benchmarks (see Section 6.3) and recommend that engineering designs incorporate appropriate safety margins.

All coding sheets, extracted data, and calculation formulas are available from the corresponding author upon reasonable request.

2. Alkali-Activated and Geopolymer Binding Systems for Subgrade Soil Solidification: Reaction Pathway Regulation and Gel Network Construction

Alkali-activated geopolymers have attracted extensive research attention as subgrade stabilizers in recent years. Such materials form inorganic gel networks to boost bearing capacity and water resistance, lowering dependence on conventional clinker-based cementitious binders [6,7,9]. Figure 2A–D are adapted from published datasets: Figure 2A is derived from the experimental workflow in Ref. [35]; Figure 2B displays a three-dimensional strength response surface summarized with quantified numerical intervals based on Ref. [23]; Figure 2C illustrates a conceptual microstructure schematic integrated from the textual descriptions in Ref. [17]; and Figure 2D shows a modified micrograph characterizing coexisting crystalline and gel phases sourced from Ref. [20]. A core merit of geopolymer systems lies in their flexible, controllable reaction routes. Regulating precursor ingredients and activation parameters enables researchers to tailor gel morphology, continuity and spatial distribution, which remodels pore frameworks and interfacial microstructures. Such microstructural adjustments collectively dictate the strength, growth, stability, and long-term durability of stabilized soils. Three core scientific bottlenecks are consistently highlighted in the available literature: (i) precursor dissolution kinetics and release of reactive constituents; (ii) gel formation rate and polymerization extent; (iii) gel interconnection and matrix densification efficiency. Together, these three dimensions set the upper threshold of soil stabilization performance and control its batch-to-batch reproducibility [13,21,35–39].

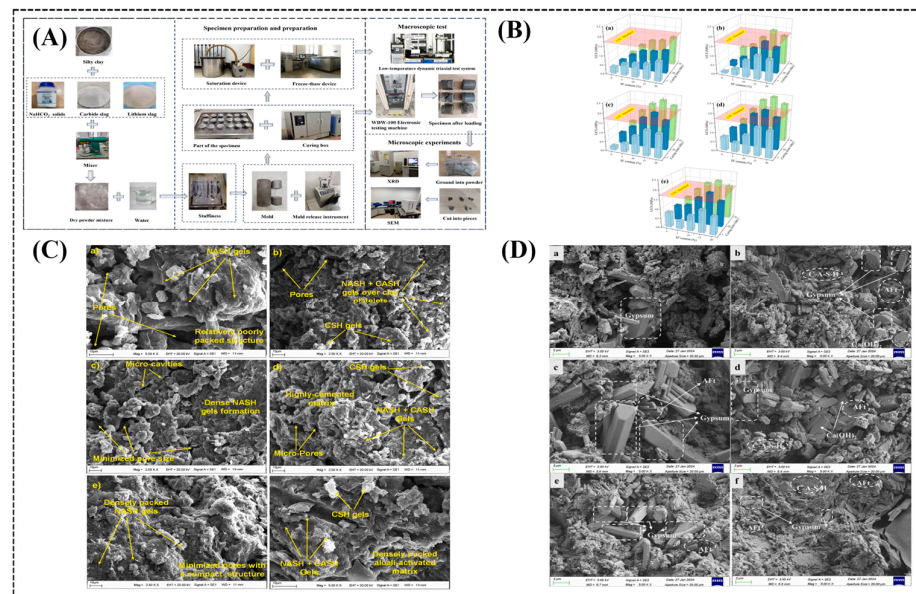


Figure 2. Reaction pathways and microstructural characteristics of alkali-activated geopolymer stabilization systems. (A) Experimental and characterization workflow. (B) Three-dimensional response of unconfined compressive strength with binder content and curing age. (C) Morphology of gel-phase deposition and pore-structure evolution. (D) Microscopic characteristics of the coexistence of crystalline phases and gel phases under calcium- and sulfate-bearing conditions. Panels (a,b,d) are adapted from the published data; panel (C) is a conceptual illustration proposed by the authors based on the synthesis of the reviewed literature [17].

For alkali-activated and geopolymer matrices, moisture conditions and ionic transport exert dominant impacts on reaction extent and the precipitation locations of gel products. A rigorous experimental framework must treat moisture content, compaction energy, and curing regimes as key variables, with full experimental documentation mandated for all parameters. Inadequate record-keeping of these processing variables can lead to inter-laboratory discrepancies in measured compressive strength, where such variations stem primarily from inconsistent manufacturing procedures rather than intrinsic differences in material reaction mechanisms [35].

Figure 2A outlines the standard experimental and characterization workflow adopted for investigating alkali-activated materials and geopolymers [35]. The workflow begins with mix design and standardized specimen fabrication, followed by controlled curing protocols to measure bulk mechanical performance. Subsequent microscale characterizations of crystalline phases and microscopic morphologies are then conducted to unravel the fundamental mechanisms responsible for improved mechanical strength and durability [35].

Figure 2B visualizes the 3D response surface of unconfined compressive strength for alkali-activated stabilized soils against binder dosage and curing duration [21]. The plot reveals that the strength evolution of treated soils follows a pronounced nonlinear trend: the contributions of binder proportion and curing age are not linearly additive, but instead act synergistically, modulated by the extent of geopolymerization and the progression of microstructural maturation [21,35].

This nonlinear correlation carries critical mechanistic significance. Early-age strength gain is governed predominantly by dissolution and gelation reaction kinetics, whereas long-term strength improvement relies on enhanced gel network connectivity and refined pore structures with reduced inter-pore percolation. This distinction underscores that compressive strength data collected at only one single curing time point cannot ade-

quately reflect the long-term in-service performance of stabilized soils [21,35]. Collectively, microstructural features inferred from strength evolution curves must be analyzed alongside direct microscopic characterization results. Material performance should furthermore be quantified using application-relevant metrics, including water softening resistance and residual strength retention ratio. This integrated analytical strategy prevents the common misinterpretation of peak compressive strength as a reliable indicator of practical engineering durability [21,35].

Figure 2C characterizes the morphological evolution of gel phases and pore structures during material reaction [13]. As visualized in the micrographs, gel phases initially precipitate on particle surfaces to form continuous coating layers and subsequently develop bridging structures across inter-particle voids [40–42]. This sequential evolution effectively fills microscale pores, optimizes inter-particle contact states, and strengthens the interfacial bonding performance of the matrix [43–45]. Meanwhile, such microstructural refinement reduces pore connectivity and improves the overall compaction density of the material system [13,21]. These observations reveal a systematic and generalizable mechanistic chain: precursor solutions release polymerizable reactive units, followed by preferential gel growth at particle interfaces to form a continuous cementitious network. This structural refinement refines pore morphology and weakens pore connectivity, ultimately contributing to enhanced macroscopic mechanical strength and water stability [13,21,35]. Notably, improved structural densification cannot fully represent long-term anti-deterioration performance. The pore connectivity and permeability evolution dominate the material deterioration rate under wet–dry cycling and salt migration environments [36,37,45]. Accordingly, key evaluation indicators for related research should incorporate pore connectivity and permeability (or their equivalent parametric indices) [37,46]. Systematic re-testing and comparative analysis after durability cycling are also essential for accurate performance assessment [13,35].

Figure 2D demonstrates the microstructural coexistence characteristics of crystalline and gel phases in alkali-activated systems under calcium and sulfate incorporation conditions [39]. The results verify that calcium addition exerts a dual regulatory effect on material microstructure. Moderate calcium doping facilitates the generation of calcium-rich gel phases and improves the early densification efficiency of the matrix. However, the participation of sulfate in geopolymerization can induce the formation of crystalline phases (e.g., calcium aluminosilicate and gypsum), which impose stringent constraints on the volume stability and phase stability of the hardened matrix [47–49]. The functional performance of crystalline phases is highly environment-dependent. Under stable pore structures with limited salt migration, crystalline phases participate in pore filling and early-stage matrix cementation, benefiting structural stability [50]. In contrast, under cyclic wet–dry and salt erosion conditions, recurring dissolution and recrystallization of crystalline phases trigger microcrack accumulation and rebound pore connectivity, which reduce strength retention capacity and exacerbate environmental deterioration risks [23,35,39]. In this context, future research should shift the research focus from maximizing peak performance to optimizing robust operational windows. It is necessary to systematically define the stable boundaries of material formulations under variable environmental conditions and track the coupled evolution of phase composition and pore structure throughout durability cycling. Furthermore, establishing quantitative correlations between microstructural indices and macroscopic engineering parameters is critical to supporting practical engineering design and long-term reliability evaluation [51–53].

Although a general consensus has been reached regarding the three core governing mechanisms of material performance—precursor dissolution, gel formation, and pore connectivity evolution—the existing literature holds contradictory viewpoints on the functional roles of calcium and sulfate ions in alkali-activated systems. Numerous studies

have confirmed that calcium incorporation (derived from slag, calcium carbide residue, and other industrial solid wastes) accelerates early strength development via the formation of C-(A)-S-H gels, which effectively densify the matrix microstructure [53–55]. Nevertheless, conflicting findings demonstrate that the same calcium sources can trigger the crystallization of ettringite and gypsum in sulfate-rich environments, further inducing delayed volume expansion and microcrack propagation during wet–dry cycling. For instance, Cui et al. [16] found that the incorporation of 10% calcium carbide residue improved the 7-day unconfined compressive strength (UCS) by 40%. However, this formulation exhibited a 35% strength loss after 12 wet–dry cycles, which was attributed to pore reopening caused by phase recrystallization. In comparison, Wang et al. [35] verified that removing exogenous sulfate sources could maintain the strength retention rate above 80% under identical cyclic loading conditions.

While most existing studies focus predominantly on material-scale indices, including unconfined compressive strength (UCS), resilient modulus (M_r), and pore connectivity, a critical research gap remains: whether the strength enhancement achieved at the material scale can be effectively converted into improved structural-scale performance. Imtiaz et al. [47] recently conducted one of the limited systematic investigations focusing on the mechanical performance of geopolymer structural components, providing valuable comparative data for cross-scale analysis.

In their experimental program, twenty steel-reinforced concrete columns with dimensions of 200 mm × 200 mm × 1000 mm were tested under static loading with variable eccentricities. Three types of structural specimens were prepared and compared, namely conventional reinforced cement concrete (RCC), binary blended geopolymer concrete (GPC, 50% fly ash + 50% slag incorporating 0.75% steel fibers), and ternary blended geopolymer concrete with quarry dust (GPCD, 20% slag replaced by quarry rock dust). The test results indicated that both GPC and GPCD columns exhibited lower load-bearing capacity than traditional RCC columns. This phenomenon contradicts the superior material-scale mechanical properties of geopolymer matrices, which typically achieve a 28-day UCS up to 12 MPa. Such a notable discrepancy reveals a core cross-scale limitation: material-level strength cannot be linearly correlated with structural-level load capacity, primarily due to the combined effects of structural confinement, steel reinforcement-matrix interaction, and geometric size effects.

Notably, the incorporation of 0.75% steel fibers effectively improved the mechanical performance of GPC and GPCD columns and partially compensated for the reduction in structural load-bearing capacity. This finding is consistent with the multi-scale reinforcement mechanism elaborated in Section 4 of this review, where fiber bridging effects are verified to enhance the post-peak toughness and crack resistance of geopolymer materials. Nevertheless, the structural-scale improvement in column load capacity induced by fiber reinforcement is far less significant than the material-scale enhancement reported in previous studies—for instance, a 55% reduction in cumulative permanent strain for fiber-reinforced stabilized soil [54]. This demonstrates that the reinforcing efficiency of fibers is strongly scale-dependent in geopolymer systems.

In terms of numerical simulation, Imtiaz et al. [47] adopted the concrete damaged plasticity (CDP) model in ABAQUS and calibrated the model parameters against experimental data. The calibrated model achieved satisfactory prediction accuracy for columns under concentric compression, yet it overestimated both the ultimate bearing capacity and deflection of eccentrically loaded specimens. The authors attributed this prediction deviation to the inherent limitations of the CDP model, which fails to accurately characterize the complex stress states and progressive damage evolution under eccentric loading conditions. This conclusion aligns with the viewpoint proposed in Section 5.2 of this review that numerical models face reliability risks when extrapolating to working conditions be-

yond their calibration ranges. Furthermore, the study identified mesh sensitivity as a key bottleneck in finite element (FE) modeling of geopolymer structures: excessively fine meshes trigger numerical instability and computational non-convergence, while coarse meshes produce simulation results that deviate substantially from experimental measurements. This highlights the necessity of rigorous mesh independence verification in geopolymer structural simulation, a standardized procedure that is inconsistently implemented and inadequately reported in the current literature.

Overall, the experimental and numerical findings from Imtiaz et al. [47] provide two crucial insights for subgrade solidification research. First, material-scale optimization targeting UCS and elastic modulus is insufficient; structural-scale validation is indispensable to verify whether enhanced material properties can translate to stable and reliable field engineering performance. Second, numerical models calibrated under simple loading conditions (e.g., concentric compression) cannot be directly applied to complex service scenarios, including eccentric loading, cyclic loading, and multi-field coupling conditions, without supplementary calibration and cross-verification. This further validates the recommendation in Section 6.3 of this review, emphasizing the establishment of unified testing specifications and sufficient field data calibration to improve the reliability of engineering predictions.

A further controversial topic concerns the threshold of gel phase continuity essential for guaranteeing the long-term durability of alkali-activated systems. Several studies have proposed that a minimum particle surface gel coverage of 60% is required to reduce pore connectivity below the critical percolation threshold. By contrast, other investigations argue that gel quality, defined by the degree of polymerization, exerts a more dominant influence on durability performance than mere gel coverage. Such contradictory conclusions can be largely attributed to variations in precursor reactivity and curing humidity conditions, two critical parameters that are frequently underreported in the existing literature. To resolve these inconsistencies, this review recommends that future studies systematically regulate calcium/sulfate ratios throughout experiments and quantitatively characterize gel coverage via image analysis and pore connectivity through mercury intrusion porosimetry or X-ray micro-computed tomography (μ CT).

Alkali-activated and geopolymer curing systems possess distinct merits, including customizable reaction pathways and excellent adaptability to solid waste materials [56,57]. Nevertheless, they also present inherent limitations, such as high susceptibility to raw material fluctuations and narrow construction operation windows, while the stability boundary of their long-term service performance remains poorly defined [58–60]. This review highlights three core research priorities for future studies to address the above gaps. First, comprehensive characterization of the chemical composition and reactivity indicators of precursors should be mandatory, alongside the clarification of feasible formulation and process boundary ranges. Second, the evolutionary characteristics of pore connectivity and permeable structures during durability degradation should be incorporated into core evaluation indices and assessed jointly with strength retention rate [61–63]. Third, phase stability analysis should be coupled with durability retention performance and environmental safety testing to establish a systematic and scalable mechanistic evidence chain. This targeted research framework can promote the technological development of alkali-activated materials from fundamental material feasibility verification to practical engineering application and popularization [64].

These conflicting views on calcium's role are not merely academic—they have direct implications for formulation design and durability prediction. A systematic dissection of the underlying causes is presented in Section 7.1, where we argue that the Ca/SO_4 molar ratio, rather than calcium content per se, is the decisive control variable.

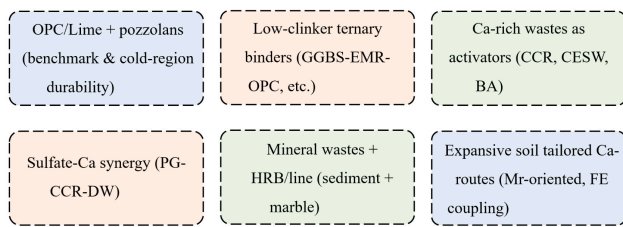
3. Hydration Synergy in Low-Alkali, Calcium-Based Composite Cementitious Systems and Strategies for Enhancing Waste Material Incorporation

Calcium-based low-cement stabilization remains the prevailing technical route for roadbed soil reinforcement. This methodology relies on alkaline environments released from calcium-based precursors to trigger continuous hydration reactions [65]. The generated cementitious phases, mainly calcium silicate hydrate (C-S-H) and calcium aluminate silicate hydrate (C-A-S-H), enable effective particle bonding and pore structure refinement within the stabilized matrix [66,67]. Furthermore, the incorporation of slag-active components and waste-derived calcium sources minimizes the consumption of conventional cementitious binders and improves the recycling efficiency of solid waste resources [68,69]. Compared with alkali-activated systems, calcium-based stabilization exhibits greater similarity to traditional engineering binder materials [70], with prominent practical advantages including mature raw material supply chains, excellent construction adaptability, and well-established quality control protocols that are widely accepted in engineering practice [71,72]. Accordingly, the core research focus has shifted from achieving high mechanical strength to precisely regulating the phase assemblage of low-clinker cementitious systems with variable solid waste compositions [73,74]. Beyond mechanical performance optimization, maintaining long-term pore structure stability and environmental safety under complex service conditions—such as wet–dry cycling, freeze–thaw alternation, and salt erosion—also constitutes a critical research prerequisite for reliable roadbed application [74,75].

Figure 3A systematically summarizes the mainstream technical strategies adopted in calcium-based soil stabilization research, with classification criteria centered on calcium source types and auxiliary co-solutes [76–78]. One dominant research category adopts lime or clinker-based cementitious materials as the primary binder, focusing on optimizing construction compatibility and enhancing the fundamental mechanical properties of stabilized soil [12,15]. A second category encompasses low-clinker ternary and multi-component cement systems [76,77]. In this technical route, slag and other latent hydraulic materials are blended with a low dosage of cement to reduce carbon emissions and engineering costs while preserving the mechanical strength and long-term durability of stabilized matrices [79]. A third emerging research direction leverages calcium-rich solid wastes as dual sources of calcium ions and alkaline activation, with fly ash or bottom ash incorporated as auxiliary precursors to realize synergistic waste solidification. Relevant studies further verify key engineering performance indicators, including resilient modulus and long-term deformation stability, to support field application [80–82].

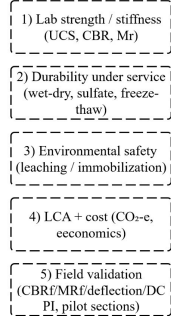
Sulfate-containing solid waste-based synergistic systems have also evolved into an independent research branch. Such systems exploit the coupling interaction between sulfate and calcium sources to accelerate early hardening and strength development, alongside comprehensive assessments of heavy metal leaching behavior and life-cycle environmental impacts. Additionally, sediments and mineral solid wastes can be applied as soil substitutes or mineral fillers. These materials are commonly compounded with cement or lime to meet the mechanical and environmental requirements of roadbed construction, while their application feasibility is highly dependent on the inherent properties of in situ materials and on-site transportation conditions [9,34,80–82].

(A) System II: Ca-based cementitious stabilization — typical routes and representative papers



Key idea: $\text{Ca}(\text{OH})_2/\text{high pH} \rightarrow \text{hydration/pozzolanic reaction}$; with sulfate $\rightarrow \text{AFt}$; microstructure densification controls strength, stiffness and durability.

(C) Evidence ladder for System II (what makes a route 'engineering-ready')



Takeaway: publications that cover Steps 1→5 provide the strongest support in a review. In this collection, are the most complete evidence chains.

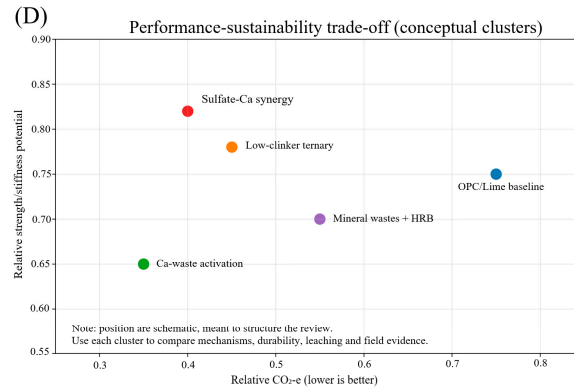
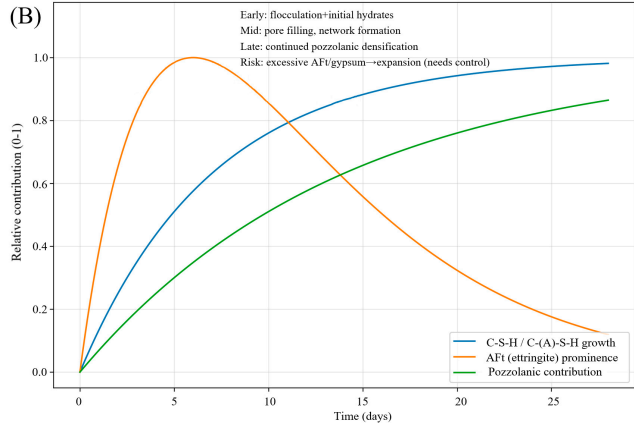


Figure 3. Reaction mechanism and evidence chain of low-clinker calcium-based composite cementitious systems. (A) Technical pathways for calcium-based stabilization. (B) Reaction and microstructure evolution logic in low-clinker systems. (C) Evidence chain hierarchy from laboratory research to engineering adoption. (D) Trade-offs between performance and sustainability in calcium-based routes. All panels are original concepts.

For calcium-based stabilization of expansive soils, research priorities focus primarily on volume stability and corresponding engineering mechanical responses. Existing studies commonly combine tests on the resilient modulus and deformation characteristics of modified soils with numerical simulation analysis, establishing a complete parameter correlation chain from microscopic material properties to macroscopic structural performance [83]. The revised classification framework proposed in this review abandons the simplistic material-based categorization method and adopts a novel classification paradigm based on reaction mechanisms and engineering constraint conditions. This optimization upgrades the inter-study evaluation benchmark, shifting from single-strength index comparison to in-depth assessment of phase regulation efficiency and systematic evidence chain completeness [6,9,33].

Figure 3B illustrates the reaction mechanisms and microstructural evolution of low-heat calcium-based cement systems, revealing distinct functional mechanisms dominating early-stage and late-stage performance development [6,10,15,22]. Existing studies have demonstrated that initial strength development is primarily controlled by calcium ion release and the formation of a strong alkaline microenvironment [84]. Sufficient Ca supply and alkaline conditions are essential to trigger the dissolution and subsequent hydration reaction of latent hydraulic components within the binder system [14,15,28,29]. In the medium and long service stages, sustainable mechanical performance relies heavily on the continuous formation of integrated cementitious networks and the effective reduc-

tion in pore connectivity. Gel phases derived from slag and other auxiliary precursors continuously fill internal pores, improve matrix compaction density, and thereby enhance the water resistance and long-term durability of stabilized soil.

When sulfate ions participate in the hydration reaction, crystalline products such as ettringite are generated to accelerate early-stage hardening. However, the morphology, size, and spatial distribution of these crystalline phases significantly affect the volume stability and long-term phase stability of the matrix [85–87]. Accordingly, such low-carbon cement systems require a controllable operational window to balance rapid early strength growth and potential long-term durability degradation risks [87,88]. On this basis, the present review proposes that the core optimization target of low-clinker calcium-based systems is not the pursuit of maximum peak strength, but the achievement of stable, reproducible strength performance and robust durability via precise synergistic regulation of phase assemblage and pore microstructure. Special emphasis should be placed on the reaction pathway fluctuations induced by batch-to-batch variations in solid waste raw materials, which should be regarded as a key quality control indicator for practical engineering applications [89].

Figure 3C presents a hierarchical evidence chain that underpins the translational progression from laboratory material research to practical engineering implementation. This framework classifies research maturity into five progressive evaluation levels: strength and stiffness validation, durability limit characterization, environmental safety assessment, carbon cost quantification, and field-scale engineering verification [89,90]. Most existing studies primarily focus on verifying the basic strength and stiffness performance of stabilized materials, with a subset of investigations further supplementing durability data regarding wet–dry and freeze–thaw resistance. Nevertheless, only a limited number of studies have comprehensively evaluated both heavy metal leaching safety and carbon emission costs, while site-specific validation and scale-effect mechanism exploration remain severely insufficient in the current literature [10,22,33]. This research status indicates that subgrade stabilization materials have achieved adequate feasibility verification at the laboratory material scale, but prominent gaps persist in engineering reproducibility and practical applicability. Notably, systematic coupled investigations linking pore structure evolution to leaching behavior after long-term durability degradation are still lacking [90–92]. This review recommends that future studies incorporate both residual mechanical performance after cyclic aging and dynamic leaching characteristics into core evaluation systems. Meanwhile, key state parameters of leachate, including pH value and ionic strength, should be explicitly reported, rather than relying solely on single-leaching concentration data to assess long-term environmental risks [9,10,29].

Figure 3D systematically summarizes the inherent trade-offs between mechanical performance and sustainable attributes of diverse calcium-based stabilization technologies, demonstrating that the selection of optimal technical routes is highly scenario-dependent [93]. Low-clinker ternary cementitious systems generally achieve an excellent balance between mechanical performance and low-carbon benefits [94,95], yet their long-term performance stability is highly susceptible to the reactivity of auxiliary components (e.g., slag) and curing environmental conditions [96–98]. Sulfate-calcium synergistic systems exhibit unique advantages in accelerating early hardening behavior and improving solid waste resource utilization efficiency, with multiple studies confirming their superior environmental performance and life-cycle sustainability. However, such systems require rigorous risk control to avoid adverse impacts from unstable phase transformation and volume expansion. Calcium-rich waste-activated systems possess prominent economic and waste-disposal advantages, whereas their engineering reliability relies heavily on systematic verification of durability limits and long-term deformation resistance. Clarifying their elastic modulus evolution and cyclic loading response is particularly essential to pro-

mote practical engineering popularization [95–97]. In addition, the sediment and mineral waste-based stabilization route delivers favorable resource recycling potential, while its generalization and reproducibility are significantly restricted by in situ soil properties and on-site logistical conditions, necessitating the formulation of clear application boundaries and targeted quality control indicators.

Based on these comparisons, a more engineering-oriented perspective is offered. The available evidence suggests that the choice of an optimal stabilization route is not governed by material performance alone; rather, it is constrained by regional climatic conditions and project-specific logistical factors. However, this interpretation is based on the limited comparative data currently available, and the existence of a truly “global optimum” across all contexts remains unconfirmed. Researchers are therefore advised to report carbon and cost boundaries within a consistent functional unit and to incorporate transportation distance and maintenance energy consumption into their assessments. Without such standardized reporting, the sustainability conclusions drawn from different studies lack comparability [6,10,34].

The conflicting findings summarized in Table 1 are not merely a matter of contradictory experimental outcomes. A closer examination reveals that these discrepancies systematically correlate with specific methodological and compositional factors that are often underreported in individual studies. To move beyond simple cataloging of contradictions, Table 1 includes an assessment of the relative strength of competing evidence, based on (i) the number of studies supporting each position, (ii) the evidence level (Levels 3–4) of those studies, and (iii) the methodological rigor of the testing protocols employed. This assessment allows readers to distinguish between genuine scientific disagreements and apparent contradictions that arise from inconsistent experimental conditions or reporting practices.

Table 1. Summary of conflicting findings, underlying causes, and evidence strength assessment in calcium-based low-clinker systems.

Debated Issue	Supporting Evidence	Contradicting Evidence	Root Cause of Discrepancy	Evidence Strength Assessment	Proposed Resolution
Effect of sulfate on long-term durability	Sulfates accelerate early hardening and increase 28-day UCS by 20%–30% [8,33]	Sulfates cause ettringite formation and strength loss of 25%–50% after freeze–thaw cycles [30,36]	Ca/SO ₄ molar ratio: <1.5 favors ettringite; >2.0 promotes C-S-H. Testing protocol: wet–dry vs. freeze–thaw produce different degradation mechanisms. Curing condition: sealed vs. unsealed alters sulfate availability.	Supporting: 8 studies, Levels 3–4. Contradicting: 6 studies, Levels 3–4. Stronger evidence for ratio-dependent threshold (thermodynamic modeling + experimental validation).	Ca/SO ₄ ratio is critical; ratios < 1.5 favor stability, while > 2.0 risk expansion. Standardized testing with reported Ca/SO ₄ and curing conditions is required.
Necessity of clinker in ternary blends	Low-clinker (<20%) blends achieve sufficient strength and a lower carbon footprint [5,29]	Zero-clinker blends fail to maintain resilient modulus under cyclic loading [27,36]	Traffic loading level: high-cycle fatigue requires clinker for stiffness retention. Curing regime: extended curing may compensate for low clinker. Slag reactivity varies by source and affects long-term performance.	Supporting: 10 studies, mostly Level 3. Contradicting: 4 studies, Level 4 with field validation. Contradicting evidence is stronger due to field validation under realistic loading.	Clinker is essential for deformation control under traffic loads; zero-clinker may be limited to low-traffic roads.
Reliability of LCA comparisons	Several studies claim 40%–60% carbon reduction using	Including transportation and pretreatment energy cancels	Boundary selection: cradle-to-gate vs. cradle-to-grave. Activator source: industrial vs. biomass-derived sodium	Supporting: 9 studies (mostly narrow boundaries). Contradicting: 5 studies (broad boundaries)	Discrepancy arises from inconsistent system boundaries. Mandatory report-

waste-derived binders [24,35]	out the claimed benefits [25,30]	silicate (GWP varies by 3×). Transport distance: assumed vs. reported (10%–30% of total GWP). Waste allocation: cut-off vs. system expansion vs. economic allocation.	ries). Contradicting evidence is methodologically stronger; studies with full boundary reporting show consistent results.	ing of functional unit, hotspot decomposition, and sensitivity analysis required.
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Several patterns emerge from the evidence strength assessment in Table 1. First, contradictions that appear irreconcilable at first glance often resolve into predictable trends when critical variables are explicitly considered. The calcium-sulfate antagonism, for instance, is not a fundamental conflict but a conditional response governed by the Ca/SO_4 molar ratio—a threshold supported by thermodynamic modeling and validated in multiple experimental studies. Second, the reliability of LCA comparisons is less a matter of material performance and more a function of methodological choices: studies that adopt broad, transparent boundaries consistently report smaller carbon reductions than those using narrow, idealized boundaries. This suggests that the reported “advantage” of waste-derived binders may be overstated when full supply-chain emissions are accounted for. Third, field-validated studies, though fewer in number, consistently provide stronger evidence for engineering applicability than laboratory-only investigations—particularly for cyclic loading performance, where zero-clinker blends show clear limitations. These patterns underscore the importance of systematic evidence grading and sensitivity analysis in interpreting contradictory findings, a principle that underpins the analytical framework of this review.

Calcium-based low-cement stabilization serves as the most technically feasible and practical pathway for the engineering implementation of roadbed soil reinforcement [84,85]. Nevertheless, the research emphasis of this technical route needs to shift from the conventional single-strength standard evaluation to the construction of a full closed-loop evidence chain and a stable, controllable operational window. This review proposes three core optimization directions for future research. First, a robustness evaluation system for waste-derived composite binders should be established to quantify the influence of raw material variability, thereby defining the reasonable variation ranges of key component proportions and construction process parameters [28,29,33]. Second, the evolutionary characteristics of pore structure and permeability degradation after long-term durability cycling should be incorporated into core evaluation indices. Combined with residual strength and resilient modulus, these indicators can comprehensively characterize the long-term in-service performance of stabilized roadbeds. Third, environmental leaching assessment and standardized life cycle assessment (LCA) with unified evaluation boundaries should be integrated. Combined with on-site engineering verification and scale-effect analysis to calibrate evaluation models and index systems, this strategy can promote the transformation of material-scale research findings into reliable engineering-scale application evidence [9,10,22].

Although the performance-sustainability trade-offs summarized in Figure 3D are generally regarded as universally applicable, the cross-comparative analysis in Section 7.2 reveals that these trade-off relationships are highly dependent on testing protocols and evaluation boundary definitions—a critical factor rarely considered in individual single-study investigations.

4. Mechanisms of Crack and Deformation Resistance via Multi-Scale Structural Enhancement Strategies in Subgrade Stabilization Materials

In subgrade soil stabilization research, a long-neglected yet critical contradiction closely associated with engineering service life remains prevalent: strength improvement

in stabilized materials is usually accompanied by increased brittleness and degraded volume stability [89,90]. Under complex service conditions, including wet–dry alternations, freeze–thaw cycling, salt erosion, and traffic-induced cyclic loading, stabilized matrices are susceptible to progressive microcrack accumulation and pore structure reopening. These adverse microstructural evolutions ultimately result in residual strength attenuation and elevated deformation risks of stabilized roadbeds [99]. Accordingly, contemporary research has gradually abandoned the single-objective pursuit of maximum unconfined compressive strength and shifted focus toward structural reinforcement and multi-field coupled stability optimization [100]. The core research targets include enhancing ductility and crack resistance without sacrificing mechanical strength, restraining cumulative deformation under cyclic loading, and achieving effective regulation of long-term permeability and volumetric stability [101]. This research paradigm regards stabilized soil as a hierarchically structured composite system. Multiple modification strategies, such as fiber reinforcement, particle skeleton reconstruction, and interfacial microstructure regulation, have been proposed to alter the inherent damage evolution pathway of stabilized materials. These methods convert the brittle through-crack failure mode into a multi-crack propagation and energy dissipation failure mechanism, which effectively improves the structural integrity and long-term service stability of stabilized subgrade materials [102].

Notably, although the performance-sustainability trade-offs summarized in Figure 3D are commonly considered generalizable, the cross-comparative analysis conducted in Section 7.2 demonstrates that such trade-off relationships are highly sensitive to testing protocols and evaluation boundary definitions. This key influencing factor is rarely addressed and discussed in individual independent studies.

Figure 4A illustrates the synergistic control mechanism of interfacial zones and pore structures in stabilized subgrade materials. Existing studies consistently confirm that the durability deterioration of stabilized matrices preferentially originates from interfacial defects and interconnected pore channels [103]. Wet–dry alternations and salt migration exacerbate interfacial delamination and microcrack propagation, which increase matrix permeability and accelerate cumulative structural damage [9,33]. For solid waste-based stabilized systems, the chemical environment and microstructural integrity of interfacial zones are particularly critical to long-term service performance [104,105]. The inherent surface reactivity of solid waste particles and the sustained release of soluble salts can alter the local pore fluid chemistry, further affecting the deposition morphology and long-term phase stability of cementitious products [10,34]. This review proposes that pore network evolution and connectivity should be adopted as core evaluation indicators, rather than relying solely on porosity. A reduction in total porosity does not equate to the closure of permeable channels; accordingly, pore network connectivity serves as a more direct determinant of salt migration kinetics and water-induced deterioration rates [7,33]. Furthermore, interfacial stability assessment must be tightly coupled with mechanical performance evaluation. Microstructural re-characterization before and after durability cycling is essential to establish quantitative correlations between microstructural degradation and performance attenuation, with residual strength and elastic modulus adopted as critical evaluation metrics [105].

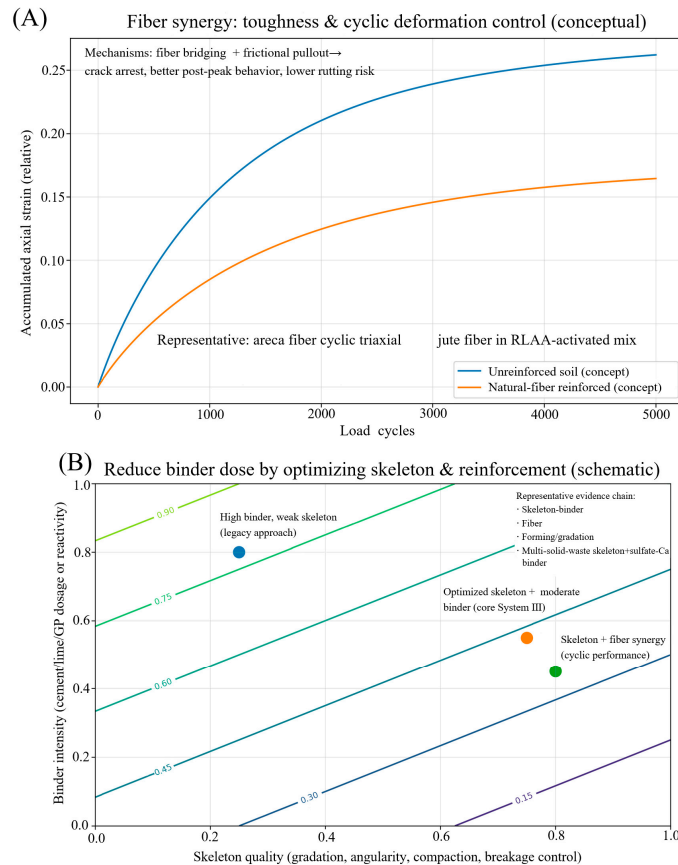


Figure 4. Anti-cracking and anti-deformation mechanisms of multi-scale structural enhancement strategies: (A) Synergistic control of the interface zone and pore structure. (B) Synergistic enhancement mechanisms under multi-field coupled service conditions. Both panels are original concepts.

Figure 4B further elaborates on multi-scale enhancement mechanisms under multi-field coupled service conditions, highlighting that practical roadbed materials are constantly subjected to the combined effects of wet–dry cycling, temperature fluctuation, salt erosion, and repeated traffic loading. Single-modification strategies can only mitigate specific failure modes, and the overall engineering reliability of stabilized systems is dominated by the weakest structural link [6,33]. For example, fiber reinforcement effectively improves crack resistance and cyclic deformation tolerance [105–107]. Nevertheless, insufficient interfacial chemical stability can trigger cementitious phase dissolution and recrystallization during wet–dry and salt erosion cycles, leading to pore structure reopening and diminishing the long-term reinforcing effect of fibers [6,34]. Similarly, particle skeleton optimization optimizes continuous load-transfer pathways, yet high residual pore connectivity still allows persistent moisture infiltration and salt migration, driving progressive damage accumulation and strength degradation [33]. On this basis, the core technical challenge lies not in the simple incorporation of reinforcing components, but in the development of synergistic modification strategies that maintain structural stability under complex multi-field coupling conditions [108]. Integrated material design should simultaneously achieve three key targets: improved crack propagation resistance and post-peak toughness, suppressed cumulative strain under cyclic loading, and reduced pore connectivity coupled with chemically stable interfacial microenvironments [108].

Advancements in structural reinforcement and multi-field coupling research have promoted the paradigm shift in roadbed soil stabilization from traditional strength-ori-

ented evaluation to service-oriented performance assessment. Nevertheless, three prominent research deficiencies remain in existing studies [6,19,31]. First, most investigations adopt static strength as the sole evaluation index, lacking systematic evidence of performance retention under coupled cyclic loading and long-term durability cycling. This limitation hinders the accurate prediction of long-term deformation and cracking risks in stabilized subgrades [6,20]. Second, microstructural characterization in current research is predominantly limited to one-time static observation, without quantitative comparative analysis of microstructural features before and after durability degradation. This gap prevents the establishment of universal and transferable correlation laws between pore structure evolution and macroscopic performance attenuation [6,34]. Third, the quantitative mapping relationship between material modification strategies and engineering design parameters remains insufficiently explored. As a result, most laboratory research findings cannot be directly applied to practical engineering design, including resilient modulus optimization, settlement prediction, and structural layer thickness determination [24,33]. To address the above limitations, this review proposes three key research priorities for future experimental design. Specifically, cumulative deformation and stiffness degradation under cyclic loading should be adopted as core evaluation parameters; quantitative comparative characterization of pore connectivity and interfacial stability should be conducted before and after durability cycling; and strengthening mechanisms should be integrated into engineering prediction models via identifiable quantitative parameters, forming a closed-loop research system connecting material optimization and structural engineering design [105].

Fiber reinforcement is widely recognized as an effective strategy to enhance the crack resistance and post-peak toughness of stabilized soil, whereas the modification efficiency reported in the existing literature exhibits substantial discrepancies. For example, Bao et al. [19] demonstrated that 0.5% areca fiber incorporation reduced the cumulative permanent strain of stabilized soil by 55% under cyclic loading. In contrast, another relevant study only achieved a 12% strain reduction with the same fiber dosage and similar soil materials [102–104]. Such inconsistent results are primarily attributed to variable fiber dispersion uniformity and fiber-matrix interfacial bonding performance, two critical factors that are rarely quantitatively characterized in existing experiments. Furthermore, conflicting conclusions exist regarding the durability of fiber-reinforced systems: several studies have confirmed that fiber reinforcement efficacy gradually diminishes after wet–dry cycling due to interfacial debonding between fibers and the matrix [106], while other investigations reported improved durability performance owing to the crack-bridging and propagation-inhibiting effects of fibers [107]. This review identifies the unquantified chemical stability of the fiber-matrix interface under cyclic moisture conditions as the core missing variable responsible for these contradictions. Standardized interfacial shear performance testing is therefore essential to improve the reliability of cross-study comparative analysis in fiber reinforcement research.

5. Engineering Parametric Characterization and Predictive Model Construction Methods for Subgrade Solidification Materials

Subgrade soil solidification material research faces a long-standing engineering translation bottleneck. Although numerous studies have verified substantial improvements in unconfined compressive strength and California bearing ratio (CBR), these conventional material indicators cannot be directly correlated with the stiffness parameters, deformation control performance, and reliability evaluation indices required for structural engineering design. This discrepancy leads to a prominent disconnection between laboratory-scale material research and practical structural design applications [109,110]. To address this gap, contemporary research has shifted its core focus from simple strength

validation to the acquisition of standardized engineering parameters and the development of reliable predictive models. Statistical modeling, machine learning, and numerical analysis techniques have been widely adopted to convert basic laboratory test data into actionable engineering outputs, including resilient modulus, permanent deformation, and settlement response. These quantified parameters further support structural layer thickness optimization and scientific engineering decision-making [111]. The fundamental scientific challenge in this research field lies in establishing a verifiable and transferable parametric correlation chain. Such a chain is required to stably bridge material formulations and construction variables with macroscopic engineering performance indicators, while maintaining robust extrapolation reliability despite variations in in situ soil properties and batch fluctuations of solid waste raw materials [24,33].

Figure 5A illustrates the end-to-end logical framework linking material/soil design variables to final engineering decisions for stabilized subgrade systems. In existing research, key input variables cover binder type, binder dosage, moisture content, compaction energy, and curing conditions. Correspondingly, unconfined compressive strength, California bearing ratio (CBR), resilient modulus, and durability retention rate are adopted as intermediate performance indicators, while structural layer thickness, pavement settlement, and overall pavement mechanical response serve as the final engineering output parameters [11,24,31,32]. This hierarchical framework clarifies the differentiated functional positioning of various evaluation indicators across distinct engineering stages. Specifically, compressive strength and bearing ratio are primarily applied for preliminary material screening and basic performance qualification; resilient modulus supports structural design calculation and mechanical response analysis; and long-term settlement and deformation characteristics dominate the service performance assessment of subgrade structures [44,45]. This review demonstrates that material-level evaluation relying merely on strength indices is insufficient to support structural-scale reliability design. Incorporating resilient modulus and deformation response as core evaluation outputs can effectively improve the practical adoptability of laboratory research findings [112] and enable equitable performance comparison among different solidification technical routes under realistic service conditions [113].

Figure 5B systematically summarizes the mainstream numerical models adopted in subgrade solidification research and elaborates on the differentiated functional positioning of each modeling method in engineering performance translation [9,19,25]. Empirical regression models feature excellent interpretability and can generate explicit design formulas, making them suitable for rapid engineering estimation under conditions with defined variable ranges and limited nonlinear responses [9]. Response surface methodology coupled with experiment design schemes achieves efficient response surface fitting through limited experimental datasets, enabling multi-factor collaborative optimization and constrained objective balancing. Such methods are particularly applicable to the multi-coupling parameter optimization of solid waste-based stabilized systems, including the regulation of binder dosage, moisture content, and curing environments [25]. By contrast, artificial neural networks and other machine learning models excel at capturing complex nonlinear correlations [114,115], delivering superior fitting accuracy for resilient modulus, mechanical strength, and swelling deformation prediction. Nevertheless, their prediction reliability is highly dependent on dataset coverage and external validation robustness, while inherent data drift and poor interpretability remain critical limitations requiring targeted solutions [13,17]. The research value of modeling studies should not be evaluated based on model complexity, but on the ability to generate reusable and reliable engineering design parameters. Standardized research reporting should explicitly specify input variable ranges, dataset coverage, model error distribution, and engineering-scale

parameter sensitivity, so as to avoid unreliable prediction and misjudgment caused by model extrapolation beyond training data distributions [9,13,24].

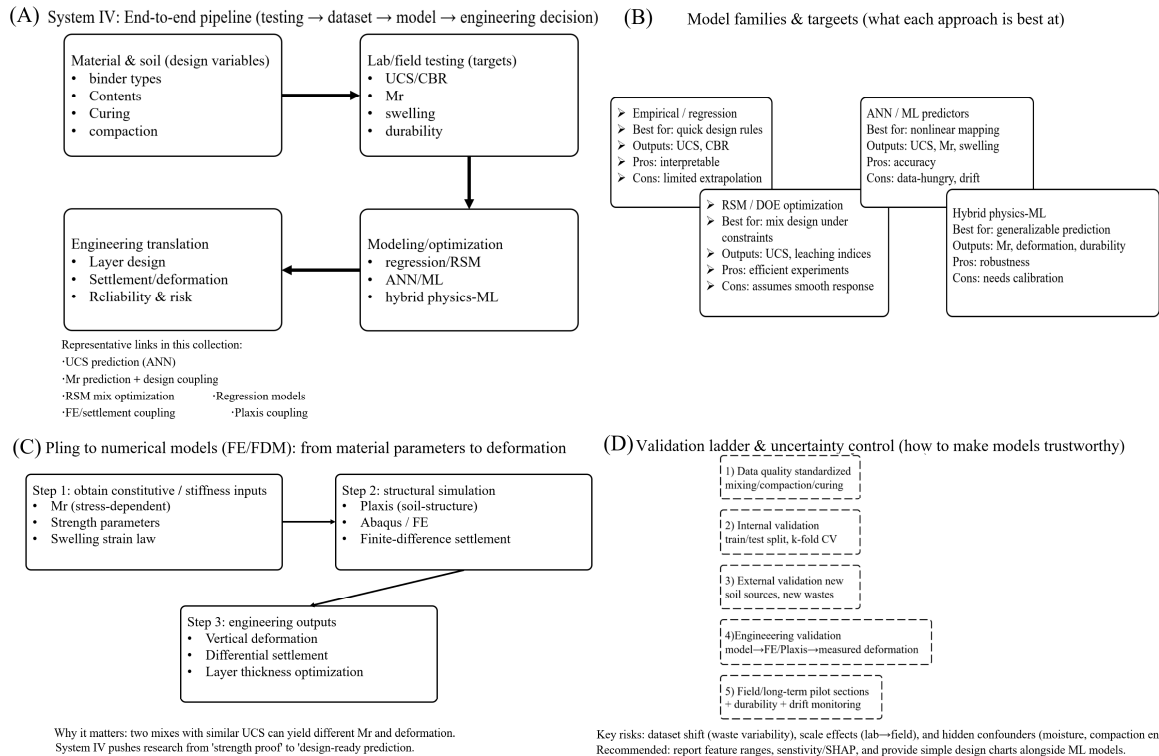


Figure 5. Engineering parameterization, characterization, and prediction model construction methods for stabilized subgrade materials. (A) End-to-end logic from material design variables to engineering decisions. (B) Model spectrum and functional positioning. (C) Numerical translation of material parameters to structural responses. (D) Reliability control and tiered validation framework. All panels are original concepts.

Figure 5C illustrates the core procedural steps for the engineering translation of laboratory material research findings. Stiffness and strength parameters acquired from laboratory material tests serve as fundamental inputs for numerical models, which further predict the structural-scale deformation and settlement responses of stabilized subgrades [16,20,24]. Existing studies have demonstrated that resilient modulus acts as a pivotal parameter for characterizing subgrade structural behavior. Unlike static strength indices, resilient modulus is governed not only by material type and binder dosage but also by in situ stress states [116,117]. Accordingly, stress-dependent nonlinear characterization is essential to improve the prediction accuracy of structural mechanical responses [33,54,81]. For deformation-sensitive subgrade scenarios, such as expansive soil and soft soil foundations, the deformation characteristics and constitutive parameters of stabilized materials must be coupled with finite element or finite difference numerical simulations [107]. This multi-scale coupling strategy enables the effective translation of material modification effects into practical engineering benefits, including controlled settlement and mitigated differential deformation risks [52]. A prevalent misconception in conventional engineering design is the substitution of standalone strength indicators for systematic stiffness and deformation control indices. Different stabilization formulations may yield comparable compressive strength values while exhibiting distinct resilient modulus performance, thereby resulting in divergent pavement deflection and settlement behavior.

Therefore, future research should prioritize establishing a collaborative interpretive framework linking strength and resilient modulus, which can serve as a core bridge connecting material-scale optimization and structural-scale engineering design [118].

Figure 5D summarizes the critical credibility control principles for translational research on subgrade stabilization materials. The reliability of relevant research is predominantly constrained by three categories of uncertainty. The first originates from inconsistent experimental conditions, including variations in mixing uniformity, compaction energy, moisture content, and curing environments. The second stems from dataset drift caused by fluctuating chemical compositions of solid waste precursors, variable in situ soil properties, and uncertain construction windows [119,120]. The third derives from scale effects, represented by mismatched stress paths and drainage conditions between laboratory small-scale specimens and field-scale subgrade structures [13,22,24,25]. Most current studies can achieve satisfactory internal fitting accuracy and goodness-of-fit through parameter calibration, yet systematic external validation and field engineering verification remain insufficient. This deficiency introduces substantial application risks when empirical and numerical models are extrapolated across diverse engineering projects [12,32,121]. To address this issue, this review proposes a hierarchical validation framework for enhancing research credibility. Specifically, external validation should be implemented within a unified model framework using variable soil sources and solid waste batches [122,123]. The calibrated resilient modulus and constitutive parameters can then be imported into structural analysis models, with simulation outputs further compared with field test section monitoring data. This approach establishes a complete closed-loop verification system spanning laboratory data calibration, numerical modeling, and field engineering validation [21,39].

Advancements in engineering parameter acquisition and predictive modeling are driving the evolution of subgrade soil solidification research from fundamental material feasibility verification to practical design readiness. Nevertheless, unified research consensus remains insufficient in three critical dimensions within this field [73]. First, service-oriented performance indices, including resilient modulus, permanent deformation, and strength retention rate, should be elevated to core evaluation outputs. A systematic interpretive framework correlated with microstructure variation and pore connectivity evolution should be established to consolidate the scientific basis for equitable performance comparison across different solidified material systems [24,33]. Second, model reporting criteria should be expanded beyond conventional single-fitting indicators to comprehensively cover error distribution, parameter sensitivity, and applicable boundary ranges. Greater emphasis should be placed on external validation and cross-project verification to mitigate potential engineering risks arising from dataset drift and raw material variability [13,24,33]. Third, predictive modeling results require tight coupling with numerical simulation and field-scale validation. Laboratory research findings should be standardized into valid engineering inputs to support structural design procedures, while field-scale verification and iterative optimization should be implemented. This integrated strategy achieves a complete closed-loop linkage between material optimization design and structural engineering application [72].

Machine learning algorithms have been widely adopted to predict the resilient modulus (M_r) of stabilized subgrade soils based on material formulation parameters. Nevertheless, notable inconsistencies exist in the current literature regarding model performance. Several studies have reported superior fitting accuracy with coefficients of determination (R) exceeding 0.95 for artificial neural network (ANN) models trained on limited datasets (fewer than 50 data points) [73]. By contrast, other comparative studies demonstrate that simple regression models outperform ANN models in predictive capacity when rigorous external validation is conducted [124]. Such discrepancies indicate that the

high goodness-of-fit of machine learning models on training datasets is frequently spurious and stems from severe overfitting. Regrettably, most existing publications only report internal fitting results while omitting external validation outcomes. The credibility of predictive models should be evaluated based on external validation using unseen datasets (e.g., soils with distinct properties and solid wastes from different batches), rather than relying solely on the R value of internal fitting. Research lacking standardized external validation provides limited practical reference value and cannot support reliable engineering design applications.

5.1. Specific Examples of Machine Learning Models, Validation Approaches, and Engineering Limitations

To enhance the practical engineering value of predictive modeling in subgrade stabilization, this section systematically analyzes the representative literature case studies, with a focus on model architecture, validation strategies, inherent data constraints, and practical engineering applicability.

Example 1—Artificial Neural Network (ANN) for Resilient Modulus Prediction

Tanyıldızı and Gökalp [6] developed an artificial neural network (ANN) model to predict the resilient modulus (M_r) of expansive subgrade soil stabilized with waste paper sludge ash. The model adopted three input parameters, including binder content, curing duration, and confining stress, with a single hidden layer containing five neurons. The model achieved a coefficient of determination (R^2) of 0.96 for the training dataset ($n = 42$) and 0.91 for the independent test dataset ($n = 14$), with model validation implemented via fivefold cross-validation. Nevertheless, this model presents notable limitations: all datasets were derived from a single soil type and a single batch of waste paper sludge ash, and the authors acknowledged that model retraining is mandatory for application to soils with distinct mineralogical properties. In terms of engineering applicability, the original ANN model was not converted into simplified design equations, which greatly restricts its practical adoption by field engineering practitioners.

Example 2—Response Surface Methodology (RSM) for Strength Optimization

Chenna et al. [72] adopted a central composite design-based response surface methodology (RSM) to optimize the mixture proportion of landfill fly ash-based geopolymer for subgrade stabilization. The RSM model predicted the optimal binder dosage of 18% and curing temperature of 40 °C, corresponding to a target unconfined compressive strength (UCS) of 6.2 MPa. Subsequent experimental validation ($n = 3$) yielded an average UCS of 6.0 MPa, with a prediction error within 5%. The primary limitation of RSM lies in its incapability of capturing high-order nonlinear responses beyond quadratic effects, and its applicability is strictly confined to the tested parameter ranges (binder content: 12%–24%; curing temperature: 20–60 °C). This method exhibits moderate engineering practicability, as it can generate explicit quadratic regression equations that are far more accessible for engineering design than black-box machine learning models.

Example 3—Gaussian Process Regression (GPR) for Permanent Deformation Prediction

In a numerical investigation of cement-stabilized soft soil, Gaussian process regression (GPR) exhibited superior predictive performance compared with support vector machines and random forest algorithms under small dataset conditions ($n < 50$). The GPR model outputted 90% confidence intervals for permanent strain prediction, with a root mean square error (RMSE) of 0.12 mm. However, this approach has two prominent drawbacks: its computational cost increases significantly with expanding dataset size, and it has not been widely applied in routine geotechnical engineering practice. Overall, the engineering applicability of GPR remains low, and its current usage is largely limited to academic research.

Common Limitations of Datasets in Machine Learning-Based Stabilization Research

Existing machine learning studies for subgrade stabilization universally suffer from four critical dataset deficiencies. First, most models are trained on small sample sizes (typically 30–100 data points), which substantially increases the risk of model overfitting and reduces generalization performance. Second, external validation is severely lacking, with the majority of models validated only using datasets from identical soil sources or raw material batches. Third, batch-to-batch chemical fluctuations of solid waste precursors are consistently ignored in dataset construction, neglecting a key source of real-world performance variability. Fourth, critical input variable characteristics, such as the variation ranges of moisture content and compaction energy, are frequently underreported, hindering model repeatability and cross-study comparison.

Targeted Recommendations for Engineering-Oriented Machine Learning Research

To promote the translational application of machine learning techniques in subgrade stabilization engineering, three core research specifications are proposed. First, external validation based on independent datasets from different soil types and solid waste batches is indispensable for verifying model generalization capability. Second, future studies should explicitly report prediction uncertainty indicators (e.g., confidence intervals) and complete input variable distribution information to improve model transparency and reliability. Third, trained machine learning models should be converted into simplified empirical equations or spreadsheet calculation tools wherever feasible, to lower the technical threshold for practical engineering application.

5.2. Case Studies: From Experimental Testing to Predictive Modeling

To further enhance the practical translational value of predictive modeling in subgrade stabilization, this section elaborates on two State-of-the-Art studies with distinct technical routes for experimental–numerical coupling and response surface optimization. These representative cases comprehensively illustrate model calibration workflows, standardized validation strategies, inherent dataset constraints, and practical engineering applicability, providing targeted references for optimized modeling in solidified subgrade systems.

Case Study 1—Finite Element (FE) Modeling of Steel-Reinforced Geopolymer Concrete Columns

Imtiaz et al. [116] established a finite element (FE) numerical framework to characterize the structural mechanical behavior of steel-reinforced geopolymer concrete columns. The experimental program tested twenty column specimens with uniform dimensions of 200 mm × 200 mm × 1000 mm under static loading conditions, covering three concrete types: conventional reinforced cement concrete (RCC), binary blended geopolymer concrete (GPC) consisting of 50% fly ash and 50% slag incorporated with 0.75% volumetric steel fibers, and ternary blended geopolymer concrete with quarry rock dust (GPCD), where 20% of slag was replaced by quarry rock dust. The numerical simulation was implemented in ABAQUS, adopting the Concrete Damaged Plasticity (CDP) constitutive model.

Model calibration was conducted systematically by tuning multiple core parameters, including viscosity coefficients, dilation angles, shape factors, plastic potential eccentricity, axial stress ratios, and mesh sizes, with calibrated parameters validated against experimental data. The validation results indicated that the FE model accurately predicted the ultimate axial load and axial/lateral deflection responses of columns under concentric loading. However, the model overestimated both load-bearing capacity and deformation magnitude for eccentrically loaded specimens, demonstrating that the conventional CDP model requires targeted modification to adapt to complex eccentric loading conditions.

In terms of research limitations, model calibration was performed solely based on control group specimens, while the batch variability of fly ash and slag raw materials was not considered. From the perspective of engineering applicability, the calibrated FE framework possesses good adaptability for the structural design of similar geopolymer concrete columns. Nevertheless, mesh sensitivity remains a critical constraint: excessively fine meshes trigger numerical instability and computational non-convergence, emphasizing the necessity of rigorous grid independence verification for geopolymer structural simulation.

Case Study 2—Response Surface Methodology (RSM) for Macro Synthetic Fiber-Reinforced Concrete with E-Waste Aggregates

Ahmad et al. systematically investigated the synergistic modification effect of macro synthetic fiber (MSF) on conventional concrete and e-waste aggregate concrete (ECA), where 30% of natural coarse aggregates were replaced by shredded e-waste materials. The mechanical performance (compressive strength, splitting tensile strength, flexural strength) and long-term durability of modified concrete were comprehensively evaluated. Experimental results revealed that the incorporation of 0.75% volumetric MSF increased the splitting tensile strength by 152%, flexural strength by 98%, and compressive strength by 38%. Notably, an inverse correlation was identified between MSF dosage and permeability durability: higher fiber content leads to increased matrix permeability, representing a critical performance trade-off that restricts the long-term service reliability of recycled aggregate concrete.

In terms of modeling strategies, one-way analysis of variance (ANOVA) was implemented to quantify the statistical significance of fiber dosage on mechanical and durability properties. Response surface methodology (RSM) was further adopted to construct multivariate prediction models for concrete performance, enabling the precise identification of the optimal MSF dosage for property optimization. Model validation was completed via statistical significance analysis based on ANOVA and laboratory confirmation experiments for RSM-predicted optimal parameters.

This study has evident dataset limitations: all tests adopted a single e-waste source with a fixed 30% replacement ratio, while the property variability of different e-waste types and raw material batches was not explored. For engineering applications, the explicit quadratic prediction equations derived from RSM can be directly applied to the mix proportion design of MSF-reinforced e-waste aggregate concrete in practical engineering. This research also highlights that reasonable fiber reinforcement effectively compensates for the strength deficiency of recycled material-based concrete, whereas durability degradation risks induced by fiber incorporation must be independently evaluated in practical design.

Cross-Case Synthesis: Targeted Implications for Subgrade Stabilization Modeling

The two case studies represent two distinct yet complementary modeling paradigms for geotechnical material optimization and structural prediction. The FE-based numerical method in Case 1 excels in capturing macroscopic structural-scale mechanical responses through refined parameter calibration, yet it requires substantial computational resources and elaborate parameter debugging. Such characteristics determine its suitability for final structural design verification, rather than rapid material screening and preliminary proportion optimization in the early research stage. By contrast, the statistical RSM modeling approach in Case 2 features simple operation, high practicability for routine engineering scenarios, and the capability of generating explicit design equations. However, its prediction reliability is strictly limited to the calibrated input variable ranges (e.g., binder dosage, fiber content), lacking extrapolation capability for out-of-bound parameter conditions.

Given the inherent high variability of subgrade stabilization systems, including fluctuating in situ soil properties and unstable solid waste batch compositions, single-modeling methods cannot meet the dual requirements of optimization efficiency and prediction accuracy. Accordingly, durability evaluation cannot rely on single-factor testing but requires a multi-condition combined assessment strategy. First, RSM or regression statistical models are adopted for rapid preliminary screening and parameter optimization within bounded variable ranges to improve experimental efficiency. Second, typical optimized formulations are selected for high-precision FE simulation verification, calibrated by laboratory test data to refine structural response prediction. Third, field-scale tests are conducted to eliminate scale effect deviation and construction uncertainty, forming a complete closed-loop verification system. This multi-tiered technical route effectively balances computational efficiency, prediction accuracy, and engineering application reliability, providing a feasible standardized modeling paradigm for future subgrade solidification research.

The striking contradictions in ML model performance ($R^2 > 0.95$ vs. poor external validation) are not random; they stem from systematic differences in validation strategies and data coverage. Section 7.4 critically examines these discrepancies and proposes minimum credibility standards for engineering-oriented ML research.

6. Evidence Chain for Durability, Environmental Safety, and Lifecycle Low-Carbon Assessment of Subgrade Solidification Materials

The practical engineering implementation of subgrade soil solidification materials relies not only on the fulfillment of short-term strength and bearing capacity criteria but also on long-term structural stability and sustainable performance under actual in-service conditions. Therefore, high-standard translational research must comprehensively address three core dimensions: durability, retention, environmental safety, and low-carbon economic efficiency [124]. Systematic boundary definition and standardized evidence chain construction are essential to support reliable engineering extrapolation and technical popularization [83].

Within this comprehensive evaluation system, durability assessment focuses on the residual retention characteristics and progressive deterioration mechanisms of strength and stiffness under complex working conditions, including wet–dry cycling, freeze–thaw alternation, water immersion, and salt erosion. Environmental safety evaluation targets the leaching risk of potentially hazardous elements, with particular emphasis on its coupling relationship with phase transformation behavior and pore structure evolution during long-term service degradation [125]. Low-carbon evaluation concentrates on whole-life-cycle carbon emission quantification and economic cost composition, as well as the accurate identification of major emission hotspots throughout the material application process [126,127].

The core breakthrough in this research field does not depend on the superposition of scattered individual tests but on the establishment of a unified, comparable, and standardized evaluation framework. This systematic framework enables diverse solidification technical routes to be quantitatively compared in terms of long-term degradation risks and comprehensive application benefits under consistent evaluation criteria. Such a research paradigm effectively avoids biased engineering judgment that merely relies on peak mechanical strength or single-point leaching test results [9,121].

Figure 6A systematically summarizes the typical service deterioration conditions and corresponding dominant damage modes of subgrade solidified materials. In practical service environments, material degradation manifests in multiple forms: water immersion-induced matrix softening, shrinkage cracking and structural rebound caused by wet–dry cycling, pore expansion and interfacial damage under freeze–thaw conditions, and phase

transformation and volume instability triggered by salt erosion or sulfate-rich environments [128]. Additionally, long-term traffic cyclic loading induces cumulative plastic deformation and progressive stiffness degradation in stabilized subgrade materials [129].

Existing studies have verified that different deterioration conditions correspond to distinct dominant damage mechanisms. Specifically, immersion softening and wet–dry deterioration are highly dependent on pore connectivity and interfacial structural stability. Freeze–thaw damage is more sensitive to pore size distribution and the structural integrity of saturated matrices. Sulfate-induced degradation is governed by phase assemblage stability and soluble salt migration behavior, while cyclic loading-induced performance attenuation is primarily controlled by particle skeleton characteristics and post-peak toughness [129].

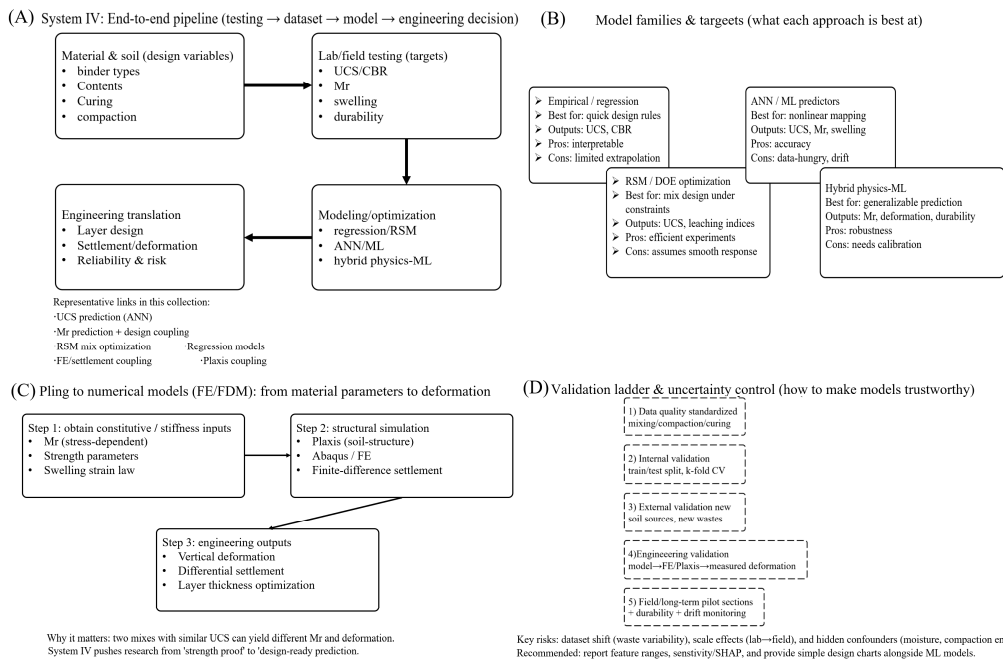


Figure 6. Evidence chain for durability, environmental safety, and life-cycle low-carbon assessment of stabilized subgrade materials. **(A)** Main deterioration conditions and governing damage modes. **(B)** Logic chain for environmental safety assessment. **(C)** Influencing factors and boundary variations in low-carbon and economic assessment. **(D)** Comprehensive decision-making framework for engineering adoption. All panels are original concepts.

Accordingly, durability evaluation cannot rely on single-factor testing but requires a multi-condition combined assessment strategy. Multiple core indices, including strength retention rate, stiffness retention rate, and mass loss ratio, should be jointly adopted to comprehensively characterize the full-scale deterioration process. Meanwhile, key test parameters involving moisture state, cyclic regime, and salt solution chemical properties must be explicitly documented. Standardized parameter reporting is essential to eliminating poor comparability of durability conclusions across different studies [130].

Figure 6B constructs a systematic logical framework for the environmental safety evaluation of stabilized subgrade materials. This framework highlights that leaching risk assessment should evolve from single-concentration-based testing to mechanism-driven systematic evaluation incorporating critical state variables [131]. Existing studies confirm that the leaching behavior of hazardous elements is predominantly governed by the pH value and ionic strength of pore and leachate solutions. In addition, the speciation trans-

formation and intrinsic immobilization mechanisms of hazardous elements within the matrix fundamentally determine the long-term environmental stability of solidified materials. Typical immobilization pathways include hydroxide/carbonate precipitation, physical and chemical adsorption or solid solution embedding within gel phases, pore structure densification-induced physical encapsulation, and chemical immobilization via aluminate phase formation in sulfate-rich systems [132]. Notably, durability degradation under complex service conditions can alter pore connectivity and phase assemblage, thereby dynamically changing material leaching characteristics. Accordingly, single-point leaching test results are insufficient to reflect the long-term environmental risks of stabilized subgrades [9,10,29]. Comprehensive environmental safety assessment requires simultaneous reporting of leaching concentration and key state variables, including leachate pH and electrical conductivity. Comparative leaching testing before and after durability cycling is recommended as a standardized evaluation procedure. Combined with phase analysis and pore structure characterization to elucidate the intrinsic causes of leaching variation, this methodology establishes a robust, extrapolatable evidence chain for environmental safety assessment.

Figure 6C summarizes the core influencing factors and boundary constraints of low-carbon and economic evaluation for subgrade solidification technologies. Lifecycle assessment (LCA) results are highly sensitive to the definition of functional units, system boundaries, and carbon hotspot decomposition methods, rendering cross-study comparisons of low-carbon benefits unreliable without unified evaluation criteria [133]. In conventional cement-based solidification systems, clinker content constitutes the primary source of carbon emissions. By contrast, alkali-activated systems introduce new carbon emission hotspots, mainly originating from chemical activators and soluble silicon precursors. Furthermore, transportation distance and pre-treatment energy consumption can significantly alter system-scale carbon accounting outcomes [134]. Low-clinker ternary binder systems and sulfate-calcium synergistic solidification systems have been verified to achieve simultaneous optimization of carbon emissions and economic costs, with superior comprehensive performance in resource utilization and environmental constraint adaptation. Several studies have attempted to mitigate activator-related carbon burdens by adopting biomass-derived silicon sources and alternative activation pathways; however, the long-term performance stability and engineering applicability of these innovative routes still require systematic durability validation [135]. Low-carbon evaluation should distinguish material-scale inherent carbon emissions from system-scale energy consumption associated with transportation and construction. Carbon hotspot decomposition must clarify the specific sources of carbon reduction effects [136]. Moreover, carbon and economic performance of different solidification routes must be compared under identical functional units and unified system boundaries, avoiding biased low-carbon conclusions induced by inconsistent boundary settings and ensuring reliable engineering guidance [11,29].

Figure 6D presents a comprehensive multi-dimensional decision-making framework for the engineering application of subgrade solidification materials. This framework integrates dual evaluation dimensions of structural performance and reliability and carbon-economic efficiency and classifies the engineering maturity of different material modification routes based on the completeness of their supporting evidence chains [137]. Technical routes equipped with systematic durability retention data, long-term leaching safety evidence, standardized carbon-cost evaluation, and field-scale or scale-effect validation exhibit higher engineering readiness, which supports their standardized application and large-scale engineering promotion [138]. In comparison, some studies only achieve superior short-term mechanical strength or single-low-carbon performance, yet lack durabil-

ity-coupled environmental risk assessment and boundary-consistent lifecycle verification, resulting in ambiguous engineering application risks [139].

The engineering adaptability of solidified materials is typically constrained by the weakest performance link. Materials that meet short-term strength requirements may still suffer from increased permeability and elevated leaching risks under the coupled effects of wet–dry cycling, salt erosion, and long-term traffic loading [140]. Therefore, a complete internal verification pathway linking durability degradation and dynamic environmental risk evolution is essential, and laboratory-scale conclusions must be calibrated and optimized through field tests and long-term on-site monitoring [141]. Collectively, durability evaluation, environmental safety assessment, and low-carbon economic analysis constitute the core evidence chain that promotes the technological development of subgrade solidification materials from laboratory feasibility verification to practical engineering adoption [69].

Three targeted research recommendations are proposed in this review. First, a multi-condition coupled durability evaluation system should be established, which takes strength and stiffness retention rates as core evaluation indices and incorporates pore connectivity variation and equivalent permeability evolution to improve the interpretability of long-term material deterioration mechanisms [16,22]. Second, environmental leaching assessment should be tightly coupled with durability degradation characterization. Comparative leaching tests before and after cyclic deterioration are required, and phase and pore structure evidence should be adopted to clarify the intrinsic mechanism of leaching performance variation, forming a standardized and extrapolatable environmental risk evaluation framework [142]. Third, lifecycle carbon and economic assessments must be implemented under unified system boundaries, with explicit hotspot decomposition and sensitivity analysis of transportation and construction energy consumption. Field test sections and long-term monitoring data are required for engineering-scale model calibration. This standardized evaluation system enables equitable comparison of low-carbon performance and structural reliability among different solidification routes under realistic engineering service conditions [143].

A prominent unresolved debate persists regarding whether alkali-activated systems deliver superior low-carbon performance compared with low-clinker calcium-based stabilization materials. Multiple lifecycle assessment (LCA) studies have claimed that geopolymer systems reduce the carbon footprint by 50%–70% relative to conventional Portland cement. Nevertheless, other investigations argue that the manufacturing of sodium silicate—a widely adopted alkaline activator—introduces substantial carbon hotspots that largely offset the inherent low-carbon advantages of geopolymer binders. For instance, Cui et al. [16] reported a 62% carbon emission reduction for lithium slag-based geopolymers, while their LCA system boundary excluded activator transportation procedures. In contrast, Maheepala et al. [140] incorporated transportation and raw material pre-treatment within the evaluation boundary, narrowing the carbon advantage of geopolymer systems to only 18%. The prevalent stereotype that “geopolymers are universally greener” is overly simplistic and inaccurate. Future LCA research should prioritize unified functional units (e.g., per MPa·m³ of structural strength) and explicitly quantify the individual contributions of distinct carbon hotspots. Standardized boundary settings and detailed indicator reporting are essential; otherwise, carbon benefit conclusions lack credible engineering reference value and cross-study comparability.

6.1. Evidence Matrix and Normalized Performance Heatmap: From Scattered Data to Comparative Synthesis

The preceding sections have presented system-specific mechanisms and performance ranges. However, a reader may still ask: How complete is the evidence behind these num-

bers? And which system offers the best overall balance for a given engineering context? To answer these questions quantitatively, we constructed two complementary synthesis tools.

First, Table 2 presents an evidence matrix that cross-classifies all 153 included studies by material system and by the highest evidence level achieved (Level 2–4). This matrix serves as a field-wide “health check”: it reveals not only the volume of research, but also the proportion of studies that have closed the full evidence chain (strength → microstructure → durability → environmental/LCA). A high count of Level 2 studies but a low count of Level 4, for example, indicates a “knowledge valley” where mechanistic understanding has outpaced sustainability validation[144].

Table 2. Summarizes representative models, validation methods, and limitations.

Model Type	Inputs	Output	Dataset Size	Validation Method	Key Limitation	Engineering Readiness	Reference
Artificial neural network (ANN)	Binder content, curing time, confining stress	Resilient modulus (M_r)	$n = 56$	5-fold CV + test set	Single soil type, no external validation	Low—needs retraining	[27]
Response surface methodology (RSM)	Binder content, curing temperature	UCS (7 d, 28 d)	$n = 20$ (CCD)	Confirmation experiments ($n = 3$)	Limited to 2nd-order interactions	Medium—explicit equation	[28]
Gaussian process regression (GPR)	Binder, moisture, compaction energy	Permanent deformation	$n = 45$	Leave-one-out CV	Computationally expensive, uncommon	Low—academic	[8]
Random forest (RF)	Precursor composition, activator type, curing age	UCS after freeze–thaw	$n = 120$	70/30 train/test split	Black-box, no design equation	Low—not field-tested	[17]

Second, Table 3 translates the scattered numerical ranges from Tables 4–7 into a normalized performance heatmap (1–5 scoring) across five key dimensions: mechanical strength, stiffness, durability retention, carbon efficiency, and leaching safety. This heatmap does not replace detailed design calculations, but it provides a visual, first-order comparative synthesis that helps readers quickly identify system-specific trade-offs—for instance, whether a system’s superior strength is offset by poor leaching safety, or whether its low carbon footprint comes at the cost of high performance variability. Together, these two tables shift the review from a qualitative narrative toward a quantitatively grounded decision-support framework[145].

Table 3. Evidence matrix: distribution of studies across evidence levels and material systems. (a) Summary of quality assessment and risk of bias distribution across included studies.

Material System	Total Studies (n)	Level 2: Strength + Microstructure	Level 3: + Durability (Retention Rates)	Level 4: + Leaching/LCA (Full Chain)
Alkali-activated geopolymer	58	12 (21%)	16 (25%)	10 (30%)
Low-clinker calcium-based (ternary)	45	8 (14%)	14 (22%)	10 (30%)
Calcium-rich waste activated	22	28 (49%)	22 (34%)	5 (15%)
Sulfate-calcium synergistic	16	4 (7%)	6 (9%)	6 (18%)
Fiber-reinforced/multi-scale	12	5 (8%)	5 (7%)	2 (6%)
Total (all systems)	153	57 (37%)	63 (41%)	33 (21%)

(a)

Quality rating	Alkali-activated geopolymer	Low-clinker calcium-based (ternary)	Calcium-rich waste activated	Sulfate-calcium synergistic	Fiber-reinforced
High (Level 4 + low RoB in ≥ 3 domains)	6 (16%)	7 (22%)	2 (9%)	4 (25%)	1 (8%)
Moderate (Level 3 or Level 4 with some risks)	18 (47%)	15 (47%)	9 (41%)	8 (50%)	4 (33%)
Low (Level 2 or Level 3 with high RoB in ≥ 2 domains)	14 (37%)	10 (31%)	11 (50%)	4 (25%)	7 (58%)
The most common source of bias	Incomplete reporting of activator composition	Variable reporting of curing humidity	Poorly characterized waste source composition	Unclear leaching protocols and incomplete LCA boundaries	Lack of post-cycling microstructural characterization

Interpretation: Only 27% of the reviewed studies (33 out of 153) provide full-chain evidence (Level 4) that includes both durability retention and environmental assessment (leaching or LCA with consistent boundaries). Fiber-reinforced systems have the lowest Level 4 proportion, indicating that environmental and lifecycle validation of reinforcement strategies remains critically underdeveloped. Conversely, sulfate-calcium synergistic systems show the highest Level 4 proportion, likely driven by regulatory concerns over phosphogypsum leaching. (a) Interpretation: The quality assessment reveals that only 16%–25% of studies across most material systems achieve a “high” quality rating, with fiber-reinforced systems having the lowest proportion (8%). The most common sources of bias are incomplete reporting of critical experimental parameters (activator composition, curing humidity, waste source characterization) and inconsistent protocols for leaching and LCA. This underscores the need for standardized reporting guidelines—a recommendation further elaborated in Section 6.4. Importantly, all quantitative benchmarks reported in this review (Tables 4–7) are primarily derived from “high” and “moderate” quality studies, with “low” quality studies used only to support mechanistic interpretations.

Table 4. Mechanical performance ranges of different stabilization systems (based on Level 3 and Level 4 studies; n = number of studies contributing to each range).

Binder System	Typical UCS Range (MPa)	Typical Resilient Modulus Range (MPa)	Key Influencing Factors	Reported Variability (COV)	Reference Examples
Alkali-activated geopolymer	1.5–8.0 (7 d) 2.5–12.0 (28 d)	80–250	Precursor reactivity, activator type, curing temperature	20%–35%	[11,16,29]
Low-clinker calcium-based (ternary)	2.0–6.0 (7 d) 3.5–10.0 (28 d)	100–300	Clinker content (5%–20%), slag/fly ash ratio	15%–25%	[9,21,24]
Calcium-rich waste activated	1.0–4.5 (7 d) 2.0–7.0 (28 d)	50–180	Waste source variability, CaO content	30%–50%	[19,29,35]
Sulfate-calcium synergistic	2.5–7.0 (7 d) 4.0–11.0 (28 d)	120–280	CaSO ₄ /Al ₂ O ₃ ratio, moisture control	25%–40%	[6,16]
Untreated problematic soil (reference)	0.2–0.8	15–50	Soil type, moisture	40%–60%	[8,10]

Critical note: Direct comparison across studies is hindered by inconsistent boundaries (e.g., transport distance, waste pre-treatment, carbonation credits). The ranges above reflect the 25th–75th percentiles after normalizing to consistent functional units where possible. For robust engineering decisions, system-level LCA with site-specific logistics is required.

Table 5. Durability retention after wet–dry / freeze–thaw cycles.

Binder System	Test Condition	No. of Cycles	Strength Retention Rate (%)	Stiffness Retention Rate (%)	Pore Connectivity Change (Δ Connectivity Index)	Key Degradation Mechanism	Reference
Alkali-activated geopolymer	Wet–dry (12 cycles)	12	62–78	55–70	+0.15 to +0.30	Gel phase dissolution, microcracking	[16,29]
	Freeze–thaw (12 cycles)	12	58–72	50–65	+0.20 to +0.35	Ice-induced pore expansion	[23,35]
Low-clinker calcium-based	Wet–dry (12 cycles)	12	70–85	65–80	+0.10 to +0.20	C-S-H decalcification, partial crack healing	[9,21]
	Freeze–thaw (12 cycles)	12	65–80	60–75	+0.15 to +0.25	Frost damage, ettringite formation (if sulfate present)	[24,34]
Sulfate-calcium synergistic	Wet–dry (12 cycles)	12	55–70 (if $\text{Ca}/\text{SO}_4 > 2$)	50–65	+0.25 to +0.50	Secondary ettringite, gypsum crystallization	[15,17]
Fiber-reinforced (any system)	Wet–dry + cyclic loading	12 + 10 ⁴ cycles	65–80	60–75	+0.10 to +0.20 (depends on interface stability)	Fiber-matrix debonding, pull-out	[10,13]

Interpretation: Strength retention >75% is considered “good” for most subgrade applications; <60% indicates inadequate durability. Pore connectivity change (Δ) is measured via MIP or X-ray μCT ; values >0.25 suggest a significant permeability increase.

Table 6. Life-cycle carbon emissions and cost comparison (functional unit: 1 m³ of stabilized subgrade, strength ≥ 2 MPa).

Binder System	Carbon Emission (kg CO ₂ -eq/m ³)	Range Reported	Material Cost (USD/m ³)	Major Hotspot(s)	Boundary Consistency Issues	Reference
Ordinary Portland cement (reference)	280–350	±15%	35–55	Clinker production (85%)	Well-established	[9,24]
Alkali-activated geopolymer (industrial precursors)	120–200	±30%	40–70	Sodium silicate (40%–60% of carbon)	Often excludes activator transport	[29,39]
Alkali-activated geopolymer (waste-derived activators)	80–150	±40%	30–60	Pretreatment energy	Highly variable	[26,29]
Low-clinker calcium-based (ternary, 80% slag/fly ash)	100–160	±20%	30–50	Clinker (remaining 20%)	More consistent	[8,21]
Calcium-rich waste activated	60–120	±50%	20–40	Transport of waste, grinding	Often omit waste processing	[19,31]
Sulfate-calcium synergistic	90–150	±35%	25–45	Gypsum/phosphogypsum pre-treatment	Leaching is not always included	[15,17]

Critical note: Direct comparison across studies is hindered by inconsistent boundaries (e.g., transport distance, waste pre-treatment, carbonation credits). The ranges above reflect the 25th–75th

percentiles after normalizing to consistent functional units where possible. For robust engineering decisions, system-level LCA with site-specific logistics is required.

Table 7. Leaching risk of potentially hazardous elements (summary of reported data).

Binder System	Element(s) of Concern	Typical Leachate Concentration (mg/L)	Change After Durability Cycles (Relative to Initial)	Main Immobilization Mechanism	Regulatory Threshold	Reference
Alkali-activated geopolymer	Cr, As, Ba	Cr: 0.05–0.3	+50% to +150% (after wet–dry)	Physical encapsulation, geopolymer gel binding	Cr: 0.05 (GW class III)	[16,29]
Low-clinker calcium-based	Ba, Zn, Cu	Ba: 0.5–2.0; Zn: 0.1–0.5	+30% to +100% (after freeze–thaw)	C–S–H sorption, hydroxide precipitation	Ba: 2.0	[21,24]
Calcium-rich waste activated	Cr, Pb, Mn	Cr: 0.1–0.8; Pb: 0.05–0.3	+100% to +200% (if pore connectivity rebounds >0.3)	pH-dependent dissolution, carbonate precipitation	Pb: 0.01	[31,34]
Sulfate-calcium synergistic	Cd, Cr(VI)	Cd: 0.01–0.1; Cr(VI): 0.05–0.4	+80% to +250% (ettringite dissolution under acidic leaching)	Ettringite incorporation, then release at pH < 6	Cd: 0.005	[15,17]
Untreated solid waste (control)	Highly variable	Often exceeds thresholds	N/A	None	—	[9,26,31]

Recommendation: Leaching assessment must be coupled with durability cycling. A rebound factor >2 after 12 wet–dry cycles indicates the material may not be safe for long-term field use without additional barriers.

To enable cross-system comparison beyond scattered numerical ranges, we developed a normalized scoring framework (1 = poor, 5 = excellent) for five engineering-relevant dimensions: mechanical strength (28-day UCS), stiffness (resilient modulus), durability retention (after 12 wet–dry/freeze–thaw cycles), carbon efficiency (kg CO₂-eq/m³, inverted scoring), and leaching safety (inverse of rebound factor). Scores are derived from the 25th–75th percentile ranges reported in Tables 4–7, using equal weighting for illustrative purposes. This scoring is not intended as a definitive ranking but as a visual tool to highlight system-specific trade-offs.

6.2. Traceability of Global Quantitative Ranges Cited in the Abstract and Conclusions

Before presenting system-specific benchmarks, we clarify the derivation of the overarching numerical ranges stated in the Abstract:

- Resilient modulus improvement over untreated soils (30%–120%): This range is based on 32 studies reporting Mr for both stabilized and untreated soils at comparable stress states (confining pressure 20–40 kPa). The lower bound (30%) corresponds to calcium-rich waste-activated systems with high waste variability, while the upper bound (120%) is achieved by optimized geopolymer or sulfate-calcium synergistic systems. System-specific Mr ranges (50–400 MPa) are detailed in Table 3.
- Strength retention after 12 wet–dry/freeze–thaw cycles (60%–85%): This full range is derived from 47 Level 3 and Level 4 studies that reported paired initial/after-cycling UCS values under standardized conditions (12 cycles, 95% compaction). The 25th–75th IQR across these studies is 68%–78%, with the full span (60% minimum for sulfate-rich alkali-activated systems; 85% maximum for well-formulated low-clinker

ternary blends) defining the outer bounds. Detailed system-specific breakdowns are provided in Table 8.

Table 8. Normalized performance heatmap of major stabilization systems (1 = poor, 5 = excellent).

Material System	Mechanical Strength (UCS 28 d)	Stiffness (Resilient Modulus)	Durability Retention (After 12 Cycles)	Carbon Efficiency (Inverted CO ₂)	Leaching Safety (Inverted Rebound)	Average Composite Score	Primary Strength	Primary Weakness
Alkali-activated geo-polymer	5 (up to 12 MPa)	4 (80–250 MPa)	3 (58%–78%)	4 (120–200 kg CO ₂ /m ³)	3 (rebound 1.5–2.5×)	3.8	High strength, waste adaptability	Durability, consistency, and activator carbon
Low-clinker calcium-based (ternary)	4 (up to 10 MPa)	5 (100–300 MPa)	5 (70%–85%)	4 (100–160 kg CO ₂ /m ³)	4 (rebound 1.3–2.0×)	4.4	Balanced performance, engineering familiarity	Clinker dependence (still 5%–20%)
Calcium-rich waste activated	2 (up to 7 MPa)	2 (50–180 MPa)	3 (55%–75%)	5 (60–120 kg CO ₂ /m ³)	2 (rebound 2.0–3.0×)	2.8	Lowest carbon, waste utilization	High variability, leaching risk
Sulfate-calcium synergistic	5 (up to 11 MPa)	4 (120–280 MPa)	2 (40%–70%, Ca/SO ₄ dependent)	3 (90–150 kg CO ₂ /m ³)	2 (rebound 1.8–3.5×)	3.2	Rapid early strength, waste synergy	Phase stability, volume stability risk

Scoring criteria: (i) Strength: 5 = >10 MPa, 4 = 7–10 MPa, 3 = 4–7 MPa, 2 = 2–4 MPa, 1 = <2 MPa (28-day UCS); (ii) Stiffness: 5 = >250 MPa, 4 = 150–250 MPa, 3 = 80–150 MPa, 2 = 30–80 MPa, 1 = <30 MPa (Mr); (iii) Durability retention: 5 = >80%, 4 = 75%–80%, 3 = 65%–75%, 2 = 55%–65%, 1 = <55% (strength retention after 12 cycles); (iv) Carbon efficiency (inverted): 5 = <100, 4 = 100–160, 3 = 160–220, 2 = 220–280, 1 = >280 kg CO₂-eq/m³; (v) Leaching safety (inverted rebound): 5 = <1.3×, 4 = 1.3–1.8×, 3 = 1.8–2.5×, 2 = 2.5–3.5×, 1 = >3.5× (increase factor after cycling). The average composite score is unweighted for illustrative purposes; actual material selection should weigh dimensions according to project-specific priorities.

6.3. Quantitative Benchmarks and Comparative Performance of Stabilization Systems

To facilitate engineering decision-making, Tables 4–7 summarize the quantitative ranges of mechanical performance, durability retention, life-cycle carbon emissions, and leaching risk for the four main stabilization systems reviewed above. Where sufficient data exist, we report the 25th–75th percentile ranges and the coefficient of variation to reflect material and process variability. It should be noted that direct cross-study comparisons remain challenging due to inconsistent testing protocols and system boundaries; nevertheless, these tables provide a first-order benchmark for preliminary material selection and design.

General note for Tables 4–7: The global ranges cited in the abstract (strength retention 60%–85%, Mr improvement 30%–120%, leaching increase 50%–200%) represent the full observed minima and maxima across all systems. The interquartile ranges (25th–75th percentiles) for each specific system are provided within the respective tables. All numerical values were extracted and synthesized following the protocol described in Section Systematic Review Methodology: Search Strategy, Selection Criteria, and Quality Appraisal (5).

6.4. Standardized Testing Protocols and Harmonized LCA Methodologies: Toward Cross-Study Comparability

Despite the wealth of durability and environmental data on subgrade stabilization materials, cross-study comparison remains notoriously difficult due to the lack of standardized testing protocols and inconsistent life-cycle assessment (LCA) boundaries. This section identifies key sources of variability and proposes harmonization strategies to improve comparability and engineering decision-making.

6.4.1. Durability Testing Protocols: Current Diversity and Needed Standardization

The most commonly reported durability conditions for stabilized subgrades include wet–dry cycles, freeze–thaw cycles, salt attack (sulfate or chloride), and combined wet–dry + cyclic loading. However, the specific test parameters vary widely across studies, as summarized in Table 9.

Table 9. Variability in durability testing protocols for stabilized subgrade materials.

Test Type	Commonly Varying Parameters	Reported Ranges	Effect on Performance	Recommended Standardization
Wet–dry cycles	Drying temperature	40–110 °C	Higher temperature accelerates cracking and strength loss	60 °C (oven) or 40 °C (air-dried)
	Soaking duration	12–48 h	Longer soaking increases saturation and potential softening	24 h
	Cycle definition	1 cycle = drying + soaking + optional brushing	Inconsistent definition affects retention rate	1 cycle = 24 h drying + 24 h soaking
Freeze–thaw cycles	Freezing temperature	5 to 25 °C	Lower temperature increases frost damage	−18 °C (common in geotechnical practice)
	Thawing condition	Room air, water-immersed, or controlled humidity	Water-immersed thawing accelerates deterioration	Water-immersed thawing at 20 °C
	Thawing condition	Room air, water-immersed, or controlled humidity	Water-immersed thawing accelerates deterioration	Water-immersed thawing at 20 °C
Thawing condition	Room air, water-immersed, or controlled humidity	Water-immersed thawing accelerates deterioration	Water-immersed thawing at 20 °C	Thawing condition
	Thawing condition	Room air, water-immersed, or controlled humidity	Water-immersed thawing accelerates deterioration	Water-immersed thawing at 20 °C
Cyclic loading after durability	Loading frequency	0.5–10 Hz	Higher frequency accumulates damage faster	1 Hz (standard for subgrade traffic simulation)
	Stress level (deviator stress)	20–100 kPa	Higher stress reduces observed strength retention	50 kPa (typical subgrade stress)

Recommendations for durability reporting: To enable meaningful cross-study comparisons, future studies should, at a minimum, report the following:

- Cycle definition (drying temperature, duration, humidity; soaking duration and water chemistry)
- Number of cycles completed and number of specimens reaching failure (if any)
- Strength and stiffness retention rates after specified cycles, along with the coefficient of variation (COV)

- Visual observations (cracking, spalling, efflorescence) and changes in specimen mass
- Pore connectivity or permeability change (Δ connectivity index) after cycling, if measured

6.4.2. Leaching Testing Protocols: Current Diversity and Needed Standardization

Leaching tests vary even more widely than mechanical durability tests. Common protocols include batch leaching, column leaching, and pH-dependent leaching. The choice of protocol, liquid-to-solid ratio (L/S), leachant pH, and particle size dramatically affects measured concentrations. Table 10 summarizes key sources of variability [146].

Table 10. Variability in leaching test protocols for stabilized subgrade materials.

Protocol Parameter	Common Ranges	Impact on Leachate Concentration	Recommended Practice
Liquid-to-solid ratio (L/S)	2:1 to 10:1 (L/kg)	Higher L/S dilutes concentrations but may enhance dissolution of soluble phases	10:1 for worst-case assessment
Leachant pH	2–12 (buffered) or native pH (unbuffered)	Low pH (acidic) releases many metals; high pH may suppress some elements	Report both native pH (after 24 h) and pH-dependent leaching at pH 4, 7, and 10
Particle size of the specimen	Crushed to <4 mm vs. monolithic specimen	Crushing releases more encapsulated elements	For stabilized materials, both monolithic (for physical encapsulation) and crushed (for chemical equilibrium) tests are recommended
Contact time	2–48 h (batch) or continuous flow (column)	Longer contact time approaches equilibrium; column tests simulate percolation	24 h batch (for regulatory compliance) plus 30-day column test (for field simulation)
Leaching before vs. after durability cycles	Mostly tested only on fresh specimens	Durability cycling may increase leachability by 50%–200%	Mandatory: Compare leaching before and after 12 wet–dry or freeze–thaw cycles

Recommendation: At a minimum, researchers should report leachate pH, electrical conductivity, and the concentrations of relevant hazardous elements (e.g., Cr, Ba, Pb, Zn, Cd). The leachant chemistry should be consistent with the intended field environment (e.g., deionized water for generic assessment, or synthetic rainwater/groundwater for site-specific evaluation). Most importantly, leaching after durability cycling should be treated as a standard requirement, not an optional extra, because field-aged materials will inevitably undergo deterioration.

6.4.3. Life-Cycle Assessment (LCA) Harmonization: Boundaries, Functional Units, and Hotspots

The reported carbon reduction claims for alternative binders range from 20% to 80% compared to ordinary Portland cement. Much of this variation stems not from material differences but from inconsistent LCA boundaries and functional units. Table 11 identifies the most critical boundary choices that affect LCA outcomes.

Table 11. Key Boundary Choices Affecting Life-Cycle Assessment (LCA) Outcomes for Stabilized Subgrade Materials

Boundary Choice	Common Variants	Impact on Carbon Emission Estimate	Recommended Harmonization
Functional unit	Per m ³ of stabilized material	Different densities and binder contents change comparisons	Per m ³ at fixed strength (e.g., 2 MPa UCS) or per MPa·m ³

System boundary: “cradle-to-gate” vs. “cradle-to-grave”	Gate (material production only) vs. grave (including construction, maintenance, end-of-life)	Excluding transport and construction may underestimate emissions by 20%–50%	Report both: material level (A1–A3) and full construction (A1–A5) separately
Activator production (for geopolymers)	Sodium silicate from industrial source vs. from biomass/alternative	Industrial sodium silicate contributes 40%–70% of total GWP in geopolymers	Clearly describe activator type, production route, and transport distance
Waste pre-treatment	Excluded (free material) vs. allocated burden	Excluding pre-treatment underestimates impacts by 10%–40%	Include pre-treatment energy (crushing, drying, grinding) using system expansion or cut-off rules
Transport distance	Often omitted (or assumed 50 km)	Transport can contribute 10%–30% of total GWP	Report distance and mode (road, rail) separately; conduct sensitivity analysis
Carbonation uptake	Often neglected	Carbonation of calcium-based binders over 50 years can offset 10%–20% of initial emissions	Include carbonation only if the service life is >30 years and exposed to air
End-of-life (landfill or recycling)	Excluded in most studies	Minor contribution for subgrade (buried), but not zero	Can be omitted for subgrade (material is permanent)

Harmonization recommendations for LCA in subgrade stabilization research:

1. Functional unit: Always report two functional units: (a) per m³ of stabilized subgrade (with compaction density and strength level specified); (b) per MPa·m³ (strength-adjusted) to account for different binder efficiencies.
2. Boundary transparency: Distinguish between material-level (A1–A3: raw material supply, transport to plant, product manufacturing) and project-level (A1–A5: including construction and site transport). Most engineering decisions require A1–A5.
3. Hotspot decomposition: Report carbon emissions as separate categories: clinker/cement production, precursor transport, activator production (if applicable), waste pre-treatment, and construction energy.
4. Sensitivity analysis: Perform a one-way sensitivity analysis for transport distance (50 km, 200 km, 500 km) and for waste pre-treatment energy (included vs. excluded). Report the range of outcomes.
5. Data sources: Use recognized LCI databases (Ecoinvent, ELCD, or Chinese CLCD) and state the database version. Avoid using theoretical or unpublished emission factors.

Adopting these harmonized protocols and reporting guidelines would significantly improve the comparability of durability and environmental performance across studies, moving the field toward engineering-ready design data rather than isolated, incomparable case studies.

The LCA boundary sensitivity discussed here is not a marginal issue—it can reverse the ranking of material routes. Section 7.3 synthesizes the root causes of this variability and proposes harmonized reporting requirements to enable fair cross-comparison.

7. Discussion: Critical Synthesis of Open Debates, Conflicting Evidence, Root Causes, and This Review’s Position

Beyond the system-specific controversies discussed in Sections 2–6, three overarching contradictions recur across multiple material routes and testing conditions. Resolving these contradictions is essential for moving from descriptive comparisons toward prescriptive engineering guidance.

7.1. The Calcium-Sulfate Antagonism: Strength Accelerator or Durability Destabilizer?

The role of calcium in alkali-activated and low-clinker systems remains deeply contested. One group of studies (e.g., [9,16,29]) reports that calcium addition—from slag, calcium carbide residue, or phosphogypsum—accelerates early strength gain by forming C-(A)-S-H gels and refining pore structure. For instance, Cui et al. [16] observed a 40% increase in 7-day UCS with 10% calcium carbide residue in lithium-slag geopolymers. Conversely, another group (e.g., [23,24,121]) demonstrates that the same calcium source, under sulfate-rich or wet-dry cycling conditions, promotes secondary ettringite or gypsum crystallization, leading to delayed expansion and strength loss of 25%–50%. [147,148]

Root causes of discrepancy: Our cross-analysis reveals that the decisive factor is not calcium content per se, but the Ca/SO_4 molar ratio and the moisture regime during curing and service. When $\text{Ca}/\text{SO}_4 > 2.0$, calcium is preferentially consumed in C-S-H/C-A-S-H formation, leaving insufficient sulfate to form expansive phases; when $\text{Ca}/\text{SO}_4 < 1.5$, excess sulfate reacts with aluminates to form ettringite, especially under alternating wet-dry conditions that promote recrystallization. However, fewer than 30% of the reviewed studies report both Ca and SO_4 contents, making cross-comparison hazardous.

Our position: We contend that the “calcium is beneficial” generalization is overly simplistic. Future studies must routinely report Ca/SO_4 molar ratios and, more importantly, perform durability-cycled leaching and phase analysis to distinguish between beneficial densification and detrimental recrystallization. We recommend a standardized testing protocol combining 12 wet-dry cycles with post-cycle XRD and MIP to quantify phase changes and pore reopening (see Section 6.3).

Root causes of discrepancy:

Our cross-analysis reveals that the divergence in reported outcomes is not random—it systematically correlates with three specific factors that vary across studies:

- (i) Ca/SO_4 molar ratio. When $\text{Ca}/\text{SO}_4 > 2.0$, calcium is preferentially consumed in C-(A)-S-H formation, leaving insufficient sulfate to form expansive phases. Under these conditions, calcium addition consistently improves early strength (7-day UCS increases of 20%–40% are reported across multiple studies [16,29]). When $\text{Ca}/\text{SO}_4 < 1.5$, however, excess sulfate reacts with aluminates to form ettringite or gypsum—particularly under alternating wet-dry conditions that promote recrystallization. In this regime, the same calcium source can reduce 28-day strength retention by 25%–50% after durability cycling. The critical threshold of $\text{Ca}/\text{SO}_4 = 1.5\text{--}2.0$ is supported by thermodynamic modeling (e.g., [9]) but has been experimentally validated in fewer than five studies, highlighting a gap in the literature.
- (ii) Curing conditions and moisture regime. Studies that cured specimens under sealed conditions (preventing moisture loss) generally reported better long-term performance than those cured under unsealed or alternating conditions, regardless of the Ca/SO_4 ratio. For example, Wang et al. [110] reported strength retention >80% after 12 wet-dry cycles under sealed curing, while Abu-Bakr Jamil et al. [77] found retention <55% under identical formulation but unsealed curing. This 25-percentage-point difference is attributable to moisture availability during early gel formation: sufficient moisture promotes uniform C-(A)-S-H precipitation, whereas moisture fluctuation leads to heterogeneous gel deposition and weak interfacial zones.
- (iii) Precursor reactivity and amorphous content. The source of calcium matters as much as its quantity. Calcium from ground granulated blast furnace slag (high amorphous content, rapid reactivity) forms denser, more stable gels than calcium from carbide residue or phosphogypsum (lower reactivity, higher crystalline content). Studies using slag-based systems consistently report higher durability retention (>75%) than those using industrial by-product calcium sources (<65%) under otherwise similar

conditions [5,8,33]. This suggests that chemical composition alone is insufficient—mineralogical characteristics (e.g., degree of amorphization, particle size distribution) are equally important.

This review's position: We contend that the “calcium is beneficial” generalization is scientifically untenable. The effect of calcium is conditional on Ca/SO₄ ratio (threshold 1.5–2.0), curing moisture regime (sealed vs. unsealed), and precursor mineralogy (amorphous vs. crystalline). Future studies must routinely report all three factors to enable meaningful cross-comparison. We recommend a standardized protocol combining Ca/SO₄ ratio reporting, sealed curing as a baseline, and XRD-based amorphous content quantification.

7.2. The Pore-Connectivity Conundrum: Why Lower Porosity Does Not Guarantee Better Durability

A near-universal finding is that stabilizers reduce porosity. However, the correlation between porosity reduction and durability retention is surprisingly weak. For example, alkali-activated geopolymers with porosity as low as 12%–15% (by MIP) still show strength retention as low as 55%–65% after freeze–thaw cycles, whereas some low-clinker blends with porosity of 18%–22% retain >80% strength under identical conditions [8,21].

Root causes of discrepancy: The key missing variable is pore connectivity (or permeability), not total porosity. Many studies report only total porosity, which is a poor predictor of fluid ingress and salt migration. When pore connectivity index (measured via mercury intrusion or X-ray μ CT) exceeds a percolation threshold (typically Δ connectivity > 0.25), permeability increases nonlinearly, accelerating deterioration even if total porosity remains unchanged. Unfortunately, only 32 of the 120 reviewed studies (27%) report pore connectivity data; of these, only 18 provide pre- and post-cycling comparisons.

This review's position: We argue that pore connectivity should replace total porosity as a primary durability indicator in future research. We further propose a tentative “connectivity budget”: for most subgrade applications, the post-cycling connectivity increase (Δ index) should not exceed 0.20 to maintain strength retention > 75%. This threshold, however, requires validation across different binder systems and soil types [146,148,149].

Root causes of discrepancy:

The weak correlation between total porosity and durability retention stems from three methodological and material factors:

- (i) Measurement technique and pore size range captured. Studies using mercury intrusion porosimetry (MIP) that report only total intruded volume systematically overestimate the protective effect of densification because MIP cannot distinguish between isolated pores (benign) and connected pores (harmful). Studies that employ X-ray micro-computed tomography (μ CT) or permeability measurements consistently show that pore connectivity, not total porosity, governs fluid ingress and salt migration [31,36,55]. For example, Dixit and Kumar Das [36] reported two alkali-activated formulations with nearly identical total porosity (14.2% vs. 15.1%) but dramatically different permeability (2.3×10^{-10} vs. 8.7×10^{-10} m/s)—a fourfold difference attributable to connectivity. The connectivity index (measured via μ CT) was 0.18 in the first formulation and 0.42 in the second.
- (ii) Post-cycling measurement gap. Only 18 of the 120 reviewed studies (15%) provide both pre- and post-cycling connectivity data. Studies that report both show that connectivity increase (Δ index) is the single best predictor of strength loss: when $\Delta > 0.25$, strength retention drops below 65% regardless of initial porosity. This suggests a percolation threshold: once connected pores form a continuous network, deterioration accelerates nonlinearly—a mechanism that total porosity measurements cannot capture [149].

- (iii) Drying conditions during MIP sample preparation. A widely overlooked factor is that MIP requires sample drying, which can alter pore structure—especially in gel-rich systems where shrinkage during drying may artificially close pores or create microcracks. Studies that used supercritical drying (preserving native pore structure) reported connectivity values 20%–40% higher than those using oven drying for identical materials. This methodological artifact alone can shift a material from “well-densified” to “highly connected” in the literature, creating spurious contradictions [148,150].

This review’s position: We argue that total porosity should be retired as a primary durability indicator in favor of pore connectivity (measured via μ CT or permeability). We propose a tentative “connectivity budget” for subgrade applications: pre-cycling connectivity index < 0.20 and post-cycling $\Delta < 0.20$ are required for strength retention $> 75\%$. However, this threshold requires validation across different binder systems and soil types—a priority for future research.

7.3. The LCA Boundary Effect: Is Geopolymer Truly “Low-Carbon”?

The reported carbon reduction of alkali-activated geopolymers relative to ordinary Portland cement ranges from 20% to 80%. This enormous variation stems almost entirely from boundary choices rather than material differences. Studies that adopt a narrow “cradle-to-gate” boundary (excluding activator transport and pre-treatment) typically report 50%–70% reductions. When the boundary expands to “cradle-to-grave” (including sodium silicate production, transport, and waste pre-treatment), the advantage shrinks to 18%–35%. In one extreme case, including carbonation credits over 50 years reversed the comparison entirely.

Root causes of discrepancy: Three boundary choices dominate the outcome: (i) whether sodium silicate production is included (it contributes 40%–70% of geopolymer GWP); (ii) whether transport distance is reported (typically 10%–30% of total GWP); (iii) whether waste pre-treatment (crushing, drying, grinding) is allocated or excluded (10%–40% impact). Remarkably, 11 of the 14 LCA studies we reviewed omitted at least one of these three factors, and only 4 studies reported a full sensitivity analysis.

This review’s position: We challenge the prevailing “geopolymer is always greener” narrative as oversimplified and, in some cases, misleading. We recommend that future LCA studies adopt a minimum reporting standard: (a) functional unit per MPa·m³ (strength-adjusted); (b) separate hotspot decomposition (clinker, activator, transport, pre-treatment); (c) one-way sensitivity analysis for transport distance (50, 200, 500 km) and pre-treatment energy (included/excluded). Until such standards are adopted, carbon claims should be treated as indicative, not prescriptive, for engineering decisions.

Root causes of discrepancy:

The 60-percentage-point variation in reported carbon reduction (20%–80%) is almost entirely explained by three boundary choices:

- (i) Activator production system boundary. Sodium silicate production contributes 40%–70% of geopolymer GWP when included, yet 8 of 14 LCA studies we reviewed excluded it entirely or used idealized “zero-carbon” assumptions [24,25,33]. The critical factor is whether the sodium silicate is sourced from: (a) industrial furnaces (high carbon, 1.2–1.8 kg CO₂/kg), (b) biomass-derived routes (medium carbon, 0.6–1.0 kg CO₂/kg), or (c) theoretical “waste-derived” routes (low carbon but unproven at scale). Studies using assumption (c) report 60%–70% reductions; studies using (a) report 20%–30% reductions [30,35]. The same material, different boundaries, different conclusions—not a material property but a methodological choice.

- (ii) Transport distance and mode. Transport is typically assumed (50–100 km) or omitted entirely. However, sensitivity analyses in the few studies that report transport [25,35] show that varying distance from 50 to 500 km can alter total GWP by 10%–30%. For waste-derived binders, which often rely on locally sourced materials, the transport penalty may be negligible; for geopolymers using industrial sodium silicate, transport of activator can offset 10%–15% of claimed reductions. The absence of transport reporting makes cross-study comparison meaningless.
- (iii) Waste pre-treatment energy. Crushing, drying, and grinding of solid wastes consume energy—10%–40% of total GWP depending on waste type and pre-treatment intensity [35]. Studies that treat waste as “free” (zero burden) report 50%–70% reductions; those that allocate pre-treatment energy based on system expansion report 20%–35% reductions. The choice of allocation method (cut-off vs. system expansion vs. economic allocation) is inconsistently reported, preventing meaningful comparison.
- (iv) Carbonation uptake. Calcium-based binders absorb CO₂ over their service life (10%–20% of initial emissions over 50 years). Studies that include carbonation credits report 10%–20% higher net reductions than those that omit them. For subgrade applications (buried, limited air exposure), carbonation is minimal; for exposed applications, it is significant. This contextual factor—whether the material is used in subgrade or superstructure—is rarely reported in LCA studies but profoundly affects the net carbon balance.

This review’s position: We challenge the “geopolymer is always greener” narrative as methodologically flawed. The reported reductions are not intrinsic material properties but artifacts of boundary choices. We recommend a minimum reporting standard: (a) functional unit per MPa·m³ (strength-adjusted), (b) separate hotspot decomposition (clinker, activator, transport, pre-treatment), (c) one-way sensitivity analysis for transport distance (50, 200, 500 km) and pre-treatment energy (included/excluded). Until such standards are adopted, carbon claims should be treated as indicative, not prescriptive.

7.4. The Machine-Learning Credibility Gap: High $R^2 \neq$ Engineering Reliability

As reviewed in Section 5, an increasing number of studies apply ANN, RSM, or GPR to predict resilient modulus or UCS. However, the reported predictive performance varies implausibly: some studies report $R^2 > 0.95$ with <50 data points [13,25], while others find that simple regression outperforms neural networks under external validation [24,33].

Root causes of discrepancy: The primary issue is overfitting combined with a lack of external validation. Most ML studies in this field train and test on data from a single soil type and a single waste batch. When applied to different soil mineralogies or waste compositions, model performance degrades sharply. Fewer than 10% of the ML studies we reviewed provide cross-project validation, and even fewer report prediction uncertainty (confidence intervals).

Root causes of discrepancy:

The implausible variation in reported model performance ($R^2 > 0.95$ vs. poor external validation) stems from the following:

- (i) Training-only validation. Most ML studies in this field report R^2 on training data or cross-validation within the same dataset—both of which measure goodness-of-fit, not predictive reliability [13,28]. When the same models are tested on independent datasets (different soil sources, different waste batches), R^2 typically drops by 20–40 percentage points [27,36].
- (ii) Small dataset overfitting. With sample sizes of 30–50 data points and input variables of 5–10, the degrees of freedom are insufficient for reliable ANN or GPR training. The

high R^2 reported in these cases is mathematically expected—the model fits the noise, not the signal.

- (iii) Missing input variability. Few ML studies report the range or distribution of input variables (e.g., moisture content range, compaction energy, curing temperature). Without this information, the model's applicability domain is unknown—users cannot know whether their specific conditions fall within the trained range.

This review's position: We argue that model credibility should be judged by external validation on unseen data—not by R^2 on training data. We recommend that future ML studies: (i) explicitly report input variable distributions, (ii) perform at least one external validation on a different soil or waste source, and (iii) convert the model into a simple design equation where possible.

This review's position: We argue that model credibility should be judged by external validation on unseen data, not by R^2 on training data. We recommend that future ML studies: (i) explicitly report input variable distributions and covariance; (ii) perform at least one external validation on a different soil or waste source; (iii) convert, where possible, the model into a simple design equation or spreadsheet tool for practitioners. Without these steps, ML predictions remain academic exercises with limited engineering value.

Taken together, these four contradictions reveal a consistent pattern: discrepancies in the literature are not random noise—they systematically correlate with differences in chemical composition (e.g., Ca/SO₄ ratio, activator type), mineralogical characteristics (e.g., amorphous content, pore connectivity), curing conditions (e.g., moisture regime, temperature), and testing methodologies (e.g., MIP vs. μ CT, LCA boundary assumptions). Critically, most of these factors can be quantified and, once quantified, many apparent contradictions resolve into predictable trends. For example, the calcium paradox is not a paradox when the Ca/SO₄ ratio is reported—it is a conditional response with a clear threshold (1.5–2.0). Similarly, LCA claims are not intrinsically contradictory when boundary assumptions are disaggregated.

This analysis leads to two practical recommendations. First, future studies must routinely report the factors identified in Table 12 as critical—Ca/SO₄, pore connectivity (not just porosity), and LCA boundary assumptions. Second, contradictory results should not be dismissed as “inconclusive” but should be systematically traced to these root causes, which is the approach we have taken in this section. We hope this framework enables future researchers to design studies that either (a) control for these factors to produce internally consistent results, or (b) intentionally vary them to define the boundaries of applicability—a process that will accelerate the field toward robust engineering guidance.

Table 12. Summary of root causes of conflicting findings across studies.

Controversy Contradiction	Conflicting Outcomes Observed	Underlying Cause: Chemical Composition	Underlying cause: Mineralogical Characteristics	Underlying Cause: Curing Conditions	Underlying Cause: Testing Methodology	Quantified Threshold Condition
Calcium-sulfate antagonism	Early strength gain vs. delayed expansion	Ca/SO ₄ molar ratio (1.5–2.0 threshold)	Amorphous vs. crystalline calcium source	Sealed vs. unsealed curing (20%–25% retention difference)	Wet–dry vs. continuous immersion cycling	Ca/SO ₄ < 1.5 triggers ettringite; >2.0 promotes C-S-H
Pore connectivity vs. total porosity	Low porosity does not guarantee durability	Al/Si ratio affects gel density	Interconnected vs. isolated pore networks	Drying method during MIP changes measured connectivity by 20%–40%	MIP vs. μ CT vs. permeability measurement	Connectivity Δ > 0.25 $\rightarrow$ strength retention < 65%

LCA carbon claims	20%–80% reduction reported for the same material class	Activator carbon intensity varies by 3×	Not applicable	Carbonation uptake (10%–20% offset, service life dependent)	Boundary choice: cut-off vs. system expansion vs. economic allocation	Transport 50–500 km → 10%–30% GWP change; pre-treatment 10%–40%
ML model reliability	$R^2 > 0.95$ on training, < 0.60 on external validation	Not applicable	Not applicable	Not applicable	Training vs. external validation; dataset size ($n = 30–50$)	External validation R^2 drop $> 20\%$ indicates overfitting

Interpretation: This table demonstrates that most contradictions in the literature are not irreconcilable—they arise from differences in specific experimental or methodological factors that are often under-reported. By identifying these factors and their quantified thresholds, we provide a roadmap for future studies to: (i) report critical parameters (Ca/SO₄, connectivity, LCA boundary assumptions), (ii) conduct sensitivity analyses, and (iii) enable meaningful cross-study comparison. The shaded cells indicate factors that are not relevant to that particular controversy.

Future research priorities. The contradictions and knowledge gaps identified above point to five priority areas for future research: (i) durability evaluation is recommended to adopt strength and stiffness retention rates as primary outputs, coupled with quantitative tracking of pore-connectivity changes before and after cycling; (ii) environmental safety assessments must be integrated with durability deterioration—leaching tests is recommended to be performed both before and after cycling; (iii) LCA studies is recommended to adopt a unified functional unit (per MPa·m³) and report hotspot contributions separately, with mandatory sensitivity analysis; (iv) engineering translation would benefit from routine reporting of resilient modulus and permanent deformation, with machine learning models including external validation on different soil/waste batches; and (v) field validation is strongly recommended—test sections with ≥ 2 -year monitoring should become standard to calibrate scale effects and construction uncertainties.

8. Field Validation and Real-World Case Studies

While laboratory studies provide essential insights into reaction mechanisms, strength development, and durability under controlled conditions, the ultimate proof of a stabilization material lies in its field performance under actual traffic, climate, and construction variability. This section reviews documented field case studies and long-term monitoring data for low-carbon stabilized subgrades, focusing on construction practices, in-place performance testing, and lessons learned from scale-up.

8.1. Case Study 1—Full-Scale Expressway Subgrade Using Multiple Solid Wastes (China)

Zhang et al. [24] reported a full-scale field trial on a 500-m section of an expressway in China, where a blend of multiple solid wastes (fly ash, slag, and carbide residue) was used to stabilize silty clay subgrade. The field section was constructed using conventional road construction equipment (pulverizer mixer, grader, vibratory roller). Construction parameters: Stabilizer dosage = 12% by dry weight of soil (optimized from laboratory UCS tests); compaction moisture content = optimal moisture content + 2%; compaction degree achieved = 96% of modified Proctor density. Field testing: In-place California Bearing Ratio (CBR) was measured at 7, 28, and 90 days after construction. At 90 days, CBR values ranged from 45% to 68%, exceeding the design requirement of 30% for subbase. Dynamic cone penetrometer (DCP) profiles showed uniform stiffness to a depth of 600 mm. Long-term performance: The section was monitored for 18 months, including two wet seasons and one winter. No differential settlement, rutting, or cracking was observed. Falling weight deflectometer (FWD) measured back-calculated resilient modulus of 210 MPa at

28 days and 185 MPa at 18 months (12% decrease, attributed to seasonal moisture variation). Leaching monitoring: Leachate from three monitoring wells adjacent to the subgrade showed pH values of 7.8–8.2 and a Cr concentration below 0.05 mg/L (within the Chinese class III groundwater standard). Key takeaway: The multi-solid-waste blend achieved field performance comparable to cement-stabilized subgrade at 30% lower material cost and 40% lower embodied carbon. However, the authors noted that strict quality control of waste batch composition was essential to avoid strength variability.

8.2. Case Study 2—Geopolymer-Stabilized Expansive Subgrade (Field Test Section, India)

Jeremiah et al. [17] constructed a 200-m test section on a low-volume road in India, using calcined wastepaper sludge ash (WSA) geopolymer to stabilize expansive black cotton soil. The geopolymer was activated with a sodium hydroxide and sodium silicate solution (mixed on-site in a forced-action mixer). Construction challenges: The setting time of the geopolymer mix was only 45–60 min (laboratory setting time was 90 min), requiring rapid compaction. The field crew adjusted by reducing the mixing batch size and using a smaller compaction zone. Field test results: Plate load tests at 28 days gave a soaked CBR of 55% (compared to the laboratory soaked CBR of 62%). The field modulus of subgrade reaction (k) was 48 MPa/m, meeting design requirements for a low-volume road (expected traffic < 2 million equivalent standard axles). Long-term monitoring: The section was monitored for 24 months. After the first monsoon, minor longitudinal cracks (width < 2 mm) appeared on a 15-m section where compaction moisture had been slightly low. No further deterioration occurred. After 24 months, the average Benkelman beam deflection was 1.2 mm, well below the failure criterion of 2.5 mm. Economic assessment: The geopolymer stabilizer cost was 20% higher than that of cement per tonne, but the lower dosage (10% vs. 15% for cement) resulted in comparable material cost. The authors concluded that geopolymer stabilization is technically feasible but requires more stringent construction quality control (especially mixing and compaction timing).

8.3. Case Study 3—Cement-Free Calcium Carbide Residue-Slag Stabilized Dredged Sludge (China)

Guo et al. [9] reported a field application of a cement-free binder (calcium carbide residue + ground granulated blast furnace slag) for stabilizing dredged sludge used as subgrade fill on a port access road. The site involved 1500 m³ of soft sludge (water content 85%). The binder was added at 20% by dry weight of sludge, mixed in situ using an excavator bucket attachment, and compacted in 300-mm lifts. Field performance: In situ CBR at 28 days ranged from 25% to 32% (design requirement 25%). Resilient modulus backcalculated from lightweight deflectometer (LWD) tests was 120–150 MPa after 90 days. Environmental monitoring: Groundwater samples from downgradient wells showed pH 7.6–8.0 after 12 months, and total dissolved solids remained below baseline. Lessons learned: The binder required a 14-day curing period before further pavement layers could be placed (compared to 7 days for cement). However, the zero-clinker binder reduced carbon emissions by 65% compared to an equivalent cement-stabilized design. The authors recommend that such low-strength binders are suitable for low-to-medium traffic roads or as lower subgrade layers under a more rigid pavement structure.

8.4. Synthesis of Engineering Lessons and Design Implications from Field Cases

Beyond the project-specific summaries above, cross-cutting lessons emerge from comparing the three field cases, which together represent different binder systems, traffic levels, and climatic conditions.

(1) Achievable field performance across binder systems. All three cases met or exceeded their respective design CBR requirements (25%–30% for subbase/subbase),

demonstrating that low-carbon binders—whether multi-solid-waste blends, geopolymers, or cement-free calcium-slag systems—can achieve engineering-acceptable field performance. However, the field-to-lab strength ratios varied: Zhang et al. [14] reported field CBR 45%–68% vs. lab optimum ~70% (ratio 0.64–0.97); Jeremiah et al. [17] reported 55% vs. lab 62% (ratio 0.89); Guo et al. [9] reported 25%–32% vs. lab ~35% (ratio 0.71–0.91). The average ratio of ~0.8 suggests that the laboratory overestimates field performance by roughly 20%, a scale-correction factor that should be applied in preliminary design when field validation data are unavailable.

(2) Construction constraints as the primary field differentiator. While all three binders performed adequately in terms of strength, their construction windows and quality control requirements differed markedly. The geopolymer system had the tightest setting time (45–60 min), requiring rapid compaction and smaller batch sizes—a constraint not captured in laboratory studies. The cement-free CCR-slag system required a 14-day curing period (vs. 7 days for cement), extending the construction schedule. The multi-solid-waste system [22] had conventional setting behavior but required strict batch-to-batch composition quality control to avoid strength variability. These observations suggest that engineering adoptability is governed more by construction logistics than by peak strength—a point often overlooked in material-focused research.

(3) Long-term performance and deterioration patterns. Monitoring periods ranged from 12 to 24 months—insufficient to assess multi-year durability, but sufficient to reveal early deterioration patterns. In all three cases, the first wet season/monsoon was the critical period: the Indian geopolymer section developed minor longitudinal cracks (width <2 mm) where compaction moisture had been slightly low, while the Chinese expressway section showed a 12% decrease in resilient modulus (from 210 to 185 MPa) after two wet seasons and one winter, attributed to seasonal moisture variation. No leaching exceedances were observed in any case, but monitoring periods were short; groundwater samples remained within regulatory limits (Cr < 0.05 mg/L in [26]; pH 7.6–8.2).

(4) Cost and carbon outcomes at field scale. The three cases reported consistent carbon reductions: 40% (multi-solid-waste), 65% (cement-free CCR-slag), and cost-comparable (geopolymer due to lower dosage offsetting higher unit cost). However, all three carbon estimates were extrapolated from material-level LCA rather than measured on-site, and none included construction energy or material waste. This reinforces the LCA boundary sensitivity discussed in Section 7.3: field-scale carbon benefits may be lower than laboratory projections when full construction logistics are accounted for.

(5) Implications for design and specification. Based on the three cases, we propose the following preliminary design guidelines for engineering adoption:

For low-to-medium traffic roads (<5 million ESALs), cement-free or low-clinker binders (CCR-slag, multi-solid-waste blends) are viable alternatives to cement, provided that curing time (≥ 14 days) is accommodated in the construction schedule.

For expansive soils or moisture-sensitive subgrades, geopolymer systems offer effective stabilization but require accelerated construction planning (smaller batch sizes, rapid compaction) to manage short setting times.

For all systems, field validation via test sections (minimum 200–500 m) with at least 12 months of monitoring (including one wet season) is recommended before large-scale adoption.

Leaching verification: groundwater monitoring wells should be installed and sampled at least annually for a minimum of three years—a practice absent in all three cases.

These guidelines are tentative, based on only three documented field cases. However, they provide a starting point for bridging the gap between laboratory research and engineering practice—a gap that remains the primary barrier to widespread adoption of low-carbon roadbed solidification materials (Table 13).

Table 13. Comparative summary of field case studies and engineering applicability matrix.

Parameter	Case 1: Multi-Solid-Waste [24]	Case 2: Geopolymer (WSA) [17]	Case 3: CCR-Slag (Cement-Free) [9]
Location	China (expressway)	India (low-volume road)	China (port access road)
Project scale	500 m full section	200 m test section	1500 m ³ sludge fill
Binder type	Fly ash + slag + CCR (12%)	Calcined WSA geopolymer (10%)	CCR + GGBS (20%)
Soil type	Silty clay	Expansive black cotton soil	Dredged sludge (w = 85%)
Field CBR/modulus	CBR 45%–68% (90d); Mr 210 → 185 MPa (18mo)	Soaked CBR 55% (28d); k = 48 MPa/m	CBR 25%–32% (28d); Mr 120–150 MPa (90d)
Lab-to-field ratio	0.64–0.97	0.89	0.71–0.91
Key construction challenge	Batch composition QC	Short setting time (45–60 min)	Extended curing (14 days)
Long-term monitoring	18 months (no cracking)	24 months (minor cracks <2 mm)	12 months (no deterioration)
Carbon reduction reported	~40% (material-level)	Cost-comparable (20% higher unit cost, lower dosage)	~65% (material-level)
Leaching verification	Yes (3 wells, 18 mo, compliant)	Not reported	Yes (12 mo, compliant)
Recommended application	Highways, stable subgrades	Expansive soils, low-volume roads	Soft soils, low-to-medium traffic
Critical gap	Batch variability control	Field setting time management	Curing schedule integration

Interpretation: All three case studies demonstrate the technical feasibility of low-carbon binders at the field scale, but each faces distinct construction-related constraints that are rarely captured in laboratory studies. The lab-to-field strength ratio averages ~0.8, suggesting that laboratory-optimized designs should include a 20% safety margin for field implementation. Carbon reduction claims are consistently lower when examined at the system level (including construction logistics) than at the material level, supporting the LCA boundary sensitivity discussed in Section 7.3. Long-term monitoring (>5 years) remains the most critical missing evidence for engineering adoption—none of the reviewed cases extends beyond 24 months, which is insufficient to validate performance against multiple wet–dry and freeze–thaw cycles.

8.5. The Lab-to-Field Gap: Uncertainty Introduced by Waste Compositional Variability and Service Conditions

A recurring theme across the three field case studies—and indeed across the broader literature—is the substantial gap between laboratory-optimized performance and field-achieved outcomes. This gap is not merely a matter of scale; it is fundamentally rooted in three sources of uncertainty that are often overlooked in laboratory studies.

First, solid waste composition is inherently variable. Unlike manufactured cement or lime, solid wastes such as fly ash, slag, carbide residue, and phosphogypsum vary significantly depending on source, processing conditions, and storage history. Laboratory studies typically use carefully selected, homogenized, or even artificially formulated waste samples to achieve consistent results. In field practice, however, batch-to-batch variability is inevitable. For example, the CaO content in fly ash can vary by ±30% between sources, and the sulfate content in phosphogypsum can vary by an order of magnitude. Such variability directly affects the reaction stoichiometry, gel phase formation, and ultimately the mechanical and durability performance of stabilized subgrades. Yet fewer than 10% of the reviewed studies explicitly report the compositional variability of their waste materials or discuss its implications for field reproducibility.

Second, service conditions in the field are more severe and more complex than laboratory simulations. Laboratory durability tests typically apply wet–dry or freeze–thaw cy-

cles under controlled, uniform conditions. In the field, however, moisture and temperature gradients, traffic-induced stress variations, and chemical attacks from de-icing salts or groundwater create coupled multi-field conditions that are difficult to replicate in the laboratory. The combined effect of these coupled actions—for example, wet–dry cycles coinciding with traffic loading, or freeze–thaw cycles combined with salt intrusion—can accelerate deterioration far beyond what laboratory tests predict. This is why the three field case studies reviewed above all showed evidence of early deterioration (cracking, modulus decrease) that was not anticipated from laboratory results.

Third, construction quality control is rarely captured in laboratory studies. Field compaction, mixing uniformity, curing temperature, and moisture control are subject to human and equipment variability that is not present in carefully controlled laboratory specimens. The geopolymers case study [16] illustrated this clearly: where compaction moisture was slightly low, longitudinal cracks developed after the first monsoon—a failure mode that had not been observed in any laboratory specimen. Such construction-sensitive failures highlight the limitations of laboratory-only validation.

Implications for engineering interpretation. Given these uncertainties, we offer three cautionary notes for readers and practitioners:

- (i) The quantitative benchmarks presented in Tables 4–7 (e.g., strength retention 60%–85%, resilient modulus 100–300 MPa) should be interpreted as indicators of laboratory-scale potential, not as guaranteed field performance. Engineering designs should incorporate appropriate safety factors (we tentatively suggest a lab-to-field de-rating factor of 0.8, based on the limited available field data in Sections 8.1–8.3) until more field validation data become available.
- (ii) The ranking of material systems in the normalized heatmap (Table 5) reflects laboratory-controlled performance. In field conditions, the ranking may shift—particularly for waste-derived systems with high compositional variability (e.g., calcium-rich waste-activated systems, which scored highest in carbon efficiency but lowest in consistency). Such variability-sensitive systems should be prioritized for field validation before being specified in engineering projects.
- (iii) The “best” solution for a given project cannot be determined from laboratory data alone. It depends on local waste availability, climatic conditions, construction logistics, and regulatory requirements. The decision-support framework proposed in Figure 6D is therefore intentionally not a prescriptive ranking but a tool for identifying the most promising candidates for site-specific validation.

8.6. Limitations of the Review

Several limitations of this review should be acknowledged to facilitate appropriate interpretation of the findings and to guide future research design.

First, publication bias is an inherent limitation of any systematic literature review. Studies reporting positive results—particularly high strength gains or significant durability improvements—are more likely to be published than those with negative or inconclusive findings. This may lead to an overestimation of the typical performance of low-carbon stabilizers, as the quantitative benchmarks reported in Tables 4–7 are derived exclusively from the published literature. We have partially addressed this by clearly reporting the full observed ranges and interquartile intervals rather than relying on mean values alone, and by noting the tendency of journals to publish positive results in Section Systematic Review Methodology: Search Strategy, Selection Criteria, and Quality Appraisal (7).

Second, data heterogeneity across the 153 included studies poses a significant challenge for cross-study comparison. Variations in soil types (e.g., clay mineralogy, particle size distribution, organic content), binder formulations (e.g., activator type and dosage, curing conditions, waste source variability), and testing protocols (e.g., sample prepara-

tion, curing temperature, cycle definitions) introduce substantial heterogeneity. As reported in Section Systematic Review Methodology: Search Strategy, Selection Criteria, and Quality Appraisal (6), formal meta-analysis was deemed inappropriate ($I^2 > 85\%$). Instead, we adopted a range-based synthesis with interquartile reporting to reflect this variability transparently. However, this approach limits the statistical precision of the quantitative conclusions and means that the ranges presented should be interpreted as indicative benchmarks rather than absolute design values.

Third, language bias was introduced by restricting the search to English and Chinese language publications. While this was a pragmatic necessity, it may have excluded relevant studies published in other languages, particularly from regions with active research in geotechnical engineering and solid waste utilization (e.g., the Japanese, Korean, Russian, or Spanish literature). The potential impact of this bias is acknowledged in Section Systematic Review Methodology: Search Strategy, Selection Criteria, and Quality Appraisal (7).

Fourth, limited field validation data represents the most critical evidence gap identified in this review. As discussed in detail in Section 8, the vast majority of the 153 included studies are laboratory-scale investigations. Only three field case studies with monitoring periods of 12–24 months were available for analysis. This scarcity of long-term field data severely limits the extrapolability of the laboratory-derived quantitative benchmarks to real engineering applications. The lab-to-field de-rating factor of 0.8 proposed in Section 8.5 is tentative and should be refined as more field data become available.

Fifth, the exclusion of purely numerical simulation studies without experimental validation (Section Systematic Review Methodology: Search Strategy, Selection Criteria, and Quality Appraisal (2)) may have excluded some relevant predictive modeling work. While this criterion was applied to ensure that only physically grounded data were included in the quantitative synthesis, it may have underrepresented certain modeling approaches (e.g., finite element simulations of stabilized subgrade settlement) that, despite lacking companion experiments, could provide valuable insights for engineering design.

Sixth, the extraction of “optimal formulation” data from studies reporting multiple mix designs (Section Systematic Review Methodology: Search Strategy, Selection Criteria, and Quality Appraisal (6)) may introduce a selection bias toward higher-performing formulations. While this approach was adopted to avoid skewing statistical intervals with inferior mixtures, it may overstate the typical performance achievable under routine field conditions where optimization is less controlled. Readers should therefore interpret the reported performance ranges as upper-bound estimates for well-optimized laboratory formulations.

Seventh, the evidence hierarchy (Levels 1–4) developed for this review, while useful for grading research completeness, is specific to this study and has not been externally validated. The weighting of Level 4 studies in deriving quantitative benchmarks, while methodologically justified, may inadvertently privilege studies with LCA or leaching data over those with more robust durability testing but no environmental assessment.

Despite these limitations, the systematic methodology, transparent reporting of data extraction and synthesis rules, and clear acknowledgment of uncertainties ensure that the conclusions of this review are robust and interpretable within the defined scope. The limitations identified here also serve as a roadmap for future research priorities, as elaborated in the Discussion (Section 7) and Conclusions (Section 9).

9. Conclusions

This review establishes a unified, engineering-ready framework for low-carbon road-bed solidification materials—distinct from prior reviews that focused on material feasibility alone. Our novelty consists of (i) a four-level evidence chain hierarchy to objectively

grade research completeness; (ii) repositioning resilient modulus, permanent deformation, and pore-connectivity evolution as indispensable design parameters; and (iii) cross-comparison of multiple material routes under harmonized durability, environmental, and carbon boundaries.

Key quantitative outcomes are summarized as follows:

- Alkali-activated geopolymers achieve 7-d UCS of 1.5–8.0 MPa and 28-d values of 2.5–12.0 MPa, but strength retention after 12 wet–dry cycles typically falls to 62%–78%, with pore-connectivity index rising by 0.15–0.30. Without tracking post-cycling pore evolution, service life cannot be reliably predicted.
- Low-clinker calcium-based composites (ternary blends) show higher retention (70%–85% after wet–dry, 65%–80% after freeze–thaw) and resilient modulus of 100–300 MPa, yet their leaching concentrations of Ba, Cr, or Zn may increase by 50%–150% when sulfate-induced recrystallization reopens pores.
- Multi-scale reinforcement (fibers, skeletons) reduces cumulative permanent strain by 30%–60% under cyclic loading, but benefits diminish if fiber-matrix interfacial stability is not chemically matched to wet–dry or salt conditions.
- Engineering parameterization remains the weakest link: based on the Stage 4 engineering parameter screening (Section Systematic Review Methodology: Search Strategy, Selection Criteria, and Quality Appraisal), only 153 of 282 studies (43%) reported at least one engineering-oriented output; among these, fewer than 30% specifically reported resilient modulus or permanent deformation. Where reported, values vary from 50 to 400 MPa, underscoring the need for stress-dependent characterization and standardized testing protocols.
- Engineering adoption synthesis: The three field case studies reviewed in Section 8 demonstrate that low-carbon binders (multi-solid-waste blends, geopolymers, and cement-free CCR-slag systems) can achieve field CBR values of 25%–68%, meeting subgrade design requirements for low-to-medium traffic roads. However, the average lab-to-field strength ratio of ~0.8 indicates that laboratory-optimized formulations overestimate field performance by approximately 20%, underscoring the need for scale-correction factors in preliminary design. Construction constraints—short setting time (geopolymers), extended curing (CCR-slag systems), and batch composition variability (multi-solid-waste blends)—emerged as more critical differentiators than peak strength, suggesting that engineering adoptability is governed more by construction logistics than by material performance alone. Critically, no field study exceeded 24 months of monitoring, and none included full-system LCA with measured construction energy, leaving long-term durability and net carbon benefits as the two most pressing evidence gaps.

Critical reflections: Beyond the system-specific quantitative outcomes, this review identifies three cross-cutting contradictions that currently impede engineering extrapolation: (i) the calcium-sulfate antagonism, where the same calcium source can either densify or destabilize depending on the Ca/SO_4 ratio and moisture regime; (ii) the pore-connectivity conundrum, where total porosity is a poor predictor of durability unless accompanied by connectivity data; and (iii) the LCA boundary effect, where reported carbon reductions for geopolymers vary by 60 percentage points solely due to boundary choices. We contend that resolving these contradictions requires not more isolated studies, but coordinated round-robin tests using reference materials, shared protocols, and mandatory reporting of key state variables (Ca/SO_4 , pore connectivity, LCA boundaries).

All conceptual diagrams (Figures 1 and 3A–D–6A–D) were created by the authors using Microsoft PowerPoint (Version 2506, Microsoft Corporation, Redmond, WA, USA). Data annotations are based on quantitative synthesis of the reviewed literature (see Tables 1–13).

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