USDOT-SLAG-26-14
MAY 2026

United States Department of Transportation
Research Initiative on the Use of Steel Slag in Concrete and Cement

Office of the Assistant Secretary for Science and Technology (OST-R)

Industry Assessment

Technical Brief

Gap Analysis on the Use of Steel Slag in Cement and Concrete for Transportation Infrastructure

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Overview

Steel slag represents a promising alternative material for the transportation sector as a potential supplementary cementitious material (SCM) to replacement portland cement, as a feedstock for clinker production, as well as an aggregate in concrete and geotechnical applications. However, knowledge gaps regarding the material's inherent variability and chemical behavior currently prevent widespread adoption within the construction industry. There is currently an insufficient understanding of the quantitative relationships between slag mineralogy and reactivity, which complicates developing predictive performance models for use in cement and concrete applications. Optimizing methods to increase reactivity of steel slag for use as an SCM are currently in the early stages of development. Further complicating this issue are the lack of standardized testing methods and slag-specific specifications (similar to those existing for blast-furnace slag), and variable terminology within the industry, which limit widespread adoption of steel slag as an SCM into the construction industry. Addressing these gaps is essential to transitioning steel slag into a reliable component of sustainable transportation infrastructure and unlocking its true financial value. A brief description of key knowledge gaps in seven overarching thematic areas is presented below.

Thematic Areas

- Material Fundamentals and Chemical Behavior
- Measurement, Testing, and Standardization
- Processing and Activation Technologies
- Environmental Impact and Long-term Durability
- Policy and Regulations
- Market Dynamics, Logistics, and Field Implementation
- Construction Specifications, Standards, and Codes

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Material Fundamentals and Chemical Behavior

A significant gap exists in understanding of how steel slag chemistry dictates performance.

- **Reactivity Relationships:** Quantitative relationships between mineralogy and reactivity are insufficiently defined, limiting predictive performance modeling for different steel slag types.
- **Minor Oxide Influence:** The role of minor and trace oxides (e.g., MgO, FeO, Cr_2O_3) in hydration kinetics, long-term strength, and durability is not well understood, particularly for specialty slags.
- **Modeling Immaturity:** Thermodynamic and kinetic models for steel slag are underdeveloped compared to GGBFS systems.
- **Activation Constraints:** Mechanisms governing the release of silicon and aluminum from crystalline phases are poorly constrained, which impedes the design of effective activators.

Measurement, Testing, and Standardization

Current testing protocols often fail to fully capture the properties and behavior of steel slag, leading to a lack of industry-standard specifications and simplistic performance assessments.

- **Lack of Reactivity Tests:** There is no accepted reactivity test for steel slag SCMs because they are not pozzolanic and do not fit existing pozzolanic activity indices.
- **Advanced Geotechnical Testing:** Most geotechnical studies rely on simple testing methods (e.g., Unconfined Compressive Strength); there is a need to assess behavior using more sophisticated testing methods such as Triaxial Compression and Direct Simple Shear to fully understand its behavior in a range of transportation applications.
- **Regulatory Disparity:** Unlike blast-furnace slag, steel slag lacks standard specifications to guide acceptance regarding leaching, expansion, and durability.
- **U.S. Contextual Data**: Most field-scale studies have been conducted outside the U.S., leaving a gap in performance data under U.S. standards and load demands.

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Processing and Activation Technologies

Research is needed to optimize how steel slag is treated before use to ensure stability, reactivity, and adequate performance.

- **Cooling and Modification:** The impact of alternative cooling strategies (e.g., pelletization or granulation) on steel slag reactivity is not well explored.
- **Mechanical Activation:** Energy-reactivity tradeoffs for grinding are not quantified, and optimal fineness thresholds remain poorly generalized.
- **Activation Durability:** The long-term stability of chemically activated systems is not established, particularly regarding alkali contribution, steel corrosion risk, and sulfate interactions.
- **Emerging Activation Methods:** Technologies such as thermal activation (~800–1400°C) and biological activation (microbial carbonation) require further exploration regarding scalability, compatibility with concrete processing and implementation, and long-term durability of systems produced with these materials.
- **Pretreatment Standardization:** While pretreatment is necessary to control expansive behavior (e.g., aging or carbonation), there is currently no standardized practice.

Environmental Impact and Long-term Durability

Concerns regarding environmental safety and long-term structural integrity remain a barrier to widespread adoption.

- **Element Release:** Further research is required to understand the release of elements from the slags themselves and from encapsulated slag in concrete or Controlled Low-Strength Material (CLSM).
- **S/S System Stability:** There is uncertainty regarding the long-term pH evolution and buffering capacity of EAF slag in stabilization/solidification (S/S) systems, which affects metal remobilization.
- **Corrosion and Carbonation:** Higher carbonation depths in slag-amended concretes compared to traditional materials raise concerns about the rate of reinforcement corrosion and overall durability.

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Policy and Regulatory Gaps

The acceptance of steel slag is severely fragmented across policy and regulatory approval pathways.

- **Lack of Unified Framework:** There is currently no unified national policy framework governing the use of processed and emerging slag materials in concrete.
- **Uncoordinated Review Systems:** Environmental, transportation, building-code, and construction approvals do not operate through one coordinated process, often functioning independently.
- **Definitional Confusion:** Policy confusion arises because "slag" is frequently treated as a single category, despite distinct origins, chemistry, and regulatory logic for materials like blast-furnace slag, steel slag, EAF slag, and BOF slag.
- **Jurisdictional Inconsistency:** States differ significantly regarding how slag materials are classified, defined permitted uses, and assigned regulatory oversight.
- **Reliance on Case-Specific Review:** Due to the lack of routine policy pathways, approvals often depend on case-specific reviews rather than standardized procedures, resulting in a system that is difficult to navigate.

Market Dynamics, Logistics, and Field Implementation

Economic and logistical hurdles limit the transition from laboratory success to industrial-scale use.

- **Limited Field Data:** There is a significant reliance on laboratory and short-term leaching tests; multi-year field demonstrations with consistent monitoring are lacking.
- **Supply Chain Logistics:** Slag facilities are highly regionally concentrated, posing limits on accessibility. There is a need to model the implications of plant location and transport costs on the supply chain.
- **Economic Assessment:** Systematic Life-Cycle Cost Assessments are needed to evaluate the financial viability of slag alternatives across different use cases, considering economic value and domestic availability.
- **Variability Impacts:** It remains unclear how plant-to-plant and batch-to-batch variability will impact performance and replicability across all potential use cases.

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Construction Specifications, Standards, and Code Gaps

While slag cement is addressed through named standards and routine pathways, steel slag does not have a unified acceptance pathway for use in concrete as an SCM in the United States.

- **Failure to Codify Research:** Research on laboratory processing methods and stabilization approaches has not yet been converted into broadly adopted specification language, standard acceptance criteria, or routine field approval procedures.
- **Technical Specification Barriers:** Volumetric instability remains the main technical concern, continuing to drive project-specific reviews, restrictions, rigorous expansion testing, and aging requirements.
- **Missing SCM Pathway:** ASTM and AASHTO define cementitious material specification pathways for slag cement, but steel slag continues to be addressed primarily through aggregate, asphalt, or base-material specifications rather than an SCM specification.
- **Unharmonized Requirements:** Qualification, expansion, conditioning, and durability verification requirements are not harmonized into one consistent framework for concrete use.
- **Absence of Named Code Pathways:** No direct named code pathway for steel slag use in concrete is in core code frameworks or across the concrete construction industry. Approval relies on interpretations of broader provisions, alternative-material approval, and project-specific acceptance.
- **Bridge Application Gaps:** Specific to bridge-related applications, no steel-slag-specific bridge-design pathway was identified in public materials reviewed.
- **Resulting Limited Implementation:** Consequently, steel slag use remains limited primarily to aggregate, asphalt, road base, and fill applications, with very limited use in concrete.

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This brief summarizes findings from a knowledge gap analysis as part of the Industry Assessment for USDOT-SLAG, "Research Initiative on the Use of Steel Slag in Concrete and Cement" under cooperative agreement 693JK42550005. Information supporting these findings can be found at: https://cait.rutgers.edu/usdotsteelslag/publications/. Inquiries about this work can be sent to: usdotsteelslaginitiative@rutgers.edu.