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REVIEW ARTICLE

Steel slag utilisation in concrete: A review of its effects on workability, flexural strength, tensile behaviour, and sustainability

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Abstract – Steel slag is a waste material derived from the steel refining process. Over the years, the steel slag has gained its potential as sustainable alternative material as a partial cement and aggregate replacement in concrete industry. This paper examines chemical composition and the impact of adopting steel slag on the workability and mechanical properties of concrete. Physically, the steel slag is angular, rough, porous and dense. Such characteristic reduces the workability of fresh concrete. In order to produce optimized mix design using steel slag, water reducing admixture should be used to ensure that the workability of the mix fall within the acceptable workability. Mechanically, the use of steel slag improves the interfacial transition zone which improve the mechanical, flexural and tensile strength of concrete. Besides that, investigation of high-performance concrete reveals that steel slag improved the ductility and serviceability of concrete. In this paper, a comprehensive use of steel slag is being discussed with the aim for broader adoption is sustainable concrete technology. Overall, steel slag emerges as a promising material that balances enhanced structural performance with environmental sustainability.

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1. Introduction

The construction industry is perceived as one of the major contributors to high carbon emissions that pollute the environment. Over the years, extensive research has been conducted to identify sustainable alternatives that can curb carbon emissions in concrete production. In general, cement production accounts for approximately 8% of global CO_2 emissions [1]–[2]. Considering environmental challenges, alternative materials have been explored, particularly derived from industrial waste, to reduce dependence on cement while maintaining high concrete performance. Steel slag, a by-product of the steel manufacturing process, is a promising alternative for partial cement replacement in concrete. The waste is generated by separating molten steel from its impurities in a furnace [3]. Traditionally, steel slag is perceived as a low-value material and is managed through landfilling or as road base construction materials [4]. High levels of steel slag in landfills may cause soil and water pollution due to leachate containing heavy metals that enter the soil and water sources. Many studies have shown that using steel slag as a partial cement replacement improves concrete properties while minimising the environmental impacts of steel slag waste and issues associated with cement production. Some studies suggest that steel slag has a favourable chemical and mineral composition, which improves the mechanical properties and durability of concrete. It is observed that the use of steel slag as partial cement replacement enhances the compressive strength of concrete. Besides, it provides a stronger, more concrete matrix, which reduces permeability and increases resistance to environmental factors such as chemical attack and freeze-thaw cycles in cold regions [5]. The improvement of the concrete matrix resulted from the pozzolanic reaction between steel slag and calcium hydroxide, which formed more calcium silicate hydrate (C-S-H) [6]. The occurrence of C-S-H improves the concrete strength development, thus producing better strength and quality of concrete. From an environmental perspective, the use of steel slag for concrete production offers several sustainability advantages. The use of partial cement replacement reduces the dependency on Portland cement. Therefore, using steel slag as partial cement replacement would significantly reduce carbon dioxide emissions. Besides, the effort to transform steel slag waste as partial cement replacement in concrete reduces the issues with landfilling by steel industrial waste. The use of slag is perceived as an effort to align with the principles of the circular economy [7]. In this way, it not only diverts waste from the landfill but also reduces the extraction of non-renewable natural resources. Thus, the overall environmental footprint of construction activities can be further reduced.

Current studies mainly focus on the optimal application of steel slag as a partial cement replacement to maximise concrete performance while mitigating potential drawbacks associated with its chemical content. Cai et al [8] suggested that the optimal steel slag replacement is very much dependent on the physical and chemical characteristics of steel slag. The physical characteristics such as the fineness and the composition of steel slag are critical to achieve acceptable results. This paper aims to explore the feasibility of using steel slag as a cement replacement in concrete, evaluating its performance, environmental benefits, and potential for broader adoption in sustainable construction. Steel slag shows promise as a sustainable concrete material. However, key research gaps limit its wider use. Most studies replace aggregates instead of cement, leaving its cementitious behaviour and hydration mechanisms unclear. Variations in slag composition and poor understanding of its reactivity and long-term durability cause inconsistent results. Few studies connect microstructure to mechanical performance or assess full life-cycle impacts. More research is needed to refine

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mix proportions, activation methods, and performance standards. This will support the use of steel slag as a green cement alternative.

2. Methods and Materials

In this study, a comprehensive literature search related to the mechanical properties of steel slag has been conducted. Scopus database from 2019 to 2025 has been explored. The search used a combination of keywords and Boolean operators to maximise coverage and relevance. This search query was applied to titles, abstracts, and keywords of journal articles, conference papers, and reviews. Studies were included if they reported experimental, analytical, or review-based data related to the mechanical behaviour of concrete incorporating steel slag, a supplementary cementitious material (SCM). Duplicate records were removed, and the remaining publications were screened for relevance based on titles and abstracts. Full-text articles were then reviewed in detail to extract data on tensile strength, compressive strength, modulus of elasticity, and microstructural characteristics. Figure 1 shows the process of comprehensive literature search for the research.

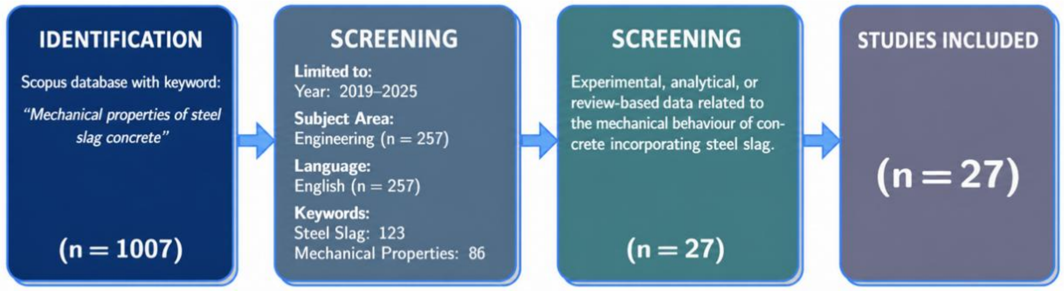

Figure 1. The process of comprehensive literature review search

3. Results and Discussion

3.1 Steel Slag Composition

Steel slag is the byproduct of the steel-making process. The chemical composition of steel slag varies depending on the steel production method, namely basic oxygen furnace (BOF), electric arc furnace (EAF), and open-hearth furnace (OHF). The comparison of the chemical composition of steel slag produced by different methods is shown in Table 1. The chemical composition of steel slag varies considerably depending on the steelmaking process, which directly influences its reactivity, stability, and overall suitability for use in concrete. Compared with other types of steel slag, BOF slag typically contains a higher amount of CaO and a lower amount of Fe_2O_3. The high CaO content with dicalcium silicate enhances the cementitious potential of BOF slag. BOF slag is more stable and functions as a partial cement replacement in aged or weathered conditions. The use of aged or weathered BOF slag enhances the mechanical strength of concrete, thus reducing the demand for clinker in cement production. However, untreated BOF slag often contains free lime (CaO) and magnesia (MgO), which can hydrate and expand, leading to internal stress, cracking, and a loss of durability if not properly managed [9] – [10].

Table 1. Chemical composition of steel slag by production method [9] –[14]

Chemical Components	BOF Slag, (%)	EAF Slag, (%)	OHF Slag, (%)
Calcium oxide (CaO)	40-55	25-45	35-45
Silicon dioxide (SiO_2)	10-18	10-20	15-25
Iron oxide (Fe_2O_3)	10-30	20-40	10-30
Aluminium oxide (Al_2O_3)	1-6	4-10	2-6
Magnesium oxide (MgO)	5-10	5-15	5-10
Manganese oxide (MnO)	2-8	3-8	2-5
Phosphorus pentoxide (P_2O_5)	0.5-2.0	0.3-1.5	0.5-2.0

AEF on the other hand, in comparatively, contain higher Fe_2O_3 and larger variable composition since it is derived from the recycled metal scrap. The chemical components in EAF slag are relatively more stable; however, they are less reactive than those in BOF slag. Since EAF slag is less reactive, it is not suitable for use as a cementitious binder but can be used in large amounts as aggregate in concrete or for road base. High metallic oxide content, namely Fe_2O_3, present in steel slag, enhanced the mechanical properties and abrasion resistance of the aggregate, making it suitable for heavy-duty applications. In other words, the strength of steel slag aggregate is not mainly due to the hydration of the steel slag, but rather to the hardness of the steel slag aggregate [11] – [12]. OHF slag contains moderate amounts of pozzolanic materials such as CaO, SiO_2, and Fe_2O_3. The aggregate is stable and provides limited cementitious potential. Due to its negative environmental impact, open-hearth steelmaking has been replaced with more efficient and environmentally sustainable methods, namely BOD and EAF [10].

Steel slag properties depend strongly on the production process, which determines their role in sustainable construction. BOF slags, rich in CaO and C_2S, are particularly suitable for binder or cementitious applications. In contrast, EAF slags, with their high density and low expansivity, are better suited for aggregate substitution. Regardless of the slag type, ageing or weathering treatments are necessary to reduce free CaO and MgO. These treatments enhance volumetric stability and ensure consistent performance in concrete [9], [11], [13]. The performance of steel slag in concrete mainly depends on its oxide composition, which influences hydration, strength, durability, and stability. CaO is the dominant component, particularly in BOF slags, and it provides both alkalinity and reactivity. Through hydration, CaO promotes the formation of C–S–H and C–A–H, which are essential for strength development. However, excess free CaO can hydrate and expand, so proper stabilisation is required before use [9]. SiO_2 also plays a key role by reacting with calcium hydroxide to produce additional C–S–H. This reaction enhances compressive strength, refines the microstructure, and improves resistance to chloride ingress and chemical attack. The extent of this reactivity depends on whether SiO_2 is in an amorphous or crystalline form, with the amorphous form being more reactive [10], [12], [14].

3.2 Workability

The use of steel slag as both a cement replacement and an aggregate in concrete mixes significantly affects the workability of fresh concrete. Workability refers to the ease with which concrete can be mixed, placed and compacted. Although using steel slag could improve the mechanical properties of concrete and promote sustainability, it reduced the workability of the concrete mix. The drying effect of the mix is more significant with high cement replacement of concrete [15]. The reduction in workability is mainly attributed to the physical characteristics of steel slag. Unlike conventional aggregates such as river gravel or crushed stone, which are typically smooth and rounded, steel slag particles are angular, rough, irregular in shape and porous. The physical characteristics of steel slag particles promote friction between particles in fresh concrete and elevate the specific surface area, thereby reducing flowability [15]. The consistent reduction in workability reported in the literature therefore represents a major practical limitation to the wider use of steel slag. In practical construction, poor workability can offset mechanical benefits by increasing placement difficulty, promoting defects, and reducing overall performance. Therefore, steel slag cannot be treated as a direct replacement for conventional cement or aggregates without careful consideration of its impact on workability. Optimised mix design, including controlled replacement levels and the use of suitable admixtures, is essential for effective use of steel slag in concrete applications.

Steel slag has a high density. This property affects the behaviour of fresh concrete. If not mixed properly, segregation can occur. Heavy slag particles tend to settle at the bottom. This causes uneven distribution and a poor surface finish. Martins et al. [6] noted that such issues make handling and placement more difficult. The experimental results by Waqas et al. [16] and Darwis et al. [17] revealed that a mix with a higher slag content produces a lower slump value, making the concrete less workable and unsuitable for concrete production. To reduce the workability problem, superplasticiser can be used to improve the flow of concrete while maintaining the concrete strength. Although adjusting the water-binder ratio would help increase concrete workability, it may affect strength development, leading to lower compressive strength. Wu et al. [18] studied the impact of different types of gypsum to the rheology of steel slag. In their investigation, three types of gypsum, namely fluorogypsum (FG), phosphogypsum (PG), and desulfurization gypsum (DG), were used. The result showed that FG gave the best results as it lowered both the yield stress and viscosity while improving the workability of the mix design. Phosphogypsum showed a moderate result, while the desulfurization gypsum showed the worst result, as it increased flow resistance, making the mix less workable. Wu et al. [18] further explained that the yield stress and viscosity of the mix increase with increasing amounts of desulfurization gypsum. The angular surface of steel slag reacted chemically with gypsum and the binder, thereby increasing the internal resistance of the mix. The result also highlighted that the rheological performance of the mix was influenced not only by the type of gypsum but also by the particle size distribution and the pH of the materials. All the properties influenced the forces between the particles and the water's behaviour, thereby affecting the workability of the mix. Wu et al. [18] concluded that the optimised mix was approximately 24% desulfurization gypsum, with 35% steel slag replacement. It is observed that the optimum mix design not only maintained good workability but also provided adequate early strength and long-term strength of the concrete. Therefore, the optimisation of chemical admixture and mineral components is vital for steel slag mixes.

The fineness and particle size of steel slag are key factors for workability. The experimental results of Cai et al. [8] showed that finely ground steel slag improves the packing effect of concrete while reducing its porosity. However, a finer particle size of steel slag increases the surface area, leading to higher water demand during mixing. As a result, the workability of the concrete mix significantly reduced without the use of superplasticisers [8]. Although finer particle size improves the properties of hardened concrete, it may negatively affect workability. Therefore, a balanced mix design with optimum amount of steel slag fineness while maintaining good workability should be considered. Kumar et al. [19] studied self-compacting concrete (SCC) with steel slag and C&D waste as sand replacements. Higher steel slag content greatly reduced slump flow due to its angular shape, rough texture, and high density. C&D waste also reduced workability, but less severely. Optimised mixes with about 33% replacement maintained acceptable flow and met SCC standards. Fly ash and GGBS improved particle packing and reduced water demand. Superplasticisers and controlled water-to-binder ratios helped preserve workability, showing the need for an integrated mix design. Yang et al. [20] studied the impact of high fly ash and steel slag volumes on the performance of SCC. The results found that the use of fly ash and steel slag separately had very minimal effects on the workability of concrete. However, when the fly ash and steel slag were added into the mix together, it reduced the workability significantly. On top of that, Yang et al. [20] tested the SCC mix using two types of superplasticisers, namely naphthalene-based and polycarboxylate-based, and a viscosity modifier (PCE-VMA). The mix with PCE-VMA showed better flowability in the mix. It is concluded that it is important to calculate the effective water-binder ratio instead of relying on the nominal value. This method considers the weight and amount of each binder material. It gives a more accurate measure of the free water in the mix. This helps to better understand and control the concrete’s workability. The use of steel slag as a cement replacement or aggregate generally reduces the workability of fresh concrete, even though it can improve strength and sustainability. This reduction is mainly due to the angular, rough, dense, and porous nature of steel slag particles, which increases particle friction and water absorption, leaving less free water for flow. As a result, concrete with higher slag content becomes stiffer, shows lower slump, requires greater compaction effort, and may be prone to segregation if not mixed properly. Increasing water content can improve workability but negatively affects strength, making it an unsuitable solution. Instead, acceptable workability can only be achieved through optimised mix design, including controlled slag replacement levels, suitable superplasticisers, supplementary cementitious materials, and careful control of the effective water–binder ratio.

3.3 Compressive Strength

In general, partial replacement of steel slag in concrete mixes improves the compressive strength of cement-based materials. However, the degree of improvement is highly dependent on the extent of replacement and on the use of steel slag as a replacement. Steel slag can be used as partial cement replacement or as an aggregate replacement. Dong et al. [21] reported that a 10% cement replacement with steel slag increased the compressive strength to 50 MPa, approximately 10% higher than that of the control samples. The results showed improved hydration, particle packing, and good pozzolanic reactivity of ground steel slag. Similar results were confirmed by Baalamurugan et al. [22], who stated that the presence of an acceptable level of steel slag promotes the formation of additional C-S-H, thereby contributing to higher compressive strength. Li et al. [23] reported that steel slag with a smaller particle size improved reactivity within the microstructure, producing a more cohesive matrix and leading to denser, higher-strength concrete. Optimisation of steel slag particle size is important when it is used as a reactive binder. In addition, steel slag can be used to replace coarse aggregates in the concrete mix. The replacement of concrete mix with steel slag can often be achieved up to 50% or more, with compressive strength between 60–80 MPa. The performance of steel slag concrete often exceeds that of concrete with natural aggregate [20]– [21]. Kalane et al. [24] conducted an experiment to study the impact of using both coarse steel slag aggregate (CSSA) and natural aggregate on grade 40 concrete. The aggregate replacement in the experiment ranged between 20% and 60%. The results showed that the 40% CSSA mix gave the highest compressive strength after 28 days. The improvement came from the angular shape and rough texture of CSSA, which enhance interlocking and bonding, particularly at the interfacial transition zone (ITZ). A 20% replacement still gave acceptable strength, but 60% showed diminishing returns. Higher content reduced workability and risked segregation. The study concluded that 40% replacement provides the best balance between strength and constructability.

For fine aggregate replacement, Waqas et al. [16]n found that a 20% steel slag replacement level resulted in optimum compressive strength, up to 30.88 MPa at 28 days. However, higher steel slag replacement levels led to reduced workability and lower early-age strength. This is attributed to the increased surface area of steel slag, which causes inefficiency in the particle packing process. Therefore, the amount of steel slag used as a replacement in the concrete mix should be carefully controlled to avoid adverse effects on concrete performance. Wang et al. [5] studied a hybrid binder with blast-furnace slag (BFS) and 30% steel slag, activated by Na_2CO_3. They found that finer BFS particles, down to 3.03 micrometres, improved compressive strength. Increasing Na_2CO_3 dosage to 5% also enhanced strength. The best mix reached 39.8 MPa at 28 days. The results revealed that the combination of particle fineness and chemical activation helps to accelerate hydration and strength development of concrete. Kumar et al. [18] used construction and demolition (C&D) waste and steel slag as partial replacements for cement and aggregate to produce sustainable high-performance SCC. The results concluded that the use of steel slag improved the compressive strength of the SCC. The angular particle size of steel slag and latent hydraulic activity improved the particle packing, leading to a stronger ITZ. In addition, the use of steel slag and C&D waste provides an environmental solution for the construction industry, enabling sustainable concrete production by reducing the consumption of natural resources and promoting waste valorisation. Martins et al. [6] did a systematic review using steel slags in cement-based composites. The findings emphasised the positive effect of steel slag, which improved the compressive strength of cement-based composites by promoting additional C-S-H formation through hydraulic pozzolanic reactions. Steel slag, which is rough in nature, improves the bonding in the ITZ. The optimal compressive strength was determined to be between 10% and 30% steel slag replacement, depending on particle size and steel slag treatment. Higher percentages of steel slag replacement can cause the compressive strength to plateau or decline due to dilution. Yang et al. [20] investigated self-compacting concrete (SCC) containing large amounts of fly ash and steel slag. It was observed that the combined use of these materials enhances compressive strength. This improvement is attributed to increased hydration and pozzolanic activity, leading to greater formation of C–S–H gel. When cement was partially replaced with moderate amounts of fly ash and steel slag, the mixes achieved compressive strengths comparable to or higher than conventional SCC. The improved particle packing and refined microstructure produced a denser and stronger matrix. Overall, the study demonstrated that incorporating industrial by-products in SCC can yield sustainable concrete with high strength and performance.

3.3 Flexural Strength

The use of steel slag or slag-based supplementary cementitious materials (SCMs) showed considerable potential to enhance the flexural performance of concrete composites. Cai et al. [8] in the comprehensive review found that partial cement replacement up to 10% steel slag consistently improved the flexural strength of concrete mixes. The use of steel slag not only acts as a filler that reduces the porosity of the mix design but also promotes the formation of additional C-S-H, leading to a stronger ITZ between aggregate and cement paste. Mekonen et al. [26] reported that replacing about 45% of fine aggregate with steel slag increased the flexural strength of reinforced concrete beams by roughly 19.04% at

28 days. The improvement was due to the angular shape and rough texture of steel slag particles. These characteristics enhanced mechanical interlocking and bond strength within the concrete matrix. In contrast, Darwis et al. [17] found that a 20% replacement level improved flexural strength, but higher percentages reduced early-age strength. The reduction was linked to the increased surface area of steel slag. This led to greater water demand and lower workability in the concrete mix. Zaki et al. [25] carried out a detailed study on reinforced high-performance concrete (HPC) beams incorporating steel slag coarse aggregate (SSA) as a replacement for natural dolomite aggregate. Results from four-point bending tests showed that SSA beams achieved higher mechanical performance, with compressive strengths of 75.6 MPa compared to 58.1 MPa for conventional mixtures. The SSA beams also demonstrated increased cracking moments and ultimate flexural capacities, with ultimate load factors ranging from 2.82 to 4.53. Despite these strength improvements, serviceability aspects such as stiffness and deflection remained largely unaffected, indicating that SSA does not compromise performance under normal service loads. In addition, the study reported favourable ductility behaviour; beams with reinforcement ratios up to approximately 3.6% achieved displacement ductility ratios above 3.0. This indicates adequate post-yield deformation capacity, essential for maintaining structural integrity under dynamic or seismic conditions. Overall, the findings support the use of SSA as a sustainable and high-performance aggregate replacement in HPC, capable of enhancing both flexural strength and structural ductility [19].

Mekonen et al. [26] expanded on previous work by examining the combined effects of fine and coarse aggregate replacement with steel slag on the flexural strength of reinforced concrete beams. Their findings indicated that replacing 50% of the coarse aggregate produced the highest improvement in flexural strength, approximately 13.1% greater than that of the control beams. For fine aggregate, the optimum replacement level was around 45%, aligning with earlier studies. These enhancements were attributed to the beneficial physical properties of steel slag, particularly its angular particle shape and rough surface texture, which improve the mechanical bond between aggregates and the cement matrix while refining the concrete microstructure. However, higher proportions of steel slag were shown to reduce workability due to increased water demand, emphasising the need for optimised mix design adjustments to maintain performance [20]. Sun et al. [28] investigated the cracking and yielding behaviour of reinforced ultra-high-performance concrete (R-UHPC) beams incorporating steel slag as a partial fine aggregate replacement. The results showed a slight reduction in cracking bending moments, attributed to a minor decrease in the tensile strength of the concrete matrix when steel slag was added. Despite this, the ultimate bending capacity remained unchanged, indicating that steel slag replacement does not compromise the ultimate flexural strength of R-UHPC beams. The study also highlighted the critical role of reinforcement ratio: higher reinforcement levels significantly improved yield bending moments and overall load-bearing capacity. This finding reinforces that reinforcement detailing remains a key factor governing beam flexural behaviour, even when sustainable materials are employed. Additionally, substituting natural aggregates with steel slag reduced the embodied energy associated with UHPC production, emphasising the environmental advantages of this approach. Sun et al [28]. further developed a predictive model that integrates traditional cross-sectional analysis with machine learning techniques to accurately estimate cracking and yield bending moments. This model provides engineers with a reliable tool for designing UHPC beams that meet both structural performance requirements and sustainability objectives [21].

3.4 Tensile Strength

Tensile strength is a key property that determines concrete's resistance to cracking under tension. It directly affects durability, serviceability, and long-term performance. Since concrete has low tensile capacity compared to compressive strength, improving it is vital for extending the lifespan of structures. Recent studies show that using steel slag as a partial replacement for aggregates or cement can significantly enhance tensile strength through physical, chemical, and microstructural effects. The inclusion of steel slag aggregates in concrete enhances tensile strength primarily by improving the ITZ between cement paste and aggregates. Physically, steel slag particles are angular, rough, and dense, which increases mechanical interlocking within the ITZ, the typical weak point in concrete where microcracks initiate under tensile stress. As suggested by Cai et al. [8], these characteristics strengthen the ITZ, reduce microcrack formation, and enable more efficient stress transfer from the paste to the aggregates. This improved bond allows the concrete to resist tensile forces more effectively, slowing crack initiation and propagation. Consequently, steel slag concrete exhibits higher tensile strength compared to conventional mixes with natural aggregates, provided the mix is properly designed, compacted, and maintains adequate workability to avoid voids that could compromise the ITZ.

In addition to its physical benefits, steel slag contributes to tensile strength through its latent hydraulic properties. Steel slag contains compounds such as free lime and silicates that can react with water under suitable conditions, producing additional calcium silicate hydrate (C–S–H) gel. Wang et al. [5] demonstrated that activating steel slag with sodium carbonate accelerates C–S–H formation, densifying the matrix and strengthening the ITZ. This chemical enhancement, combined with the mechanical interlocking provided by angular, rough slag particles, improves stress transfer within the concrete, reduces microcrack formation, and results in consistently higher tensile performance compared to conventional mixes.

Steel slag can significantly enhance the tensile strength of concrete by improving both microstructure and aggregate–paste bonding. Experimental studies show that replacing 45–50% of natural aggregates with steel slag maximises tensile performance, increasing the modulus of rupture by up to 19% [26]. Beyond this replacement level, strength may decrease due to poorer workability, uneven particle packing, and the formation of voids or microdefects. Reviews of steel slag in concrete and mortar also highlight its ability to refine the microstructure, strengthen the aggregate–paste interface, reduce pore connectivity, and limit microcracks, all of which reduce crack initiation and propagation under tension [9]. In ultra-high-performance concrete, the effect on tensile cracking strength is smaller, with only minor reductions observed;

ultimate tensile performance remains largely unaffected, suggesting that steel slag does not compromise overall structural behaviour when reinforcement and curing are properly managed [27]. Overall, steel slag can improve tensile strength and crack resistance, but careful mix design is essential to balance workability, particle packing, and structural performance. From a sustainability perspective, steel slag aligns with green construction and circular economy goals. Replacing natural aggregates with steel slag diverts industrial waste from landfills and lowers embodied energy and carbon emissions from aggregate processing [1] –[2] , [4]. Steel slag thus improves both mechanical performance and environmental sustainability, making it a promising material for eco-efficient, high-performance concrete.

3.5 Modulus of Elasticity

The modulus of elasticity measures concrete's stiffness and its resistance to deformation under load. It is critical for predicting deflections, crack widths, and serviceability. Stiffer concrete improves structural performance and durability. Steel slag, used as a partial replacement for aggregates or as a supplementary cementitious material, can significantly affect this property by altering microstructure, density, and bonding within the concrete. Steel slag aggregates are generally denser, harder, and stiffer than conventional aggregates like gravel or crushed granite. Cai et al. [8] noted that their angular shape and rough surface improve the interfacial transition zone between cement paste and aggregate. A stronger ITZ reduces microcracks and enhances mechanical interlocking, allowing more efficient stress transfer. This typically results in a higher modulus of elasticity compared to concrete with smoother natural aggregates. The chemical reactivity of steel slag also contributes to stiffness. Wang et al. [5] reported that activating steel slag with sodium carbonate accelerates hydration and produces additional calcium silicate hydrate (C–S–H) gel. Since C–S–H governs stiffness and compressive strength, this enhances elastic performance. The combination of chemical activation and physical interlocking produces a denser, more rigid matrix.

Particle size and gradation further affect stiffness. Li et al. [22] showed that finer steel slag improves packing density, fills voids, and reduces porosity, increasing load-bearing capacity. However, excessively fine particles can raise water demand, reduce workability, and introduce micropores if not properly managed with admixtures. Balanced mix design is therefore essential to optimise both fresh and hardened properties. Moderate steel slag replacement (up to 40–50%) generally increases stiffness. Rashad [15] and Kalane et al. [24] warned that higher contents can cause segregation, poor compaction, or increased porosity, which reduce the modulus of elasticity. Careful control of water-to-binder ratio, aggregate gradation, and compaction is necessary to ensure consistent performance. In high-performance (HPC) and ultra-high-performance concrete (UHPC), steel slag has shown positive results. Zaki et al. [25] found that beams with steel slag coarse aggregates had higher compressive strengths and corresponding stiffness. Sun et al. [28] observed that UHPC beams maintained satisfactory modulus of elasticity and stable cracking behaviour. These findings demonstrate that steel slag can be used in advanced concrete without compromising mechanical performance, making it suitable for demanding structural applications. Steel slag also improves sustainability. Habert et al. [1] - [2] highlighted that its use reduces reliance on natural aggregates, diverts industrial waste from landfills, and lowers the embodied carbon of concrete. Thus, steel slag enhances stiffness, structural performance, and environmental efficiency, supporting eco-friendly, high-performance concrete solutions.

4. Conclusions

The use of steel slag as a partial replacement for cement or natural aggregates in concrete enhances both performance and sustainability. Its angular shape, rough texture, porosity, and high density can reduce workability, but these effects can be controlled with optimised mix designs. Using high-range water reducers and supplementary cementitious materials helps maintain flowability without sacrificing strength or durability. Mechanically, steel slag improves both flexural and tensile strength. This is due to microstructural refinement, stronger bonding at the interfacial transition zone, and beneficial hydration reactions. Optimal replacement levels are typically about 10% for cement and 45–50% for fine or coarse aggregates. At these levels, strength gains are maximised while workability issues remain manageable. Studies on reinforced high-performance and ultra-high-performance concretes confirm that steel slag also enhances ductility, cracking behaviour, and serviceability, making it suitable for demanding structural applications. Steel slag also improves the modulus of elasticity. The hard, angular particles create a stiffer aggregate skeleton, while better particle packing and hydration produce a denser matrix. Stronger interfacial bonding enables efficient stress transfer, resulting in greater stiffness and reduced deformation. However, consistent results require careful control of replacement ratios to prevent segregation and excess porosity.

Environmentally, steel slag reduces embodied energy and carbon emissions by lowering cement use and replacing natural aggregates. This aligns with sustainable construction goals and circular economy principles by reusing industrial byproducts. Advances in predictive modelling and machine learning now aid in optimising slag-based mix designs for strength and sustainability. In Malaysia, widespread adoption of steel slag concrete faces challenges such as variability in slag quality, limited local standards for slag processing, and supply chain constraints. The high density and angularity of slag may complicate batching and placement, particularly in large-scale projects or in regions with limited access to high-range water reducers and admixtures. Training for construction personnel on proper handling, compaction, and curing practices is also critical to ensure consistent quality. Malaysian construction policy increasingly emphasises sustainable and low-carbon materials, but clear guidelines for the use of industrial byproducts such as steel slag remain limited. Establishing national standards for slag characterisation, mix design, and performance criteria would facilitate adoption while ensuring safety and structural reliability. Incentives for recycling industrial byproducts and integrating steel slag into green building rating systems could accelerate its use, supporting Malaysia's goals for sustainable construction and circular economy implementation. In summary, steel slag is a promising material for modern concrete in Malaysia. It enhances tensile, flexural, and elastic properties while improving ductility and reducing environmental impact. With proper mix design, technological support, and supportive policies, it can contribute to greener, high-performance, and resilient concrete structures across the country.

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Declaration of Competing Interest
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J. Hao (Methodology; Investigation; Writing - original draft; Funding acquisition)
S. I. Doh (Conceptualisation; Analysis; Visualisation; Writing - review & editing; Supervision)
Z. Z. Wang (Investigation; Visualisation; Resources; Writing - review & editing)

Availability of Data and Materials
The data supporting this study's findings are available on request from the corresponding author.

Ethics Declarations
This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Declarations
The authors claim that artificially intelligent-assisted technologies, such as generative AI, were not used to generate content, ideas, or theories. We have just utilised AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

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