

Industry Assessment

Technical Brief

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Activation Technologies of Steel Slags for Use in Concrete

Overview

This technical brief discusses the activation technologies that have been proposed as potential methods to improve the reactivity of steel slag (SS) for use as a supplementary cementitious material (SCM) in concrete. Steel slags have a bulk oxide composition that is generally suitable for use as an SCM; however, the reactivity of SS is inherently low primarily due to their high crystalline content resulting from slow cooling during production, not unlike iron slags that are not granulated (e.g. slow cooled). The low amorphous content of the SS (primarily in the form of reactive SiO_2 and C_2S) limits hydraulic reactivity and pozzolanic reactivity. Additionally, free CaO and MgO in steel slag can cause volume instability, Fe-rich phases decrease reactivity, and poor grindability raises production costs, further limiting its direct use in concrete. Activation technologies address these challenges by modifying the phase assemblage, enhancing dissolution kinetics and reactivity, and mitigating expansion-related issues. The effectiveness of any activation method depends on the steel slag type (BOF, EAF, or LF), its chemical and mineralogical composition, and processing route.

Key Takeaways

- Steel slag has low reactivity as produced due to high crystalline content resulting from slow cooling during production, not unlike iron slags that are not granulated.
- Activation is necessary to enable its use as an effective SCM in concrete. Multiple activation strategies exist – mechanical, chemical (reagent-based and carbonation), thermal, and biological – each offering distinct mechanisms for improving SS reactivity and soundness.
- Activation method selection must account for SS type, oxide composition, and intended concrete application. New reactivity testing, experimental data, microstructural characterization, thermodynamic modeling, and field trials are needed to evaluate and optimize activated SS systems.

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August 2026



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The flowchart in Figure 1 summarizes the activation technologies described in this document.

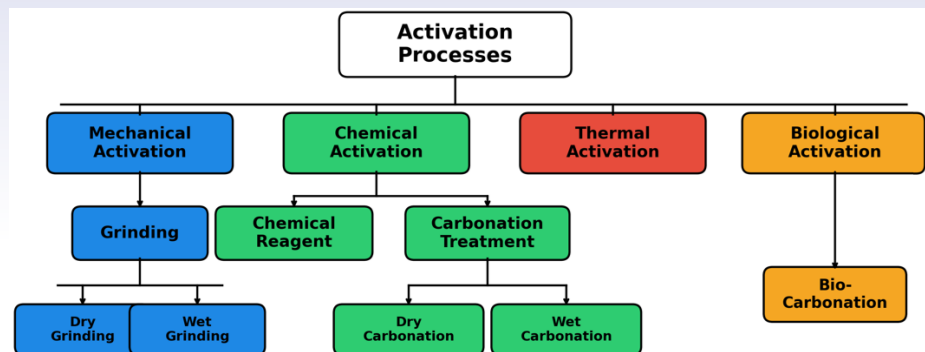


Figure 1: Activation processes possible for steel slag for use as a supplementary cementitious material in concrete.

Mechanical Activation

The particle size of SS is typically larger than conventional SCMs, closer to fine aggregate. Mechanical activation involves grinding SS to a finer powder, increasing surface area and ability to react. Grinding may also promote dissolution of certain crystalline phases such as gamma-C₂S. Wet grinding is more energy-efficient than dry grinding, though the liquid-to-solid ratio is an important parameter. The use of grinding aids such as triethanolamine (TEA) has been shown to be effective in improving grinding efficiency and the resulting reactivity of the processed SS.

Chemical Activation

In general, most SS have low C₃S and low reactive SiO₂ contents. Due to slow cooling of SS, most C₂S is typically in gamma form, which is not very reactive. Although SiO₂ content of most SS are high, SiO₂ is typically locked in Al- and Fe-rich phases. Chemical activation technologies provide ways to increase the reactive SiO₂ and C₂S content to increase pozzolanic reactivity, as described below.

Using chemical reagents aims to alter the chemistry of SS by breaking down stable crystalline phases or increasing the solubility of Ca-, Si-, and Al-bearing phases. *Dry etching* of raw SS (e.g., using formic acid) increases surface area and roughness, while reducing free CaO to improve volume soundness. *Alkali activation* during concrete mixing, using activators such as NaAlO₂, Na₂SO₄, or Na₂SiO₃ can increase the solubility of Ca-, Si-, and Al-phases and promote formation of C-S-H, C-A-S-H, and N-A-S-H reaction products. Some studies showed that chelating activators (e.g., Na₄EDTA) during concrete mixing can help form complexes with Ca⁺², Mg⁺², and Fe^{+2/+3}, increasing C-S-H, hydrogarnet, and EDTA-modified hydrotalcite.

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Carbonation-based activation can be applied either as a pre-treatment on raw SS or during concrete mixing. Dry carbonation of raw SS can help release silica gel from $(\text{Ca}, \text{Mg})\text{SiO}_3$ phases and react with free CaO and MgO to mitigate volume expansion. However, a carbonate shell effect can limit effectiveness by encapsulating unreacted material, which might require coupling the process with other activation technologies such as grinding. Wet carbonation during mixing can carbonate gamma- C_2S to release reactive SiO_2 , while added water promotes further reaction of C_2S and C_3S phases. The efficiency of carbonation is strongly influenced by moisture conditions, temperature, and CO_2 pressure.

Thermal Activation

Thermal activation involves heating SS to break Si-O and Al-O bonds, disrupting the crystalline structure of mineral phases and increasing amorphous content of SS. Typical treatment temperatures are higher than 800°C ; therefore, this process cannot be performed during construction. Treatments in the range of $\sim 800\text{--}1400^\circ\text{C}$ may provide limited increase amorphous content. At temperatures $\geq 1400^\circ\text{C}$ the slag becomes molten, allowing quenching as a potential mechanism to promote amorphization, albeit with a higher energy cost. Furthermore, high-temperature curing ($40\text{--}100^\circ\text{C}$) applied after mixing can also accelerate reactivity, though potential for other issues such as delayed ettringite formation (DEF) should be considered.

Biological Activation

Biological (microbial) carbonation is an emerging approach that may overcome the shell effect limitation of direct CO_2 carbonation. Certain microorganisms such as *Bacillus mucilaginous* can produce carbonic anhydrase, an enzyme that catalyzes the conversion of CO_2 to carbonic acid, thereby increasing calcite formation and potentially maintaining a favorable high-pH environment for continued reactivity.

This brief summarizes findings on Activation Technologies of Steel Slag for Concrete Use 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/>. Inquiries about this work can be sent to: usdotsteelslaginitiative@rutgers.edu