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Review Article

Reimagining steel slag in sustainable concrete: A bibliometric and experimental review

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Abstract

This review paper offers a comprehensive investigation into the use of steel slag in concrete, integrating bibliometric analysis with experimental findings to evaluate its performance, durability, and sustainability. Steel slag, a by-product of steel manufacturing, is generated in large volumes and presents environmental challenges due to improper disposal and leaching of harmful elements. Simultaneously, the construction industry's heavy dependence on Portland cement significantly contributes to global greenhouse gas emissions. Owing to its chemical similarity with cementitious materials, steel slag shows promise as a partial replacement for cement and natural aggregates. A bibliometric review of 880 Scopus-indexed publications reveals growing research interest worldwide—particularly in China, India, and Iraq—with main focus areas on mechanical properties, durability, and circular economy strategies. Experimental studies indicate that optimal replacement rates (10–15% for cement, 30–50% for aggregates) enhance compressive strength, chloride resistance, sulphate durability, and freeze–thaw performance. Treatments such as carbonation improve slag reactivity and stability. However, issues remain regarding workability, slag quality control, and extreme condition performance. Future research directions include smart concrete, geopolymer–slag hybrids, and nanomaterial enhancements. Life-cycle analysis and regulatory frameworks are essential for scaling adoption. Overall, steel slag presents a viable, sustainable solution in concrete, promoting resource efficiency and emission reduction.

1. Introduction

The degradation of the ecological environment has emerged as a pressing concern in civil engineering. Alongside rapid economic advancement, the volume of industrial solid waste is escalating [1,2]. This surge poses substantial risks to ecological stability and environmental safety [3]. Among such wastes, steel slag and fly ash are generated in large quantities, making their effective disposal and reuse vital to environmental preservation. Unlike blast furnace slag, steel slag is a by-product of the steelmaking process and primarily comprises ferrites and calcium-bearing compounds formed during the cooling of molten steel [4]. Its heterogeneous composition necessitates tailored treatment and reuse strategies. Unfortunately, much of this waste is either landfilled or stored unsafely [5], leading to the leaching of alkaline substances and heavy metals [6], which threaten water quality, ecological integrity, and human and animal health [7,8]. This highlights the urgent need to develop sustainable management strategies for these materials to reduce their environmental footprint [9].

Cement-based materials continue to dominate the construction sector due to their mechanical and structural advantages. However, the production of Portland cement is resource-intensive, consuming vast amounts of raw materials and energy [10]. Additionally, it is a major contributor

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to greenhouse gas emissions, with an estimated 0.79 tons of CO_2 released per ton of cement produced [11]. The cement industry is responsible for nearly 8–9% of global CO_2 emissions [12], prompting global discourse on more sustainable construction materials [13]. While industrial restructuring is imperative [14], efforts must also focus on the development of environmentally friendly, low-impact alternatives [15]. Minimizing resource consumption and emissions throughout the material lifecycle from production to disposal is essential, including strategies for recycling cementitious waste [16]. Thus, promoting energy efficiency and sustainable material use is becoming integral to the future of the construction industry [17].

Steel slag contains a wide range of chemical constituents, including major elements like Fe, Ca, Mg, and Si, along with trace components such as MnO_2 and Al_2O_3 [18]. Its composition features reactive phases like $CaSiO_3$ and SiO_2, closely resembling that of Portland cement [19]. Additionally, it includes mineralogical phases such as dicalcium silicate (C_2S), tricalcium silicate (C_3S), and calcium ferrite aluminate (C_4AF), which can actively participate in cement hydration [20]. Its SiO_2 content indicates promise as a filler material to improve the strength of cementitious composites [21].

Recent research has focused on advancing both cementitious and geopolymer composites through various material modifications. Notably, the chemical durability of geopolymers enhanced with silica fume and nano-silica has been studied under diverse curing regimes, offering insights into their resistance under aggressive environments [22]. Parallel investigations have explored the flexural behavior of self-compacting with steel fibers and silica fume, highlighting improvements in ductility and mechanical performance [23,24].

In the realm of construction applications, steel slag has emerged as a viable substitute for natural aggregates in structural concrete, subgrade layers, and railway ballast. Its mechanical characteristics are often comparable to those of traditional aggregates, reinforcing its role as a sustainable alternative [25,26]. Additionally, the integration of nanomaterials into geopolymer matrices continues to gain momentum, owing to their ability to refine microstructure and enhance performance [27].The use of steel slag in concrete systems presents a promising pathway for improving resource efficiency, reducing environmental pollution, and fostering industrial symbiosis between the steel manufacturing and construction sectors [28,29].

While numerous individual studies have investigated the use of steel slag in concrete, there remains a lack of comprehensive synthesis that integrates both quantitative bibliometric trends and technical performance evaluations across multiple domains—including workability, strength, durability, and microstructure. This review bridges that gap by combining a data-driven bibliometric analysis of 880 Scopus-indexed articles with a critical assessment of experimental findings. By mapping research evolution, international collaboration patterns, and emerging themes, this work not only identifies strategic research clusters and influential contributors but also highlights underexplored areas such as smart concrete, carbonation treatment, and slag quality standardization. Consequently, the research community benefits from a consolidated reference that supports evidence-based decision-making, guides future experimental design, and fosters collaborative innovation in sustainable concrete technologies.

2. Composition and Characteristics of Steel Slag

In the context of this study, the term "steel slag" refers to the by-product generated from steelmaking processes, particularly from basic oxygen furnaces (BOF) and electric arc furnaces (EAF). This type of slag is chemically and mineralogically distinct from ground granulated blast furnace slag (GGBFS), which is a by-product of pig iron production and widely used as a supplementary cementitious material. Unlike GGBFS, steel slag contains significant amounts of free lime (f-CaO) and magnesium oxide (MgO), which can lead to volumetric instability if untreated. Due to its complex mineral composition and variable chemistry, proper characterization and processing are essential before its application in cementitious systems.

2.1 Chemical and Mineral Composition

Steel slag, a by-product generated during steel production, is characterized by a complex mixture of chemical oxides. Dominant constituents typically include calcium oxide (CaO), silicon dioxide

(SiO_2), ferric oxide (Fe_2O_3), aluminum oxide (Al_2O_3), magnesium oxide (MgO), manganese oxide (MnO), ferrous oxide (FeO), and notably, free lime (f-CaO) [30]. The relative proportions of these oxides vary significantly depending on several factors, including the composition of the input materials, the specific steelmaking process used, and the type of steel produced [31].

In addition to its chemical complexity, steel slag also exhibits a diverse mineralogical profile. The primary crystalline phases commonly identified in slag include tricalcium silicate (C_3S), dicalcium silicate (C_2S), and dicalcium ferrite, alongside complex silicate compounds such as calcium–magnesium olivine and pyroxene derivatives [32]. A distinct feature of steel slag is the presence of the RO phase, which represents a solid solution composed primarily of MgO, FeO, and MnO, as well as unreacted free lime particles. The presence of these mineral phases is confirmed by X-ray diffraction (XRD) analysis, as illustrated in Fig. 1, which identifies dominant crystalline peaks corresponding to C_3S, C_2S, RO phase, and other silicate compounds. The typical morphology of steel slag, including the presence of angular particles and crystalline phases such as C_2S and RO compounds, is shown in Fig. 2.

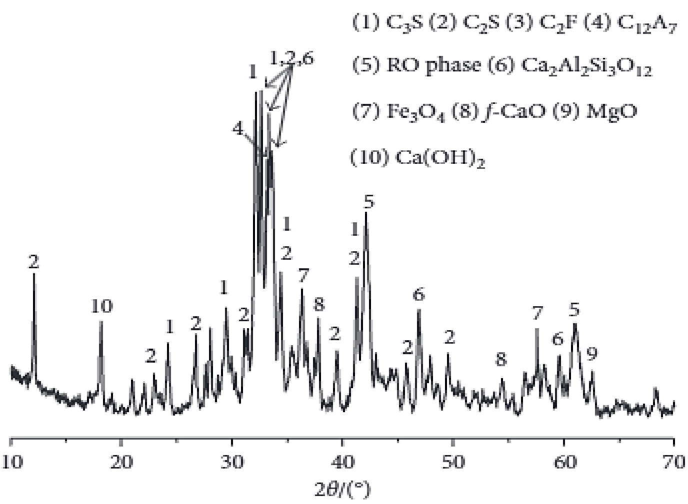

Fig. 1. X-ray diffraction (XRD) pattern of steel slag indicating dominant crystalline phases [33]

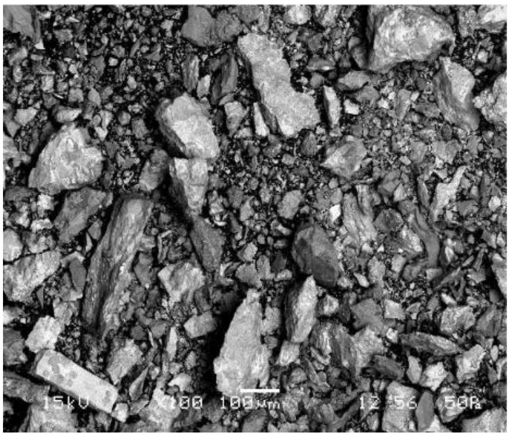

Fig. 2. Microstructure of steel slag [34]

The mineral composition of slag is closely tied to its basicity, which is typically expressed as the CaO/SiO_2 ratio [35]. As observed by Lin et al. [36], slags with lower basicity values tend to be rich in olivine, pyroxene, and RO phases. In contrast, medium to highly basic slags promote the crystallization of silicate-rich phases, such as C_3S and C_2S, which are relevant to the material's reactivity and cementitious potential. These trends are reflected in the representative chemical composition ranges summarized in Table 1, where the varying proportions of CaO and SiO_2 directly influence slag basicity and, consequently, the formation of specific mineral phases.

Table 1. Typical chemical composition ranges (wt.%) for various types of metallurgical slag [37]

Oxide	Range (wt.%)
CaO	40.04 - 50.64
MgO	6.40 - 7.12
Al2O3	22.84 - 41.73
SiO2	10.25 - 70.00
FeO	Up to 51.00
MnO	Trace amounts
P2O5	Trace amounts
K2O	Trace amounts
Na2O	Trace amounts
TiO2	Trace amounts
PbO	Higher in Pb smelting slags
ZnO	Trace amounts
Cr	Trace amounts
Ni	Trace amounts
V	Trace amounts

2.2 Physical Characteristics and Engineering Behavior

The physical appearance and density of steel slag vary with basicity and cooling conditions. Typically, the color transitions from dark gray or brown in low-basicity slag to light gray or white in high-basicity slag [38]. The bulk density of steel slag typically ranges from 3.1 to 3.6 g/cm^3. This range is supported by the specific gravity values mentioned in the abstracts, which indicate that steel slag has a high density compared to other materials. The moisture content of steel slag can vary between 3% and 8. This range is consistent with the findings in the abstracts, which discuss the water absorption properties and the impact of moisture content on the material's properties [39].

Steel slag exhibits three major engineering properties. First, its latent hydraulic activity stems from the presence of reactive silicate and aluminate minerals, which contribute to cementitious behavior under suitable conditions [40]. Second, the dimensional stability of steel slag is a concern due to its content of free CaO and MgO, which can hydrate over time, causing volumetric expansion. This poses a risk of cracking or instability in structures if the slag is not properly processed [41]. Third, the abrasion resistance of steel slag is influenced by its microstructure and mineral content. However, empirical studies have shown that its apparent poor wear resistance is often attributed to residual metallic iron particles rather than its crystalline phases. Specifically, grinding and sieving processes reveal that the coarse residue typically comprises iron, which deteriorates mechanical integrity when left unremoved [42].

3. Workability of Cement-Based Materials Containing Steel Slag

The fresh-state performance, or workability, of cementitious systems incorporating steel slag has been a central focus in numerous studies. A properly designed concrete mixture must demonstrate good cohesion, adequate flowability, and water retention without exhibiting bleeding or segregation. Researchers widely agree that optimizing the dosage and application method of steel slag is critical to achieving desirable workability in cement-based materials [43–48]. Table 2 maps the effects of steel slag substitution strategies on slump behavior and water demand. As shown, binder substitution with steel slag exhibits a non-linear trend: a 15% replacement improves slump due to better particle packing and lubricating effects, while 10% and 20% substitutions may reduce slump, likely due to insufficient or excessive particle interaction. When used as fine aggregate, steel slag improves workability up to an optimal replacement level of 30%, beyond which performance may decline. Conversely, using slag as coarse aggregate tends to deteriorate workability, attributed to its angular shape and higher density. In addition, the carbonation of steel slag introduces further complexity. Although it enhances early-age hydration, it also increases water demand, necessitating careful balance in mix design. These nuanced effects underscore the importance of tailoring slag application to achieve desired fresh-state properties while maintaining compatibility with other mix components.

Table 2. Effect of steel slag utilization forms on fresh-state performance of cementitious materials, including setting time, slump, and hydration behavior

Steel Slag Usage Type	Replacement Level	Performance Indicator	Observed Effect (Fresh State)	Source
Cement replacement (SCM)	25%, 50%	Setting time; Hydration rate	Setting time significantly prolonged; early hydration kinetics noticeably slowed	[49]
Cement replacement (SCM)	25%, 50%	Setting time; Water demand	Setting was delayed, and required mixing water content was lowered by ~5–9% (reduced water demand)	[50]
Cement replacement (SCM)	30%	Setting time	Initial and final setting times extended by roughly 60% and 40% compared to plain cement (OPC)	[51]
Aggregate replacement	30%, 60% (fine aggregate)	Slump (workability)	Concrete maintained adequate slump at these replacement levels, indicating acceptable workability (steel slag concrete met standard slump requirements)	[52]
Aggregate replacement	10–50% (fine & coarse aggregate)	Slump (workability)	Concrete slump decreased significantly as steel slag content increased (e.g. from ~35 mm at 0% to ~3 mm at 50% coarse slag replacement. Very high slag replacement can lead to mix instability (segregation) due to the higher density of slag particles.	[53]

3.1 Steel Slag as a Binder Substitute

Martins [61] developed a blended binder using steel slag powder (SSP), cement, and linear alkylbenzene sulfonate (LAS). The introduction of SSP was shown to extend the setting time and modify the hydration process (Fig. 3). Interestingly, SSP improved the spread diameter of mortar mixtures, with the largest observed increase reaching 58.1 mm compared to mixtures using only Portland cement , confirming the trend reported by Bullerjahn [62].

Substituting cement with 10% steel slag generally results in a decrease in slump. This is supported by findings that incorporating steel slag reduces the workability of concrete, leading to a lower slump value. Specifically, one study noted a reduction in slump by up to 45.87% when 10% steel slag was used [54,55]. At 15% substitution, the slump increases. This could be due to the optimal balance between the cementitious properties of steel slag and the overall mix design, which might enhance the fluidity of the concrete mix. Although direct evidence for a 15% substitution is not provided, the trend of improved workability at certain substitution levels is noted in studies where steel slag improved the filling and passing ability of self-compacting concrete [56].Increasing the substitution to 20% results in another decrease in slump. This aligns with findings that higher proportions of steel slag can adversely affect the workability of concrete, leading to reduced slump values [54]. One study specifically mentioned that the workability of concrete decreases with increasing steel slag content, which supports the observed trend [57]. This behavior was attributed to multiple effects: (1) the filler effect, where slag particles provide nucleation sites that increase water demand; and (2) the ball-bearing effect, where smaller quantities of slag improve particle packing and enhance flowability [45]. The interaction between slag content and water availability plays a key role in modifying these rheological properties.

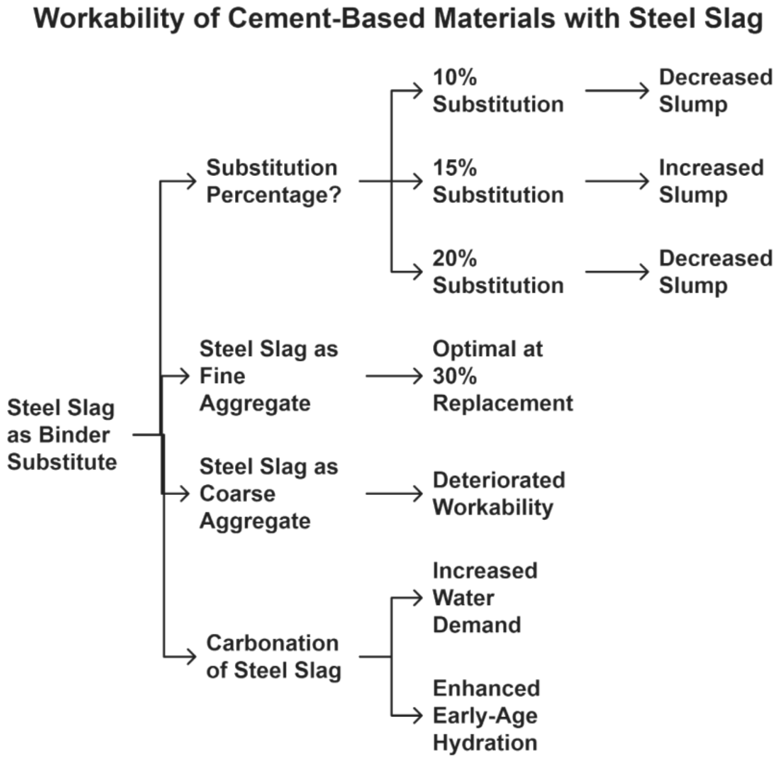

Fig. 3. Workability of cement-based materials with steel slag

3.2 Steel Slag as Fine and Coarse Aggregate

The use of steel slag as a replacement for natural aggregates—both fine and coarse—has been widely explored in concrete production. A study by Yehualaw et al. [58] evaluated the partial substitution of natural river sand with steel slag as fine aggregate. Their findings indicated that the concrete maintained acceptable workability, with slump performance more closely tied to the proportion of slag used rather than the water-to-cement (w/c) ratio. This emphasizes the importance of optimizing slag content to ensure consistent workability in structural applications. Supporting this, another investigation identified 30% replacement of natural sand with steel slag as an effective threshold, balancing both fresh properties and mechanical performance [59]. At this level, the concrete retained desirable slump values while benefiting from the strength-enhancing attributes of the slag particles.

Van Dao et al. [60] applied AI models to predict concrete properties with various mineral admixtures and confirmed that mixes containing steel slag consistently exhibited lower predicted slump values compared to mixes with fly ash or GGBS. The reduction in workability is also linked to the slower hydration kinetics of steel slag, which does not contribute significantly to early paste formation, causing stiffer fresh concrete. Moreover, Koniki et al. [61] highlighted that while geopolymer systems incorporating steel slag benefit from slag's latent hydraulic properties, higher dosages can still compromise flow without the use of superplasticizers.

Comparative analyses involving the replacement of both fine and coarse aggregates further reveal a decline in workability as the replacement percentage increases. However, fine aggregate substitution consistently outperforms coarse aggregate substitution in maintaining fresh concrete flow. This performance disparity is largely attributed to the particle angularity and grading of steel slag, which affect the internal friction and flow dynamics of the concrete mix [53].

3.3 Carbonation of Steel Slag and Its Impact

Carbonated slag increases the water demand for achieving standard consistency in cement mortars. This is attributed to the weight gain from carbonation, which correlates positively with the increased water requirement[62,63]. The carbonation process alters the microstructure of the slag, leading to a refinement of the pore structure and an increase in specific surface area. This change in microstructure is likely responsible for the increased water demand, as more water is needed to wet the larger surface area and fill the refined pores[62].

Rui & Qian [64] evaluated the hydration response of cementitious systems containing CO_2-cured steel slag. The carbonated slag enhanced early-age hydration and shortened the setting time. steel slag processed with CO_2 fixation increased the specific surface area, which accelerated the cement hydration process by improving water absorption and reducing the availability of free water [65]. These findings indicate that carbonation pretreatment can significantly alter the fresh behavior of slag-containing concrete mixtures. Moreover, Gencel et al. [7] discussed how pre-wetting steel slag aggregate or using optimized gradation can mitigate workability loss. In high-performance concrete, partial replacement (up to 50%) tends to balance workability loss with mechanical and durability gains. This was corroborated by Nguyen et al.[66] , who reported that moderate slag aggregate content provided acceptable slump values when paired with appropriate water-reducing admixtures.

4. Influence of Steel Slag Incorporation on the Strength Properties of Cementitious Composites

In civil engineering applications, the mechanical behavior of materials remains a cornerstone for structural design and material selection. Key strength parameters compressive, tensile, and flexural serve as indicators of performance under both service and extreme conditions [67–71]. Table 3 outlines the impact of various steel slag applications on these strength characteristics. To complement this data, Fig. 4 illustrates the variation in compressive strength performance associated with different steel slag application methods. As shown, using steel slag as a 50% coarse aggregate replacement significantly enhances compressive strength, with results reaching up to 87.6 MPa. When steel slag undergoes carbonation treatment, the strength gain becomes even more pronounced, achieving a peak of 124.4 MPa, which demonstrates the synergistic effect of mineral reactivity and CO_2 curing. Other applications, such as 10% cementitious content or cement substitution, show moderate strength levels (42–49 MPa), while CO_2-cured composites yield intermediate performance at 72 MPa.

4.1 Steel Slag as a Cementitious Component

The effectiveness of steel slag as a cementitious material has been closely linked to its replacement level within the binder matrix. Studies indicate that compressive strength tends to peak around specific substitution thresholds. For instance, an optimal dosage of 10% steel slag has been reported to yield a 28-day compressive strength of 49.01 MPa, highlighting its potential to partially replace Portland cement without compromising structural performance [72].

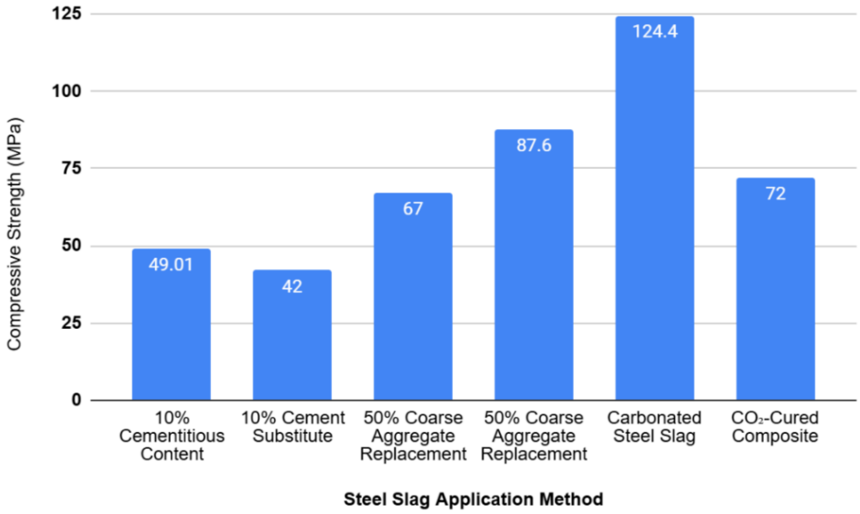

Fig. 4. Compressive strength improvements with steel slag

In a related study, Roslan evaluated steel slag powder as a partial cement replacement at levels of 5%, 10%, 15%, and 20%, identifying 10% substitution as the most effective, achieving 42 MPa at 28 days and a 27% improvement in early strength at 3 days compared to conventional concrete [73]. These results suggest that moderate slag inclusion can accelerate early hydration and enhance strength development. Beyond single-component replacement, steel slag has shown potential in hybrid binder systems. Ranjbar et al. [74] explored calcium carbonate-activated steel slag binders, observing improved microstructure and densification, which translated into higher long-term strength. Ganter et al. [75] examined steel slag combined with cement in stabilized soils and found that slag inclusion significantly enhanced the early and long-term strength, demonstrating promise for infrastructure applications beyond traditional concrete. Further performance enhancement is observed when steel slag is used in combination with ground granulated blast furnace slag (GGBFS) and desulfurized gypsum (DG). When applied as a coarse aggregate, this blended system demonstrated a 22.71% increase in compressive strength, reflecting synergistic effects between supplementary cementitious materials and the slag aggregate framework [76].

Table 3. Strength performance of cement-based composites incorporating steel slag as a partial binder or aggregate replacement

Steel Slag Usage Type	Replacement Ratio	Strength Parameter(s)	Performance Outcome	Reference
Cement replacement	5%, 10%, 15%, 20%	Compressive, flexural, splitting tensile	10% replacement provided peak strength: f_c= 42 MPa, f_t = 5.3 MPa, f_{ts}= 4.1 MPa	[73]
Coarse aggregate	40%, 45%, 50%	Compressive, splitting tensile	50% mix achieved f_c= 87.6 MPa, f_{ts}= 6 MPa (↑12.2% vs control)	[77]
Fine/coarse aggregate	Coarse: 0–80%, Fine: 0–60%	Compressive	Optimal at 50% coarse + 30% fine: f_c= 73.5–74.9 MPa (↑5–19% depending on age)	[78]
Carbonated slag additive	80%, 100% (14-day CO_2 curing)	Compressive	Improved strength; f_c= 72.0 MPa in slag–cement mixes after carbonation.	[79]
Carbonated slag additive	30% (15–240 min CO_2 curing)	Compressive at 3–90 days	Low-carbonated slag ↑ strength (↑8% at 28d); high-carbonated slag ↓ early but ↑ late strength (↑14.7% at 28d).	[80]

4.2 Steel Slag as Aggregate Replacement

Several studies have reported that substituting natural aggregates with steel slag enhances the mechanical performance of concrete, particularly in terms of compressive and flexural strength. For example, incorporating steel slag as a partial replacement for fine aggregates—up to 75%—has been shown to increase compressive strength by approximately 12% compared to conventional mixes [81]. A lower replacement ratio, such as 30%, has also produced favorable strength results when benchmarked against control specimens [82]. Additionally, the flexural performance improves with steel slag integration; a 75% substitution of both fine and coarse aggregates resulted in flexural strength gains of 13% and 15%, respectively [81]. Similar enhancements in tensile strength were observed across varying replacement levels [82].

Yang et al. [77] investigated the substitution of natural coarse aggregates with steel slag and assessed strength development over time. Their findings indicated that a 50% replacement ratio yielded optimal results, achieving 67 MPa compressive strength at 120 days—an 18.2% improvement over traditional concrete. This enhancement was linked to the formation of calcium aluminosilicate compounds during hydration, which contributed to a stronger bond between the aggregate and cement paste. However, beyond this optimal level, the strength benefit diminished due to reduced formation of calcium silicate hydrate (C–S–H) gel. In another study, Lai et al. [78]

examined combined replacement strategies involving up to 80% coarse and 60% fine aggregate substitution. The most effective mix—50% coarse and 30% fine replacement—achieved compressive strength increases of 5.32%, 5.76%, and 19.32% at 7, 28, and 90 days, respectively, highlighting the long-term performance benefits of optimized slag usage.

Meanwhile, Miah et al. [83] reported that partial replacement of natural coarse aggregate with untreated steel slag yielded significant enhancements in compressive, tensile, and flexural strength, indicating its robust structural potential. Work by Mekonen et al. [84] explored moderate substitution levels in reinforced concrete beams. Incorporating 30% steel slag as fine aggregate and 45% as coarse resulted in notable improvements: compressive strength rose at both 7 and 28 days, while flexural strength peaked around 45% replacement—suggesting optimal dosage windows. Table 4 presents a concise summary of key findings from recent studies on the use of steel slag as an aggregate replacement in concrete. The table highlights various replacement strategies—including partial and full substitutions of coarse and fine aggregates—and their corresponding effects on compressive, tensile, and flexural strength. These results demonstrate that optimized steel slag incorporation can significantly enhance the mechanical properties of concrete, offering promising pathways for sustainable construction practices.

Table 4. Summary of steel slag aggregate replacement levels and their associated performance impacts on concrete strength properties

Replacement Type & Level	Performance Impact
100% coarse + fibers	+70% to +170% compressive strength
60% carbonated SSFA	+1–7% compressive gain
Partial (30–45%) slag	Peak 28-day compressive/flexural strengths
25–100% slag pervious mix	Enhanced multi-modal strengths & abrasion resistance

4.3 Influence of CO_2 Treatment on the Functional Properties of Steel Slag

Carbonation increases the compressive strength of steel slag. For instance, carbonated steel slag aggregates showed a compressive strength improvement, with optimal conditions yielding a strength of 124.4 MPa [85]. Additionally, the use of chemical additives like EDTA and Na_2SO_4 further enhances compressive strength [86]. Carbonation reduces the expansion rate of steel slag, addressing the issue of harmful expansion due to free CaO. The formation of $CaCO_3$ during carbonation fills the pores, improving volume stability [87] The CO_2-cured composite reached up to 72.0 MPa in compressive strength [88], consistent with findings by Bukowski and Berger [89].

The effect of low- and high-carbonated steel slag (15 and 240 minutes, respectively) on cement mortars showed 5.3% and 8.0% increases in strength at 7 and 28 days, respectively. However, high-carbonated slag reduced early-age strength by 11.1% but enhanced later-age strength by 14.7% [80]. The early reduction was linked to excessive $CaSiO_3$ consumption reducing hydration reactivity, whereas the later gain stemmed from improved pozzolanic activity due to SiO_2 gel formation [90].

4.4 Optimal Compositions and Recommended Dosages for Steel Slag in Concrete

To facilitate practical implementation and support further research, this section summarizes optimal replacement levels of steel slag in concrete as reported across the literature. These numerical values offer guidance on effective dosages for various performance targets, ranging from mechanical strength to durability under harsh environmental conditions.

The literature consistently identifies 30% steel slag replacement of natural coarse aggregate as an effective threshold for improving compressive, tensile, and shear strength, particularly in structural concrete applications [91–93]. In sulfate-rich environments, increasing the replacement to 40% coarse aggregate has been shown to enhance resistance against chemical attack, improving the long-term performance of concrete exposed to wet–dry or saline cycles [94]. As for fine aggregates, a replacement level of 30% also yields favorable results, contributing to increased compressive strength and enhanced durability [58,95].

When used as a partial cement replacement, steel slag powder demonstrates optimal performance at 20% substitution, enhancing compressive strength, dimensional stability, and long-term hydration [96]. In the case of ultra-high-performance concrete (UHPC) systems, steel slag powder shows improved synergy at a 30% binder replacement level, where it contributes to denser packing and better mechanical outcomes [97]. In self-compacting concrete (SCC), steel fibers derived from slag-enhanced mixes at a dosage of 2% by volume have been found to significantly boost ductility and strength while maintaining workability [98].

These recommended dosages provide a benchmark for mix design in both research and practice. While the optimal percentages may vary slightly depending on slag source, treatment method, and application type, the summarized data serve as a practical reference point for engineers, material scientists, and sustainability researchers aiming to integrate steel slag into durable and eco-efficient cementitious systems.

5. Long-Term Durability Characteristics of Cementitious Systems Incorporating Steel Slag

Ensuring long-term durability is critical for structural integrity and sustainability in concrete applications as in Table 5. This section highlights the performance of steel slag cementitious systems under durability-related stress conditions, including freeze–thaw cycles, sulfate attack, and permeability resistance [99–102]. Fig. 5 provides a visual summary of steel slag's impact on concrete durability across various conditions. As depicted, finer steel slag particles exhibit low resistance, often suffering from high mass and strength losses, particularly when subjected to repeated freeze–thaw cycles or aggressive chemical environments. Steel slag powder, while potentially useful as a partial cement substitute, tends to have lower resistance to chloride ion penetration, which may compromise durability in marine or saline-exposed structures.

Freeze–thaw resistance is a major concern for concrete exposed to cyclic freezing conditions, particularly in temperate and cold regions. Several studies have reported that replacing cement with 4–10% steel slag leads to excellent freeze–thaw performance, with the strength ratio remaining close to 100% even after 80 cycles [103]. When steel slag is used as fine or coarse aggregate at replacement levels of 20–60%, the concrete exhibited limited mass loss (2.2–3.0%) and retained a dynamic modulus in the range of 74.9–91.1% after up to 150 cycles [104]. These findings demonstrate the material's ability to resist microcracking and maintain elasticity under thermal stress, attributed to its dense microstructure and reduced pore connectivity.

Sulfate resistance, another critical durability indicator in environments subject to chemical exposure (e.g., coastal, saline, or sulfate-rich soils), also improved significantly with the use of steel slag. Concrete containing 30–90% slag as coarse aggregate maintained its mechanical properties over a 56-day exposure period, showing a three-phase behavior in strength loss: an initial gain, a mild decline, and subsequent stabilization [105]. This pattern reflects the formation and densification of hydration products such as ettringite and C–S–H, which impede sulfate ingress and reduce cracking potential.

Regarding impermeability and porosity, steel slag incorporation—especially in the range of 0–80% for coarse and 0–60% for fine aggregates—contributes to substantial pore structure refinement. Microstructural investigations using SEM and mercury intrusion porosimetry revealed a notable decrease in harmful capillary pores and overall porosity, leading to improved compactness and reduced permeability [78]. Such characteristics are essential for enhancing resistance to chloride ion penetration and carbonation, particularly in marine and urban environments where durability dictates long-term performance.

Table 5. Performance of concrete with steel slag under freeze–thaw cycles, sulfate attack, and chloride permeability tests

Durability Parameter	Steel Slag Use Type & Replacement Level	Test Conditions / Parameters	Observed Durability Effect	Reference
Freeze–thaw resistance	Cementitious: 4%, 8%, 10%	30–80 cycles; strength ratio test	Strength ratio remained ~100% with increasing slag dosage	[103]
	Fine/coarse aggregate: 20%, 40%, 60%	Up to 150 cycles; dynamic modulus, weight loss	2.2–3.0% weight loss; modulus retained at 74.9–91.1% range	[104]
Sulfate resistance (wet–dry)	Coarse aggregate: 30%, 60%, 90%	56 days; compressive strength & modulus testing	Sulfate resistance improved; strength loss curve shows 3-phase behavior (initial ↑ then ↓)	[105]
Impermeability & porosity	Coarse: 0–80%, Fine: 0–60% (aggregate)	SEM & mercury intrusion analysis	Reduced harmful pores and total porosity; enhanced compactness and impermeability	[78]

5.1 Resistance to Freeze–Thaw Cycles

The incorporation of calcium sulfoaluminate (CSA) cement in concrete formulations has been shown to significantly enhance durability under freeze–thaw conditions. In salt-rich environments, the number of freezes–thaw cycles endured by CSA-modified concrete increased from around 30 to 175, while in fresh water, it rose from approximately 150 to 300. These improvements are primarily attributed to the development of a denser interfacial transition zone (ITZ) and a reduction in matrix microcracking, both of which contribute to greater freeze–thaw resilience [106]. Abendeh et all. [81] investigated 0–75% replacement of fine and coarse aggregates with steel slag found up to 12% higher compressive strength at 75% replacement, coupled with superior freeze–thaw stability, as measured by ultrasonic pulse velocity retention after 250 cycle.

Steel slag, particularly when used as a fine aggregate at a 60% substitution level, has also demonstrated notable improvements in freeze–thaw resistance. Mixes incorporating this level of slag substitution exhibited minimal losses in both mass and compressive strength, along with elevated relative dynamic elastic modulus values, indicating strong resistance to structural degradation under cyclic thermal stresses [107].

5.2 Resistance to Sulfate-Induced Deterioration

The incorporation of steel slag as coarse aggregate in concrete has been shown to significantly improve resistance to sulfate-induced deterioration. In one study, concrete specimens with 60% steel slag replacement demonstrated a 20.7% increase in compressive strength when subjected to a 15% sulfate environment. This enhancement is primarily attributed to the presence of reactive mineral phases such as dicalcium silicate (C_2S) and tricalcium silicate (C_3S), which contribute to the formation of calcium silicate hydrate (C–S–H) gel, thereby improving structural integrity and reducing vulnerability to chemical attack. Further investigation by Cheng et al. [105] assessed sulfate durability under cyclic wetting and drying exposure. Their findings indicated that a 60% replacement level significantly increased the crack resistance coefficient (Kc), signifying enhanced resistance to sulfate ingress. The improved performance was linked to the hydration of free lime (f-CaO), which facilitated the formation of ettringite (AFt) and calcium hydroxide, leading to a denser microstructure and lower permeability.

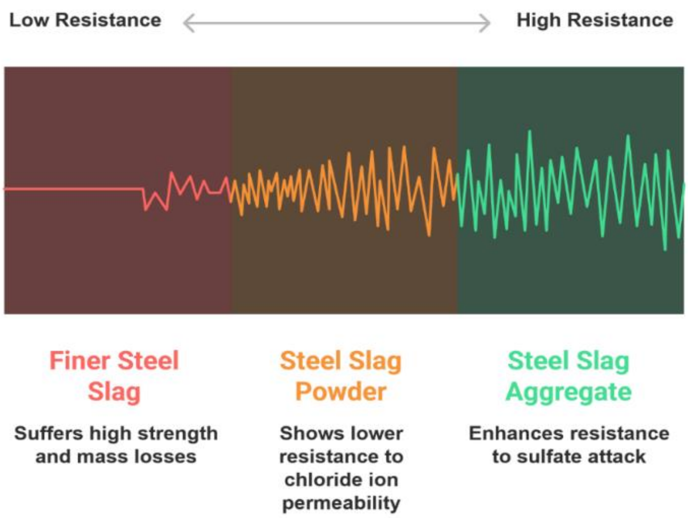

Fig. 5. Steel slag's impact on concrete durability under different conditions

Similarly, blended alkali-activated mixes composed of ground granulated furnace slag, lithium slag, and steel slag (GLS) achieved robust resistance to sodium sulfate attack, maintaining high compressive strength (> 70 MPa at 28 days) and showing minimal formation of expansive phases after prolonged exposure [108]. Another study focusing on cement mixes with 60% steel slag as aggregate confirmed that such mixes attained optimal sulfate resistance; the inclusion of slag's f-CaO hydration products enhanced internal densification, limiting sulfate ingress and reducing susceptibility to ettringite formation [109]. Finally, comparisons between steel-slag and natural-aggregate concretes immersed in sulfate-rich environments demonstrated that slag-containing concretes exhibited less surface deterioration and cracking under wetting–drying cycles, proving that steel slag contributes to denser microstructure and a more resistant interfacial transition zone—critical in halting sulfate penetration [110].

5.3 Chloride Permeability and Pore Structure

The use of steel slag, whether in the form of aggregate or powder, contributes to improved pore structure in concrete, particularly by reducing macrovoids and refining capillary pores. This densification helps lower chloride diffusion coefficients and enhances the material's ability to bind chlorides, largely attributed to the presence of FeO-rich phases within the slag matrix [111]. Such effects are particularly beneficial in marine environments, where delaying chloride ingress is essential to minimizing corrosion risk and prolonging service life.

Chloride permeability performance varies depending on curing conditions and water-to-binder (w/b) ratios. In steam-cured mixes with steel slag, permeability remains moderate at higher w/b ratios but shows marked improvement when lower ratios are employed. When used in conjunction with ultrafine ground granulated blast furnace slag (UGGBS), the chloride resistance is further enhanced due to synergistic pore refinement and reduced ionic mobility [112].Meanwhile, investigations into alkali-activated mixtures containing steel slag showed that elevated slag content and optimized activator blends produced highly refined pore geometry, yielding low chloride diffusivity and superior permeability performance [113]. Other research confirmed that integrating iron and steel slag into concrete contributes to formation of dense, uniform interfacial transition zones and enhanced pore filling through secondary C–S–H and calcium carbonate, reducing total porosity and restricting pore connectivity [114].

Despite these advantages, long-term exposure studies have highlighted some limitations. Over a five-year period, concrete mixes containing steel slag powder exhibited lower resistance to chloride ion penetration than ordinary Portland cement (OPC) concrete. However, this drawback is mitigated when lower w/b ratios are used, suggesting that proper mix design can offset the material's inherent permeability issues [115]. Additionally, comparisons with other pozzolanic materials reveal that ground phosphate slag delivers superior chloride resistance compared to ground granulated blast furnace slag (GGBS) or fly ash. This is attributed to its more compact and uniform pore network [116].

5.4 Microstructural Analysis via Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) offers a detailed view of the microstructure of concrete, particularly in assessing the influence of steel slag incorporation. It is frequently used to observe surface morphology, identify interfacial transitions, and detect microcracking or porosity that arise from hydration and drying processes. In concrete systems, the hydration of cement does not fully occupy the original water-filled voids, resulting in a network of pores ranging from a few nanometres to several microns, which directly impacts frost resistance and long-term durability. SEM analysis enables the visualization of these pore structures and microstructural changes caused by steel slag inclusion [104]. As shown in Fig. 6, notable differences can be observed between the control specimen (Fig. 6a) and the steel slag-modified concrete (Fig. 6b). The control sample exhibits visible microcracks and a loose matrix, indicating weaker interfacial bonding. In contrast, the steel slag-incorporated concrete shows a much denser and more compact structure, with tightly connected particles and fewer microcracks. This improved microstructure is attributed to the filler effect and nucleation sites provided by slag particles, which enhance hydration and packing density.

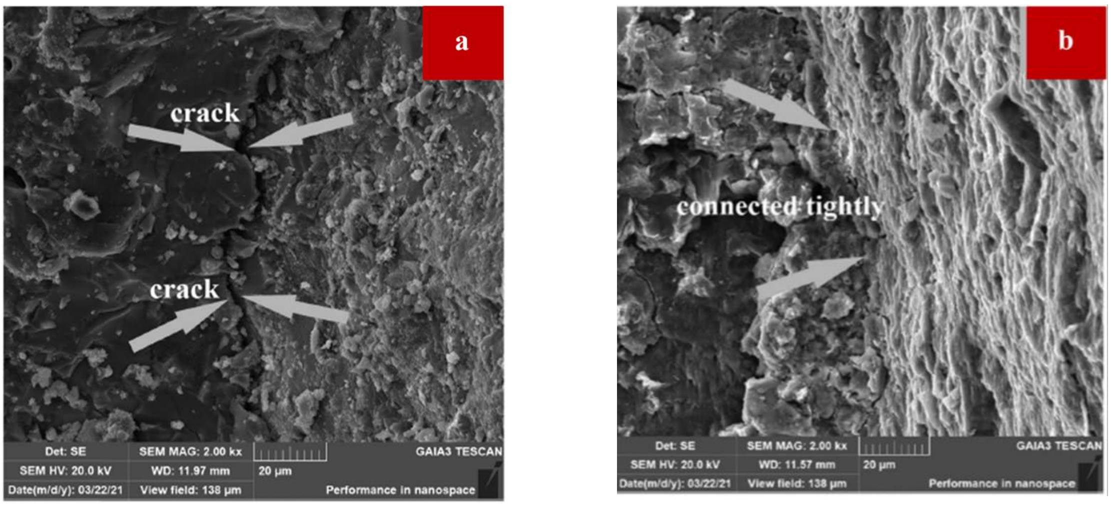

Fig. 6. SEM images of concrete: (a) Control mix with cracks; (b) Steel slag mix with dense, well-bonded structure [104]

6. Methodology

This study employed a bibliometric analysis to systematically examine the global research landscape surrounding the use of steel slag in concrete. The objective was to identify major thematic trends, uncover strategic research clusters, and chart future directions in this evolving field. Bibliometric analysis is a well-established, computer-assisted method for quantitatively evaluating scientific output. It enables researchers to track the development of knowledge domains, detect influential contributors, and expose underexplored areas [117,118]. Given its methodological rigor and capacity for large-scale synthesis, bibliometric analysis is increasingly recognized as a critical tool for strategic research planning across civil engineering and materials science disciplines.

The analytical framework in this study integrated two robust bibliometric tools: VOSviewer and the bibliometrix package in R. VOSviewer was used for visualizing bibliometric maps based on co-authorship, co-citation, and keyword co-occurrence data. The bibliometrix package, on the other hand, enabled comprehensive statistical evaluations and thematic classifications [119]. In constructing bibliometric networks, the study considered both full counting and fractional counting methods. Full counting assigns equal weight to all co-authors or keywords, offering a straightforward interpretation, while fractional counting apportions credit based on contribution, providing more nuanced insights into collaboration patterns. The visual maps generated through these tools depict research entities such as authors, institutions, keywords, and journals as nodes, with their connections represented as edges signifying collaborative or thematic relationships.

The bibliometric methodology followed a structured multi-phase process. First, a dataset of relevant publications was retrieved from the Scopus database, chosen for its broad coverage of peer-reviewed literature in engineering, materials, and environmental science [120]. A dual-layered keyword search strategy was developed. The first layer targeted specific technical terms such as “steel slag concrete,” “slag aggregate,” “slag binder,” and “slag replacement,” while the second included broader sustainability terms like “green concrete,” “waste utilization,” and “low-carbon construction.” This hybrid approach ensured that both technical performance and environmental implications of steel slag usage were captured.

The initial query retrieved 943 records. To ensure analytical reliability, a rigorous two-stage screening protocol was applied. In the first stage, only peer-reviewed journal articles and reviews were retained, excluding conference proceedings, book chapters, and editorials. Publications were restricted to the English language but included all years to allow longitudinal insights into research evolution. In the second stage, articles were evaluated for topical relevance, retaining only those that directly investigated the mechanical, durability, or environmental performance of steel slag in cementitious materials. The remaining dataset was refined further through dedication and metadata standardization using R, following the cleaning protocols outlined by Burnham [120]. This resulted in a final curated dataset of 880 unique publications. Additionally, Fig. 7 presents a conceptual framework linking historical research mapping with the identification of thematic clusters and the development of future research directions in the field of steel slag utilization in concrete.

These records formed the foundation for subsequent analyses. Using VOSviewer and bibliometrix, co-authorship networks were mapped to identify collaborative patterns among researchers and institutions, while keyword co-occurrence analysis revealed dominant and emerging themes in the literature. Citation analysis further highlighted seminal works and influential contributors. The integration of these methods provided a holistic view of the field, facilitating a data-driven exploration of both historical trajectories and emerging research frontiers in the utilization of steel slag for sustainable concrete production.

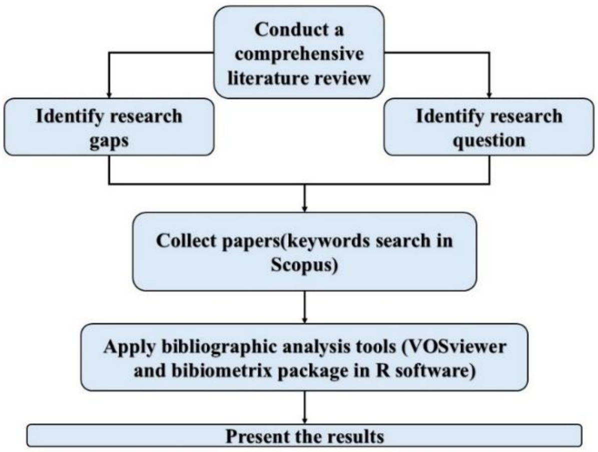

Fig. 7. Conceptual framework for bibliometric and experimental review of steel slag utilization in concrete

7. Document Analysis

7.1 Research Output Trends (2019–2024)

Analyzing publication trends provides critical insights into the evolution and maturity of research domain. Fig. 8 presents a detailed analysis of publication trends related to steel slag utilization in concrete from 2019 to 2023, capturing both annual outputs and cumulative growth. The data show a steady increase in scholarly activity, with annual publications rising from 84 in 2019 to 169 in 2023, more than doubling over the five-year period. The cumulative number of publications reached 656 by 2023, highlighting a significant and sustained growth trajectory in the field.

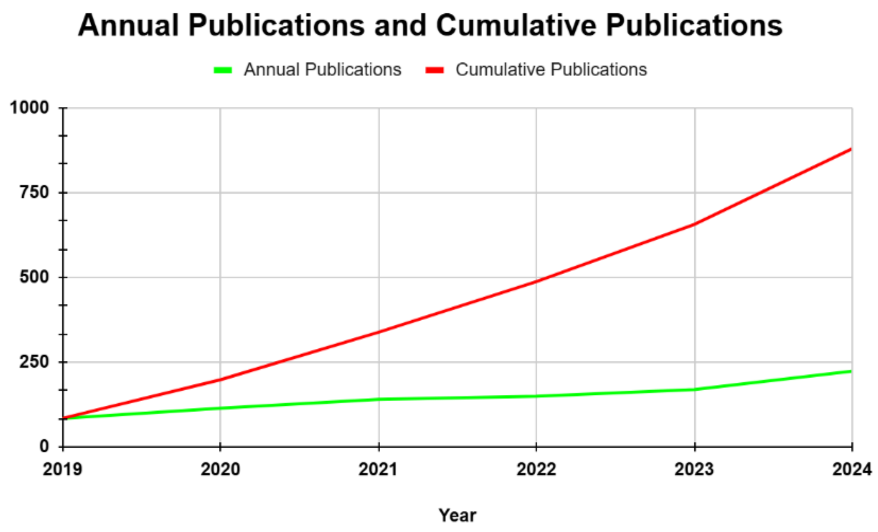

Fig. 8. Trend of publications on steel slag (2019–2024)

This upward trend indicates deepening academic interest in steel slag as a sustainable material in concrete production, driven by increasing global focus on circular economy practices and low-carbon construction alternatives. Although annual growth rates vary slightly from year to year, the consistent cumulative expansion points to the consolidation of steel slag research as a credible area within construction material science. The acceleration in annual outputs, particularly between 2021 and 2023, suggests an active shift from preliminary investigations to more advanced research addressing durability, mechanical performance, and environmental benefits.

The observed publication pattern reflects the rising importance of steel slag in addressing critical issues such as industrial waste management, resource efficiency, and cement reduction. Moving forward, research is likely to concentrate on optimizing slag processing techniques, enhancing its compatibility with supplementary cementitious materials, and assessing long-term structural performance under diverse environmental conditions. The cumulative publication surge affirms steel slag's emerging role in advancing sustainable and resilient infrastructure solutions.

7.2 Global Research Contributions by Country

Identifying the key contributing countries in the domain of steel slag utilization in concrete provides valuable insights into global research leadership, collaboration intensity, and knowledge dissemination. Fig. 9 and 10 offer a comparative analysis of the global distribution of research outputs and citation impacts in this field.

As presented in Fig. 9, China leads the global research landscape with 7,668 citations across 380 documents, indicating both prolific output and substantial scholarly influence. India follows with 1,844 citations from 163 publications, reflecting strong national commitment and growing visibility. Other notable contributors include Viet Nam (926 citations), Iraq (559 citations), and the United States (649 citations), each contributing significantly to the scientific discourse. Fig. 10 highlights the volume of publications by country. China again dominates with 380 documents, followed by India (163), South Korea (31), Viet Nam (32), and the United States (36), demonstrating concentrated research activity across Asia and North America. Countries like Australia, Saudi Arabia, Brazil, Malaysia, and Italy also show consistent engagement with 17–27 publications each, indicating broader international interest in steel slag applications.

Interestingly, there are discrepancies between publication counts and citation impact. For example, Germany and Portugal have fewer documents (9 and 21, respectively) but relatively high citations per paper, suggesting focused, high-impact studies. Similarly, Iraq and Viet Nam exhibit notable citation strength despite smaller research volumes, likely attributed to internationally collaborative or innovative research outputs.

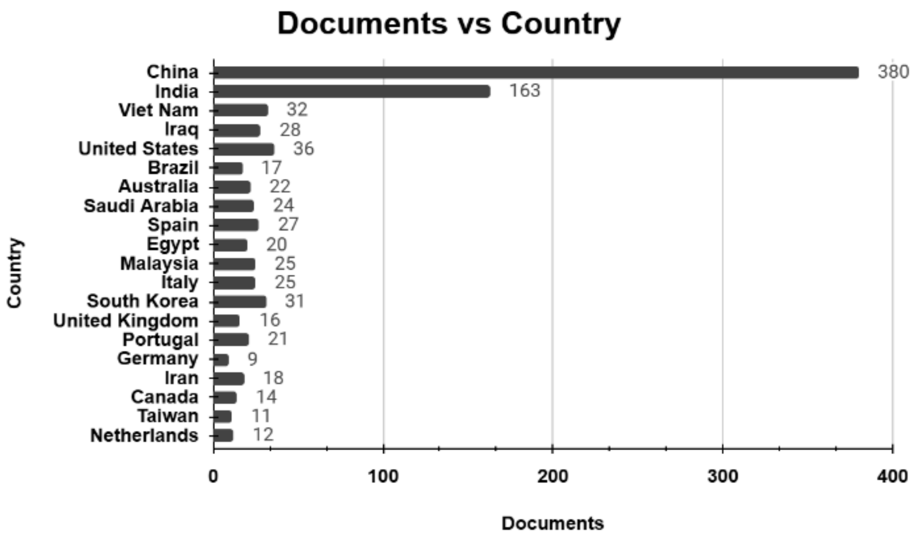

Fig. 9. Publication volume by country on steel slag concrete research

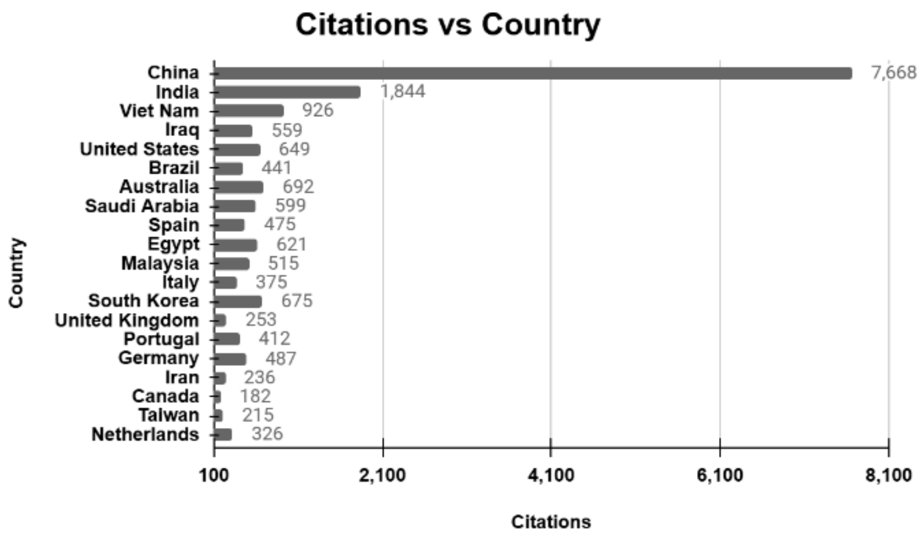

Fig 10. Citation impact of leading countries in steel slag concrete research

7.3 International Collaboration and Co-authorship Networks

The global distribution of research activity, as illustrated in Figure 11, highlights the highly interconnected and collaborative nature of the research landscape surrounding steel slag utilization in concrete. The visualization reveals dominant and densely linked research hubs, with China and India emerging as the most central and influential contributors evident from their large node sizes and extensive linkage with other countries. Other notable countries with strong collaborative networks include Iraq, Vietnam, South Korea, and the United States, indicating their significant roles in advancing knowledge through international partnerships.

The visual clustering of countries from different regions such as Europe (Germany, Italy, Portugal, Netherlands), Asia (China, India, Iraq, Malaysia, Vietnam), and the Middle East (Saudi Arabia, Egypt, Iran) underscores the global and multidisciplinary nature of the research community. The network density and cross-continental connections reflect a robust ecosystem of scientific exchange, where nations with varying technological capacities and research infrastructures collaborate on shared objectives, such as sustainable construction, circular economy practices, and low-carbon concrete solutions.

The sharp increase in publication volume reflects not only scholarly interest but also the rising industrial demand for steel slag as a sustainable construction material. As environmental regulations tighten and the push for low-carbon infrastructure accelerates, many countries are incentivizing the reuse of industrial by-products like steel slag in concrete and pavement applications. Global steel production continues to grow, generating over 250 million tons of slag annually—of which a substantial portion remains underutilized. This underlines the enormous untapped potential of steel slag in replacing natural aggregates and cement, particularly in emerging economies facing raw material scarcity. Based on current publication trajectories and global infrastructure trends, it is anticipated that steel slag utilization in cementitious systems could double within the next decade, especially with the adoption of smart concrete technologies, carbonation treatments, and circular economy frameworks.

7.4 Temporal and Geographic Distribution

Fig. 12 illustrates the global distribution of research activity on steel slag utilization in concrete between 2019 and 2024, with countries shaded according to their average publication year, indicating the recency and maturity of research engagement. The map highlights significant contributions from China and India, both of which demonstrate high publication volumes and recent research activity, with average publication years of 2022.09 and 2021.95, respectively. These countries also exhibit strong international collaboration, reinforcing their leadership roles in the global steel slag research network.

Notably, countries such as Canada (2022.83), Egypt (2021.82), and Brazil (2021.59) reflect sustained and timely engagement, suggesting their growing interest in sustainable construction materials. Australia (2021.00), while showing slightly earlier average activity, remains a consistent contributor to international efforts. This trend underscores the geographical expansion of scholarly participation, with newer entrants like Malaysia, Iran, and South Korea also playing increasingly prominent roles in regional research ecosystems.

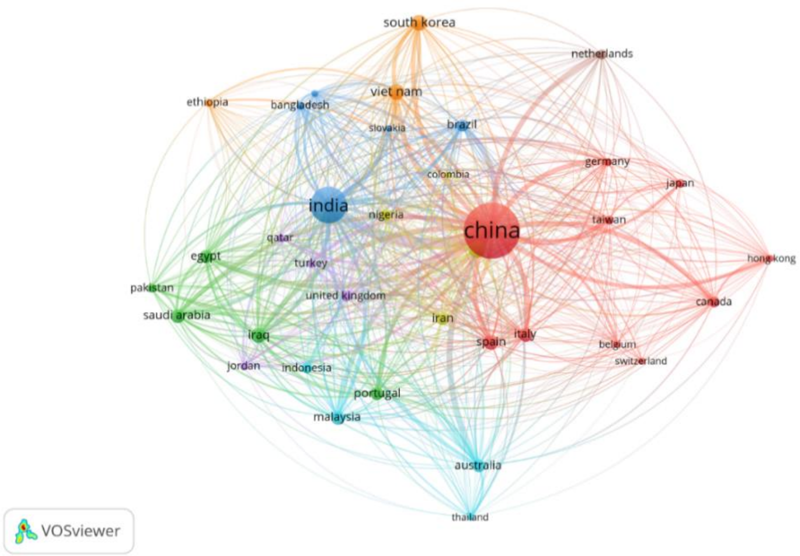

Fig. 11. Global co-authorship network showing collaboration intensity in steel slag research

The color gradient in the spatial visualization—ranging from earlier to more recent average publication years—demonstrates both the temporal dynamics and geographic breadth of research. Countries with darker shading reflect more recent academic focus, pointing to ongoing innovation and growing institutional attention. This global map reinforces the importance of cross-border collaboration and knowledge exchange, emphasizing how diverse nations are collectively contributing to the advancement of low-carbon, resource-efficient concrete technologies using steel slag.

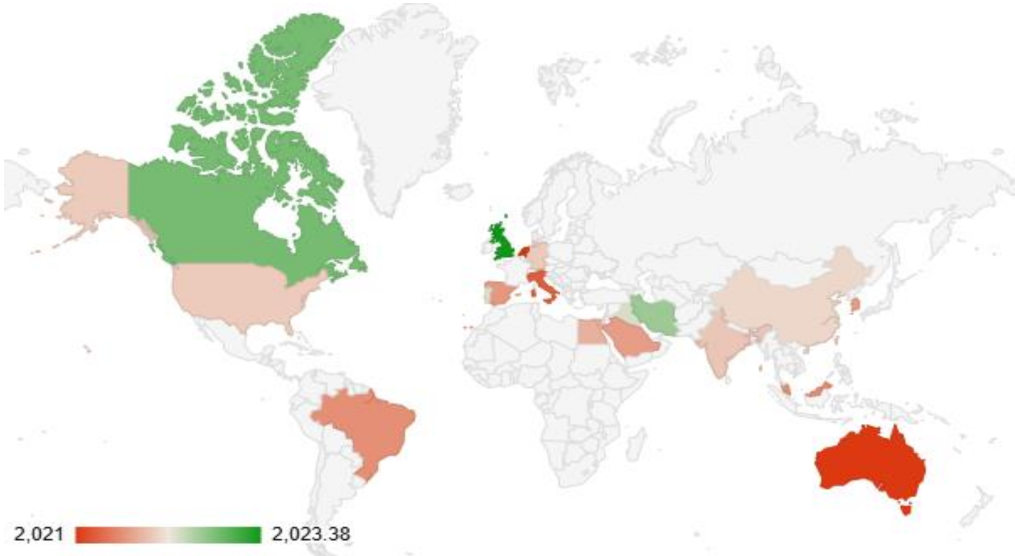

Fig. 12. Average publication year by country in steel slag concrete research (2019–2024)

7.5 Leading Institutions and Research Organizations

The analysis of institutional contributions to steel slag utilization in concrete research reveals a dynamic and globally interconnected academic landscape. Fig. 13 highlights the most active organizations in this domain, with the State Key Laboratory of Silicate Materials for Architectures at Wuhan University of Technology (China) leading with 25 publications and 624 citations, underscoring its central role in advancing sustainable construction materials.

Following closely are prominent institutions such as the Civil Engineering Department, University of Sulaimani (Iraq) with 8 publications and 264 citations, and the Department of Highway and Bridge Engineering, Erbil Polytechnic University (Iraq) with 6 publications and a notable total link strength of 8,747, reflecting strong research connectivity and collaboration.

Several other institutions also demonstrate sustained contributions, including the School of Civil Engineering at Central South University (China), Soran University (Iraq), and Shenyang Jianzhu University (China), each with 6 publications, indicating robust regional engagement. Specialized research centers such as the State Key Laboratory of Solid Waste Reuse for Building Materials and the School of Civil and Resource Engineering at the University of Science and Technology Beijing further emphasize China's extensive investment in steel slag innovation.

This institutional distribution reflects not only the multidisciplinary nature of steel slag research but also the growing global commitment to transforming industrial waste into high-performance construction materials. The breadth of contributing universities across Asia and the Middle East highlights an expanding international research network addressing critical challenges in cement reduction, resource recovery, and sustainable infrastructure development.

At the individual level, Fig. 14 highlights the most prolific authors contributing to the advancement of steel slag utilization in concrete. Ni, Wen leads the field with 13 publications, reflecting both consistent scholarly output and a strong presence in collaborative networks. Wu, Shaopeng follows closely with 11 publications, indicating sustained engagement in research focused on sustainable pavement and concrete materials. Other highly active contributors include Hamad, Samir M. and Mo, Liwu, each with 8 publications, suggesting their significant roles in advancing technical understanding and environmental applications of steel slag. Lai, M.H., also with 8 publications, has contributed notably to performance analysis and materials innovation. These leading researchers exemplify the growing depth and specialization within the field, driving innovation through both experimental research and international collaboration.

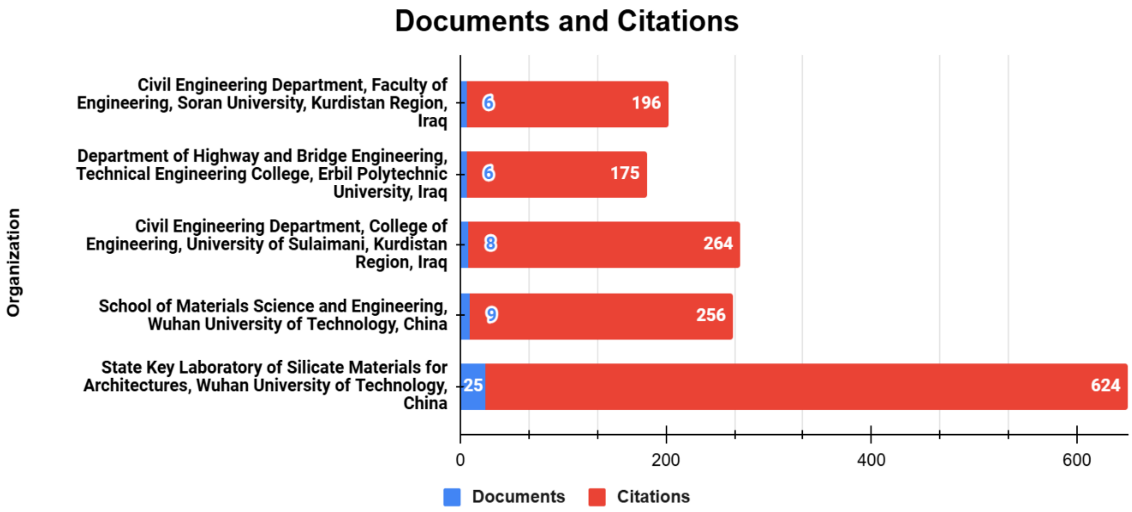

Fig. 13. Top contributing organizations in steel slag concrete research, with data on publications, citations, and research link strength

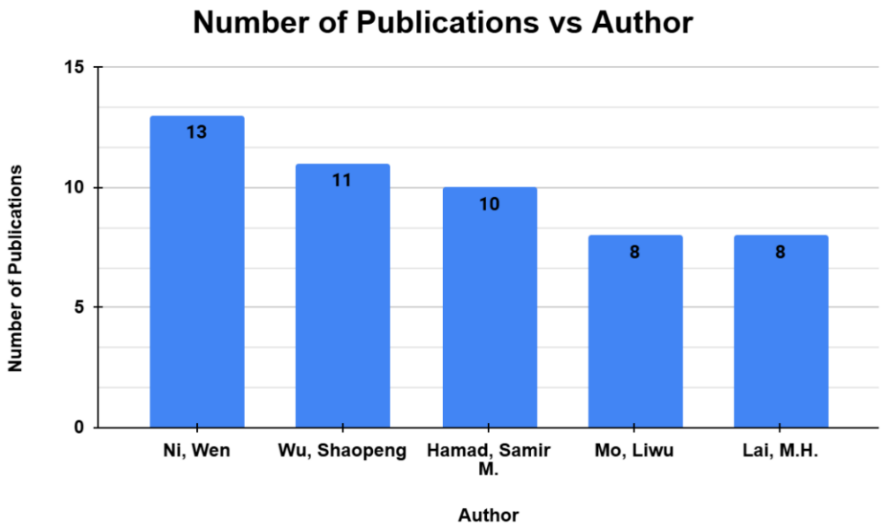

Fig. 14. Top five most active authors in steel slag research based on publication count

7.6 Citation Impact and Influential Publications

Another important consideration for researchers is identifying publications that have significantly contributed to advancing academic knowledge in the field of steel slag utilization in concrete. Citation analysis serves as a key indicator for determining the impact of scholarly work, revealing foundational studies, emerging research directions, and influential technological developments. Highly cited publications often represent pioneering research that has shaped scientific discourse and laid the groundwork for further innovation.

To identify the most influential articles and their contributions, Table 6 presents the top five highly cited publications in the domain. These studies encompass diverse themes such as material reuse, durability, mechanical performance, and sustainability in concrete production. The publication titled “Use of steel slag as sustainable construction materials for artificial reef: Engineering and ecological perspectives” by Song et al. leads with 286 citations, reflecting its groundbreaking role in both engineering application and ecological assessment. Closely following is the paper “Steel slag and its applications in cement and concrete technology: A review” by Gencel et al., also with 285 citations, which provides a comprehensive review of steel slag’s performance as a cementitious material and aggregate substitute.

Another major contribution is the study by Van Dao et al., “Artificial intelligence approaches for predicting properties of concrete containing industrial waste: A review”, which garnered 283 citations, showcasing the growing relevance of AI-based modeling in sustainable materials research. Also notable is "Recycling of steel slag aggregate in portland cement concrete: An overview" by Dong et al., with 196 citations, emphasizing the practical implications of steel slag in concrete recycling and infrastructure design. Finally, the study "Performance of geopolymer concrete containing steel slag aggregate: Mechanical and microstructural properties" by Aly et al., with 191 citations, highlights the integration of steel slag into geopolymer systems for enhanced sustainability and performance.

Table 6. Most highly cited publications on steel slag applications in concrete, indicating foundational contributions to the field

Ref	Title	Year	Total Citations
[121]	Use of steel slag as sustainable construction materials: A review of accelerated carbonation treatment	2021	286
[7]	Steel slag and its applications in cement and concrete technology: A review	2021	285
[60]	Artificial intelligence approaches for prediction of compressive strength of geopolymer concrete	2019	283
[122]	Recycling of steel slag aggregate in portland cement concrete: An overview	2021	196
[123]	Performance of geopolymer concrete containing recycled rubber	2019	191
[124]	Preparation, microstructure and property of carbonated artificial steel slag aggregate used in concrete	2020	150
[125]	Strength performance of cement/slag-based stabilized soft clays	2019	145
[126]	Application of steel slag in cement treated aggregate base course	2020	143
[127]	Environmental benefit assessment of steel slag utilization and carbonation: A systematic review	2022	143
[78]	Improving mechanical behavior and microstructure of concrete by using BOF steel slag aggregate	2021	141

Fig. 15 illustrates the publication trends from 2019 to 2024 in the five most prolific journals contributing to research on steel slag utilization in concrete. The data clearly show that Construction and Building Materials stands out as the dominant publication outlet, with a strong and increasing output that peaked sharply at 40 publications in 2024, underscoring its central role in disseminating cutting-edge research on sustainable concrete technologies.

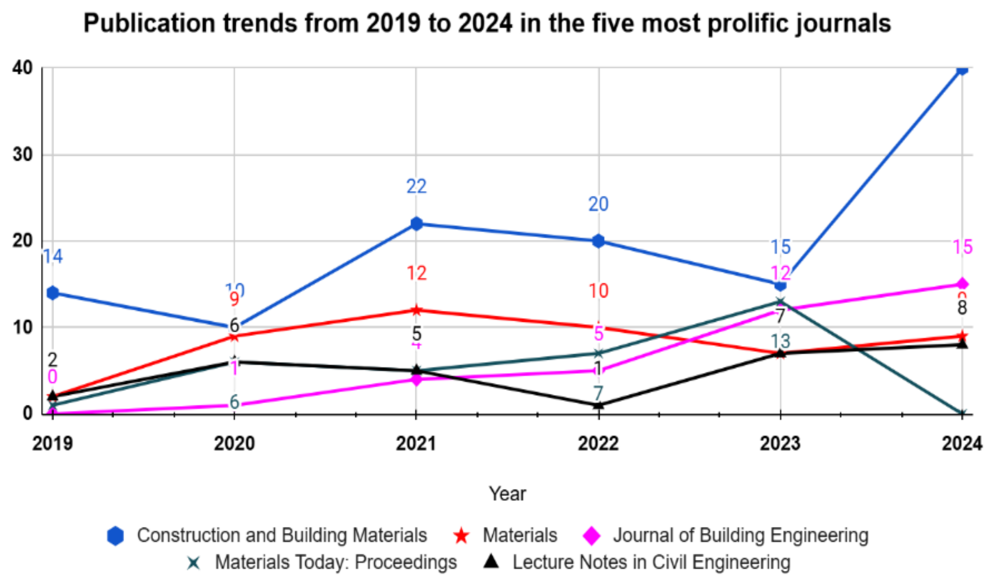

Fig. 15. Publication trends in the five most productive journals contributing to steel slag concrete research from 2019 to 2024

Materials follow as another key contributor, maintaining a steady upward trend in publication volume, particularly between 2020 and 2021, and sustaining consistent contributions through

2024. This highlights the journal's significance in addressing materials innovation and waste valorization in cementitious systems. Journal of Building Engineering shows a dramatic rise in output beginning in 2021, increasing to 15 publications by 2024, indicating growing attention to steel slag applications in practical and structural engineering contexts. Materials Today: Proceedings also demonstrated significant productivity, especially in 2023, with earlier peaks in 2020 and 2021, reflecting the importance for conference-based dissemination of emerging research. Meanwhile, Lecture Notes in Civil Engineering maintained stable activity throughout the period, with notable publication counts in 2020, 2021, and 2023, emphasizing its role in presenting steel slag research within academic and technical proceedings. Overall, these publication trends reveal the interdisciplinary and practice-oriented nature of steel slag research. The consistent and growing output across engineering and materials science journals underscores the critical role of these platforms in supporting sustainable construction innovation and circular economy approaches in civil infrastructure.

7.7 Keyword Co-occurrence and Thematic Clustering

The keyword co-occurrence network generated using VOSviewer, as shown in Fig. 16, reveals distinct clusters that reflect the thematic focus of steel slag research in concrete applications. These clusters emerge from the frequency and co-usage of keywords across hundreds of publications and represent the structure of scientific discourse in this field. Prominent terms such as "steel slag," "compressive strength," "durability," "concrete aggregates," and "hydration" dominate the network, indicating the core technical concerns related to mechanical performance, mix design, and material sustainability. The clustering also points to research pathways in waste valorization, microstructure evaluation, and structural optimization.

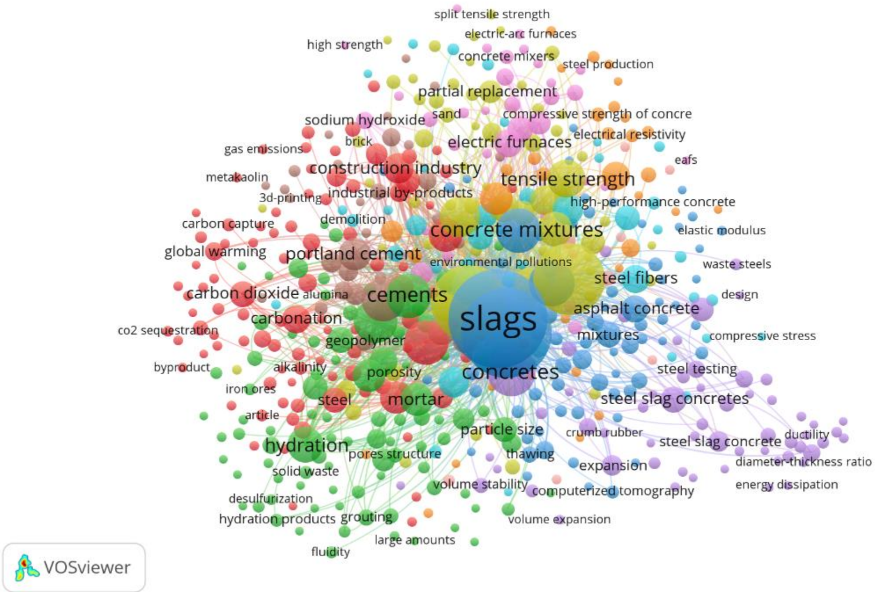

Fig. 16. Keyword co-occurrence network visualizing thematic clusters in steel slag research, generated using VOSviewer.

This cluster centers on the incorporation of steel slag in cementitious systems and the optimization of concrete mixtures. Core keywords include steel slag, concrete aggregates, cements, portland cement, coarse aggregates, and blast furnaces. Research in this area focuses on evaluating steel slag as a replacement for natural aggregates or as a supplementary cementitious material. Studies emphasize its influence on workability, setting time, and hardened properties Key challenges include ensuring particle compatibility, preventing excessive expansion due to free lime or magnesium oxide, and maintaining consistency across slag sources. Researchers are also investigating the role of hydration behavior and cement chemistry in mixtures with varying slag contents.

This cluster highlights performance-related themes such as compressive strength, tensile strength, durability, microstructure, and mechanical properties. These studies evaluate the effects of steel slag on the physical and structural behavior of concrete under short- and long-term loading. Advanced characterization techniques—such as scanning electron microscopy (SEM), X-ray diffraction (XRD), and ultrasonic pulse velocity (UPV)—are often used to investigate microstructural refinement, pore structure, and strength development. Numerous studies report that steel slag incorporation improves mechanical resilience due to its angularity, hardness, and mineral content. For example, reports increased compressive and tensile strength when steel slag is used as a coarse aggregate, particularly in synergy with fly ash or silica fume. Meanwhile, durability evaluations address carbonation resistance, sulfate attack, and freeze-thaw performance—key considerations in structural and pavement applications.

A third thematic group focuses on environmental concerns and sustainability frameworks. Dominant terms include recycling, sustainable development, construction industry, global warming, carbon dioxide, and carbonation. This cluster reflects the circular economy potential of steel slag and its role in reducing the carbon footprint of traditional Portland cement production. Researchers explore the lifecycle benefits of using industrial by-products, including lower greenhouse gas emissions, reduced reliance on virgin raw materials, and long-term resource efficiency. Studies such as emphasize the dual benefits of performance and environmental impact reduction, especially when slag is sourced from electric arc furnace (EAF) or blast furnace (BF) processes. The integration of steel slag into low-carbon construction strategies, combined with supportive policy and industry practices, underscores its growing relevance in achieving sustainability targets and enhancing the resilience of infrastructure.

8. Future Research Pathways in Steel Slag Utilization in Concrete

Building upon the bibliometric findings and keyword clustering shown in Fig. 17, several underexplored and emerging directions in the field of steel slag-based concrete have been identified. These future research pathways not only reflect ongoing advances in sustainable construction materials but also align with global efforts to reduce industrial waste, decarbonize cement production, and enhance infrastructure resilience. As the construction industry seeks innovative, eco-efficient solutions, the following areas warrant focused investigation. With increasing demand for decarbonized materials, steel slag is expected to play a pivotal role in green construction strategies, especially as policy and performance standards evolve to support large-scale industrial reuse.

One promising avenue is the development of smart concrete systems using steel slag, particularly through the integration of embedded sensors and self-monitoring technologies. Despite the rising interest in structural health monitoring and durability tracking, there remains a gap in applying these innovations to slag-containing concrete. Future research should explore self-sensing concrete using conductive steel slag fillers, enabling real-time monitoring of crack formation, temperature, and stress conditions—especially in harsh environments or critical infrastructure applications.

Another important direction is the optimization of binder systems incorporating steel slag. While blended cements with fly ash, GGBS, and steel slag have demonstrated improved mechanical properties and durability, the performance of alkali-activated binders, geopolymers, and carbonated slag systems remains under-researched. Future studies should investigate how varying activation methods and mix proportions influence hydration kinetics, shrinkage behavior, and long-term performance across diverse exposure conditions.

Additionally, research should focus on long-term durability and microstructural evolution of slag-based concrete. Though compressive strength and tensile behavior are widely reported, fewer studies have examined sulfate attack, chloride ingress, alkali-silica reaction, or freeze-thaw resistance in slag-rich mixes. Life-cycle studies combining mechanical degradation with environmental exposure are essential to validate steel slag's reliability in large-scale structural applications.

A critical challenge remains in standardizing slag quality and treatment. Due to variations in chemical composition and mineralogy between blast furnace slag and electric arc furnace (EAF) slag, establishing pre-treatment protocols (e.g., aging, carbonation, or magnetic separation) is key to ensuring consistent performance. Future research should establish internationally harmonized guidelines for slag classification, processing, and suitability for concrete production.

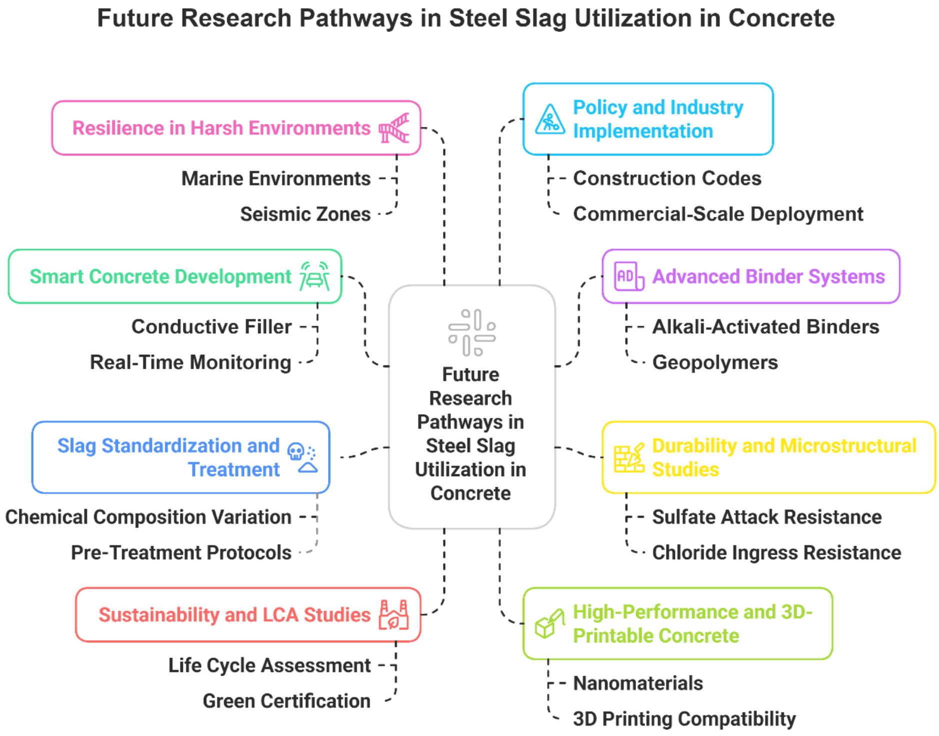

Fig. 17. Future research pathways in steel slag utilization in concrete

From a sustainability perspective, comprehensive life cycle assessment (LCA) and carbon footprint analysis of slag-concrete systems are urgently needed. While environmental benefits such as reduced clinker demand and waste reuse are well acknowledged, data on embodied energy, transport emissions, and economic feasibility remain limited. Future work should develop standardized LCA frameworks integrating environmental, economic, and social dimensions to support green certification and policy adoption.

Moreover, high-performance concrete (HPC) and ultra-high-performance concrete (UHPC) with steel slag present untapped potential. The synergy of steel slag with nanomaterials (e.g., nano-silica or graphene oxide), fiber reinforcements, or superplasticizers in HPC systems can yield advanced mechanical properties, ductility, and toughness. Investigations into 3D-printable slag-based concrete for digital construction could further revolutionize applications in sustainable building technologies.

Resilience under extreme environmental conditions—such as aggressive marine exposure, high thermal gradients, and seismic loading—is another vital frontier. Future studies should prioritize the adaptation of slag concrete for coastal defenses, transport infrastructure, and post-disaster reconstruction, ensuring durability and performance under climate-induced stressors.

Finally, there is scope for exploring policy frameworks and industry implementation models. Despite technical feasibility, widespread adoption of steel slag concrete faces regulatory, logistical, and market challenges. Research into construction codes, public procurement incentives, and supply chain optimization can facilitate the transition from lab-scale innovation to industry-wide application.

9. Conclusion

This study presents a holistic and multidisciplinary assessment of steel slag utilization in concrete, bridging bibliometric mapping with detailed experimental evidence to draw meaningful insights for sustainable construction practices. Through the analysis of 880 Scopus-indexed publications and the critical synthesis of material performance data, the review provides a clear roadmap for transforming steel slag from a high-volume industrial by-product into a strategic component in low-carbon cementitious systems.

- Material Suitability and Composition: Steel slag, owing to its mineralogical composition—including reactive phases like C_2S, C_3S, and RO solids—exhibits promising cementitious and pozzolanic properties. Its high density, angularity, and latent hydraulic reactivity make it suitable for use as both binder and aggregate replacement, albeit requiring pre-treatment to mitigate expansion risks due to f-CaO and MgO.
- Workability Considerations: The fresh-state performance of slag-based concrete is highly dosage-sensitive. As a binder, steel slag enhances slump at around 15% replacement but reduces it at higher dosages. As fine aggregate, 30% substitution maintains cohesion and flowability. Coarse slag negatively affects workability due to angular morphology, though this can be offset using admixtures or optimized grading.
- Mechanical Performance Optimization: Experimental findings confirm that steel slag can significantly enhance mechanical properties. Optimal compressive strength (up to 124.4 MPa) was recorded in CO_2-cured mixes with 50% coarse aggregate replacement. Cement replacement at 10–15% consistently delivered compressive strengths above 42 MPa, while hybrid systems involving GGBFS or silica fume showed synergistic strength gains.
- Durability Enhancement: Durability outcomes further reinforce steel slag's suitability for long-life infrastructure. Notable improvements were observed in sulfate resistance, freeze–thaw durability, and chloride impermeability. SEM analysis confirmed denser microstructures with reduced pore connectivity, supporting long-term performance under aggressive environmental exposures.
- Optimal Compositions: Based on an extensive literature review, ideal substitution ratios include 10–15% for cement, 30% for fine aggregates, and 30–50% for coarse aggregates. In SCC and UHPC, 2% slag-derived steel fiber and 30% slag powder yielded high ductility and strength, supporting structural applications with enhanced sustainability.
- Bibliometric Insights: The bibliometric component highlighted exponential growth in steel slag research from 2019–2024, with China, India, and Iraq leading in both output and influence. Keyword clustering revealed thematic foci in mechanical performance, durability, and environmental optimization. VOSviewer analysis illustrated growing international collaboration and identified underexplored niches such as self-sensing concrete and slag–geopolymer synergy.
- Research Gaps and Future Pathways: Despite significant progress, several challenges remain. These include slag heterogeneity, lack of universal treatment standards, limited field-scale validations, and incomplete understanding of long-term performance under extreme conditions (marine environments, seismic zones). Future work must address smart concrete systems, nanomaterial integration, alkali activation mechanisms, and life-cycle cost–benefit analysis.
- Policy and Industry Relevance: From a policy perspective, encouraging steel slag usage through incentives, green labeling, and performance-based codes can accelerate market uptake. Industry implementation will benefit from robust standards, pre-treatment protocols, and validated mix designs tailored to regional material characteristics.

In conclusion, steel slag offers a high-potential route toward sustainable, durable, and resilient infrastructure. Through targeted optimization, interdisciplinary research, and policy support, this material can transition from an industrial burden into a key enabler of circular economy in the construction sector. This review provides a comprehensive foundation for researchers, engineers, and policymakers to collaboratively advance the large-scale adoption of steel slag in next-generation concrete systems.

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