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Sustainability in Road Base and Sub-base Applications: The Role of Steel Slag Use

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Highlights

- Steel slag's eco-mechanical benefits make it a sustainable alternative in road construction.
- Steel slag outperforms aggregates in base and sub-base layers with better strength and durability.
- Using steel slag in infrastructure enhances waste management and mitigates environmental issues.

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Abstract

The large amount of industrial waste and its disposal are becoming increasingly serious problems, growing year by year. With technological advancements in various fields, it is crucial to effectively evaluate the use of steel slag (SS) waste. SS is a durable by-product formed during crude steel production, and one of the common methods for handling it involves storing it in specific disposal sites for slag. Throughout the years, the substantial production of steel slag and the ongoing utilization of disposal sites have caused significant utilization of land resources and brought about serious environmental concerns. Stabilization of steel slag with existing industrial by-products is also feasible and has attracted growing interest from researchers. When bulk steel slag is used in combination with other potential waste materials, significant economic and environmental benefits can be achieved. Consequently, extensive studies have been conducted to explore various methods for stabilizing steel slag to enhance its strength and durability for widespread use in road base and sub-base layers. The present research provides an overview of the chemical, physical characteristics, and mechanical behavior of steel slag while examining the existing studies on its application in base and subgrade layers of roads.

1. INTRODUCTION

The steel manufacturing process results in the formation of various slags as secondary outputs [1]. Blast furnace steelmaking represents the initial stage in steel production, during which raw iron ore is transformed into pig iron containing carbon, silicon, manganese, sulfur, and phosphorus in varying amounts. With its elevated carbon content, pig iron is highly brittle and not suitable for further processing, such as shaping [2]. To address this, pig iron undergoes refinement in the basic oxygen steelmaking (BOS) process, which results in the formation of a slag by-product. Another form of secondary steelmaking is the electric arc furnace (EAF). This furnace's by-product is slag, commonly categorized as steelmaking slag when it originates from BOF or EAF processes [3].

SS exhibits a mineralogical composition comparable to that of cement clinker, including components like amorphous silicon dioxide (SiO_2), calcium oxide (CaO), tricalcium silicate (C_3S or $3CaO \cdot SiO_2$), dicalcium silicate (C_2S or $2CaO \cdot SiO_2$), and tetracalcium aluminoferrite (C_4AF or $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$) [4]. As such, it can be utilized as an additive in cement or concrete production. This is because they have active hydration compositions [5].

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SS provides advantages like superior strength, excellent abrasion resistance, long-lasting performance, and remarkable consistency. As a result, SS aggregates serve as a viable substitute for natural aggregates [6]. Due to the intensive consumption of alternative aggregate resources, these materials stand out as a promising solution for road construction. Thanks to its technological strengths and commercial potential, the road construction industry stands out as a key area for the reutilization of solid waste [7]. In particular, European countries, Japan, and the United States are among the leading regions in terms of SS usage rates in road construction (43%, 32%, and 50%) [8,9].

This article examines the generation of steel slag (SS), its characteristics, and recent insights into its application in road base and subgrade layers. Additionally, this study focuses on the processes involved in obtaining SS, such as oxidation and reduction, and aims to investigate the specific requirements for these materials in the granular layers of transport systems. A preliminary study was conducted on 150 articles related to the application of SS in roadway construction. 20 research articles were covered in this study, considering the repeated studies.

2. PROPERTIES AND MANUFACTURING PROCESS OF STEEL SLAG

Steel production is categorized into two groups based on the type of raw material used: fully integrated steel production facilities and partially integrated steel production facilities. In integrated steel production facilities, steel is obtained from ores, and the manufacturing process takes place in blast furnaces; during this procedure, three primary by-products are generated: granulated blast furnace slag (GBFS), air-cooled blast furnace slag (AC-BFS), and spherical or porous blast furnace slag [10]. Within semi-integrated steel production facilities, steel is produced by melting reclaimed materials or scrap metal using an electric furnace system [11]. Three steel production processes employ different refining methods: Siemens-Martin (Open Hearth (OH)), Oxygen Converter (Linz-Donawitz (LD) or Basic Oxygen Furnace (BOF)), and the EAF [12] as defined by Yıldırım and Prezzi (2011). The name of the slag is based on the type of furnace used to generate it. Figure 1 illustrates a flowchart detailing the iron and steel manufacturing processes and the corresponding slag types produced at each stage [13,14].

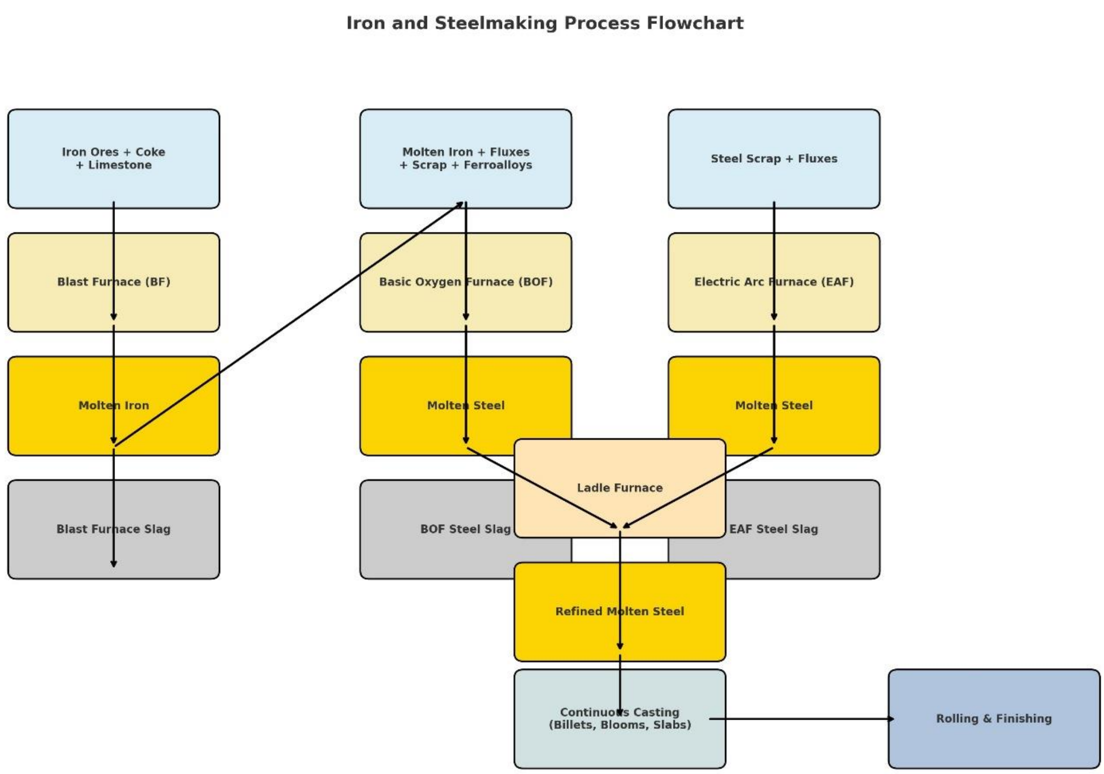

Figure 1. *A diagram representing the various stages involved in the steelmaking process (redrawn from [11])*

According to the World Steel Association, global crude steel production in 2021 totaled 1.951 billion tons. China accounted for the largest share with 1,032.8 million tons, followed by India with 118.2 million tons and Japan with 96.3 million tons [15]. Such large-scale steel production results in the generation of significant amounts of solid waste, particularly slag. The slags obtained during steel production using BOF, Crucible Furnace (LF), and EAF are categorized as SS. Japan reported that approximately 14 million tons of SS were produced in 2017, while China announced that 100 million tons of SS were produced in 2016 [16], which is consistent with available data indicating that the waste by-products generated during steel production are at the level of 10-15% [17].

Turkey, on the other hand, is the largest steel producer in Europe and the 7th largest in the world, producing 40.4 million tons of steel in 2021 [18]. As of 2021, 26 out of 37 facilities in Turkey produce crude steel using EAF, and 3 use BOF. The SS generated per ton of crude steel ranges between 150 and 200 kg. In 2018, 5.562.018 tons of slag were produced as a result of the production of 37.311.733 tons of crude steel across Turkey [19-21].

The quantity of slag produced is determined by both the steel production technique and the quality of raw materials, including iron ore, ferroalloys, and fluids [22]. Steel production has continued to increase since 1950 and has accelerated since 2021 (Figure 2).

SS emerges as a major by-product of steel manufacturing worldwide, accounting for approximately 15 to 20% of the total steel output [23,24]. Initially, this material was regarded as an industrial byproduct and dumped in landfills, leading to the depletion of land resources and causing significant harm to ecosystems and public well-being due to the release of highly alkaline leachate [25]. Today, for example in Europe, approximately 77% of the material is employed as an alternative in the manufacture of green cement or as construction materials such as blocks and aggregates [26,27].

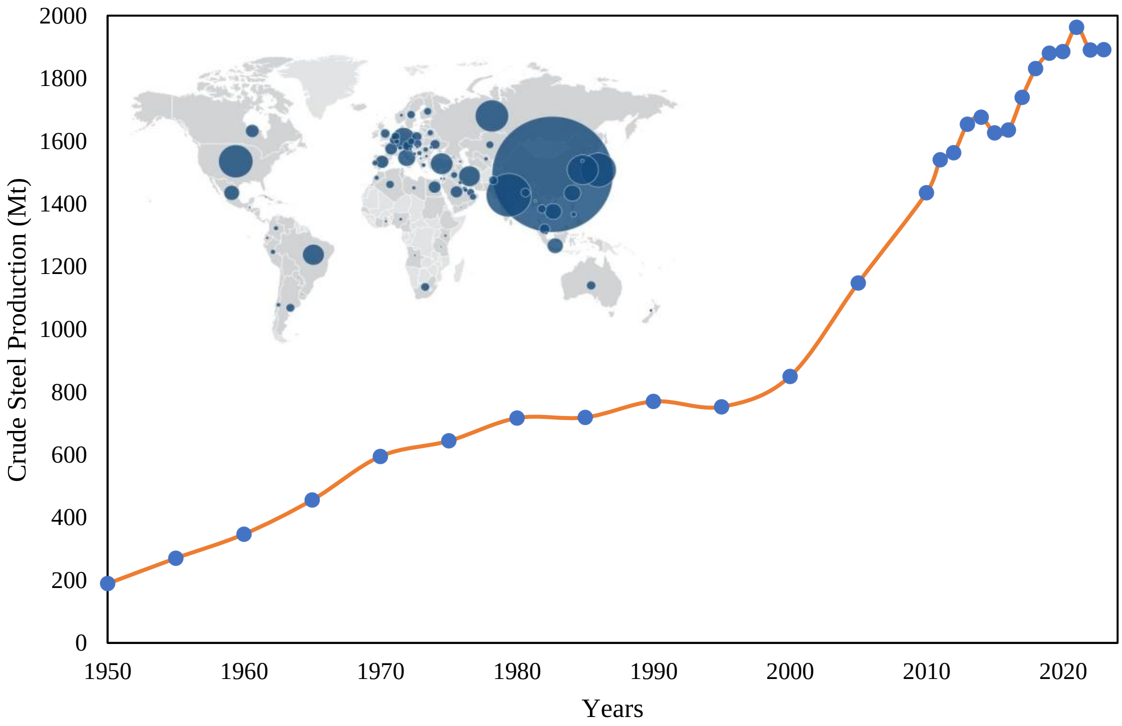

***Figure 2**. World crude steel production 1950 to 2023*

3. PHYSICAL, CHEMICAL AND MINERALOGICAL PROPERTIES

3.1. Physical Properties

Steel slag's engineering properties have been outlined by the United States Department of Transportation and the Federal Highway Administration, with support from the Turner Fairbank Highway Research Center (TFHRC) [28–30]. Table 1 presents the common physical characteristics of SS. As can be seen from Table 1, all values are by the standards of major crude steel-producing countries such as the USA, UK, Australia, and India [31–34]. The specific gravity reported in the table is generally around 3.21, which is higher than that of aggregates traditionally used as ballast material [35,36].

Table 1. *Common attributes of steel slag's physical properties*

Properties	Value
Specific Gravity	3,2-3,6
Approximate Dry Rod Unit Weight (kg/m³)	1600-1920
Water Absorption	˜3%

SS particles consist of sharp-edged, irregularly cubic shapes that may be flat or elongated. Additionally, they possess a coarse, porous structure with numerous isolated cells, offering a larger surface area for the same volume compared to more uniform aggregates [37]. Figure 3 presents a representative view of typical SS aggregate particles.

Figure 3. *Surface image of a typical steel slag aggregates*

As per TFHRC, treated SS demonstrates favorable mechanical characteristics, making it appropriate for use as aggregate in construction, such as excellent wear resistance, robust strength attributes, and high load-bearing capacity (Table 2).

Table 2. *Standard mechanical characteristics of steel slag (TFHRC)*

Properties	Value
Los Angeles Abrasion (ASTM C131), %	20-25
Sodium Sulfate Soundness Loss (ASTM C88), %	<12
Internal Friction Angle	40°-50°
Hardness	6-7
California Bearing Ratio (CBR), %	˜300

3.2. Chemical Properties

The general chemical composition of steel slag is provided in Table 3 [37]. This by-product primarily contains silicate-based compounds, mixed structures of alumina and calcium, as well as various forms of iron oxides [38]. During the steelmaking process, a portion of the molten iron does not integrate into the final product and remains in the slag as elemental iron. As a result, steel slag typically contains a higher concentration of iron components compared to blast furnace slag [39]. In slag analysis, basicity refers to the ratio of CaO to SiO_2 in the sample [40]. SS exhibits greater basicity [41], which influences its potential applications and distinguishes it from blast furnace slag [42]. Additionally, the quick crystallization of SS leads to a marked increase in viscosity, making it more difficult to break and granulate. As a result, the utilization of SS is much lower compared to BF slag [43,44].

Table 3. *Mass percent composition of steel slag constituents*

Calcium Oxide (CaO)	Silicon Dioxide (SiO_2)	Iron(II) Oxide (FeO)	Aluminum Oxide (Al_2O_3)	Magnesium Oxide (MgO)	Manganese (II) Oxide (MnO)	Titanium Dioxide (TiO_2)	Chromium (Cr)	Phosphorus (P)	Sulfur (S)
30 to 35	8 to 20	10 to 35	1 to 6	5 to 15	2 to 8	0.4 to 2	0.1 to 0.5	0.2 to 2	05 to 0.1

3.3. Mineralogical Properties

The crystallization behavior of SS is primarily influenced by cooling rate and chemical composition. SS samples, when analyzed by X-ray diffraction (XRD), displayed a complex pattern with numerous peaks, suggesting the presence of various crystalline phases and overlapping structures [44].

The close and overlapping structures of these peaks reflect the multiphase and complex mineralogical structure of SS. The mineral phases described in the literature on steel slags are outlined in detail in Table 4. The most commonly encountered mineral phases include olivine ($2MgO\ 2FeO\ SiO_2$), β-C_2S ($2CaO\ SiO_2$), α-C_2S, C_4AF ($4CaO\ Al_2O_3\ FeO_3$), C_2F ($2CaO\ F_{e2}O_3$), free lime (CaO), ($3CaO\ MgO\ 2SiO_2$), FeO, MgO, C_3S ($3CaO\ SiO_2$), RO phase and CaO-FeO-MgO-MnO [45,46]. These mineral phases directly influence the slag's material characteristics and determine its performance and potential for use in engineering applications. For example, the presence of free lime (CaO) can affect the stability and long-term behavior of the slag by causing volumetric expansion. On the other hand, phases such as C_4AF and C_2F are important in terms of the binding properties of the slag. Therefore, understanding the crystal phases of slag is of critical importance for the development of sustainable material applications in engineering. Especially in road construction and other infrastructure projects, a good understanding of the mineralogical structure of slag ensures the safe and effective use of the material.

Table 4. *The various mineral constituents present in steel slags [41]*

Reference	Type	Mineralogical Phases
Ghan et al. [46]	EAF	$CaFe_2O_4$, $Ca_2MgO_2AlFeO_6SiO_2O_5$, Ca_2SiO_4, FeO
Ghan et al. [46]	BOF	$CaFe_2O_5$, $Ca_xMn_{(1-x)}O$, Ca_2SiO_4, FeO
Tsakiridis et al. [47]	EAF	$CaSiO_4$, $4CaO.Al_2.Al_2O_3.FeO_3$, $Ca_2Al(AlSiO_7)$, Ca_3SiO_5, $2CaO.Al_2O_3SiO_2$, FeO, Fe_3O_4, MgO, SiO_2
Tossavainen et al. [48]	EAF	$Ca_3Mg(SiO_4)_2$, β-Ca_2SiO_4, (Mg, Mn) (Cr, Al)$_2O_4$, (Fe, Mg, Mn)O), $Ca_2(Al, Fe)_2O_5$
Tossavainen et al. [48]	BOF	B-Ca_2SiO_4, FeO-MnO-MgO, MgO solid solution
Wachsmuth et al. [49]	BOF	Ca_2SiO_4, Ca_3SiO_5, FeO, $2CaO.Fe_2O_3$
Nicolae [50]	BOF	$2CaO.Al_2O_3.SiO_2$, Fe_2O_3, CaO, FeO
Nicolae [50]	EAF	MnO_2, MnO, Fe_2SiO_4, Fe_7SiO_{10}
Reddy et al. [51]	BOF	$2CaO.Fe_2O_3$, $2CaO.P_2O_5$, 2CaO, SiO_2, CaO
Belhadj [52]	BOF	C_2S, C_2F, $Ca(OH)_2$, CaO, $Fe_{(1-x)}O$, $CaCO_3$, MgO, SiO_2, Fe_2O_4
Qian et al. [53]	EAF	ϒ-Ca_2SiO_4, CMS_2, CFMS, FeO-MnO-MgO solid solution

4. ENVIRONMENTAL IMPACTS AND SUSTAINABILITY

Slag is a discarded material and like other wastes, it can negatively affect the environment when dumped into nature. To address this situation, finding new uses for slag has become an important focus for protecting nature. Since civil engineering is considered a major sector that consumes natural resources intensively, the areas of use of waste materials have expanded greatly in recent years [54]. Wang and Thompson [55] stated that the full utilization of SS offers three key benefits: a substantial reduction in the disposal and storage of this waste, the conservation of natural resources and the energy needed to extract natural materials, and the potential to modify or enhance the properties of base materials, leading to the production of unique and specialized construction materials for specific applications [56].

To enable the use of SS in construction projects, it is essential to age or hydrate the free CaO and MgO compounds responsible for expansion. In the initial stage of aging, CaO and MgO are hydrated and converted into $Ca(OH)_2$ and $Mg(OH)_2$. In the case of a prolonged hydration process, $Ca(OH)_2$ and $Mg(OH)_2$ are transformed into $CaCO_3$ and $MgCO_3$ with low solubility respectively under the effect of CO_2 [57]. The American National Slag Association has assessed the risks associated with using steel slags in various applications and concluded that steel slags do not present a threat to human or environmental health. When used as a filling material, slags may cause leachate formation in different colors upon contact with water. To prevent this issue in steel slags that are not sufficiently aged, proper drainage and aging processes should be conducted in the environments where the slags are used [57]. Some metals in slag may be present at higher concentrations than those found in soil. A study has evaluated that slag particles do not cause ecological harm when mixed with water or soil [58]. Several studies have examined elements like As, Cd, Pb, Cr, Hg, and Ag in the eluate extracted from SS, with the results compared to the limits set by the United States Environmental Protection Agency (USEPA). Based on these comparisons, it was established that steel slags are a non-harmful by-product [59-61].

To ensure the safe and effective use of SS in construction, it is crucial to address both its aging process and its leaching properties. As outlined, the aging of SS allows the transformation of free CaO and MgO compounds into more stable forms, which reduces expansion risks. Simultaneously, the leaching behavior of SS is affected by its pH level. In acidic conditions, harmful metals are more likely to leach, while controlling the pH can effectively reduce this release. Therefore, both aging and pH management are essential to minimize environmental risks and ensure the sustainable use of SS in various industries [62].

5. WHY IS STEEL SLAG IMPORTANT FOR ACHIEVING SUSTAINABILITY GOALS? ENVIRONMENTAL, ECONOMIC, AND INDUSTRIAL PERSPECTIVES

The increasing emphasis on sustainability, driven by rising environmental awareness and the limited availability of natural resources, has made the use of SS more significant. While SS, a by-product of steel production, is often seen as waste, it can be transformed into an economically valuable and environmentally beneficial material when processed and recycled correctly. In this way, the application of SS offers substantial environmental and economic benefits. Its use across various industries helps conserve natural resources, reduces the need for traditional raw materials, and minimizes the environmental impact of waste disposal. By serving as an alternative in construction and other sectors, SS supports both sustainability and resource conservation.

5.1. Conservation of Natural Resources and Use of Limited Resources

SS is increasingly utilized in the construction industry, especially for road foundations, infrastructure projects, and concrete manufacturing. The slag produced during steel production shares characteristics with traditional building materials like aggregates and cement, enabling it to serve as a viable replacement. This application helps conserve natural resources and minimizes the need for mining operations. By incorporating SS in this manner, the demand for the extraction of raw materials, such as natural stones and sand, is reduced, thereby contributing to the protection of ecosystems [63].

5.2. Environmental Impact Reduction and Waste Management

If improperly managed, SS can have detrimental environmental effects. However, by recycling this by-product, we not only reduce environmental contamination but also ease the strain on landfills. SS can be repurposed in the production of concrete and asphalt, which aids in the recovery of construction waste that would otherwise contribute to soil pollution. This process helps prevent industrial waste from harming ecosystems and bolsters overall environmental sustainability [64].

5.3. Resource and Energy Savings

SS is frequently utilized in cement production, a process characterized by significant energy use and considerable carbon emissions. Cement produced with SS requires less energy and results in reduced carbon emissions. This contributes to the reduction of the carbon footprint in industrial processes and supports the promotion of eco-friendly construction methods. Additionally, SS is often more durable than traditional materials, leading to long-term savings in maintenance and repair costs [63].

5.4. Economic Contributions and Sustainable Development

The use of SS presents substantial economic advantages as well. Offering a cost-effective and environmentally friendly alternative, can lead to significant savings in construction. Additionally, processing and using SS creates new job opportunities in local industries, fostering economic growth. In this way, SS plays an integral role in achieving the goals of sustainable development [63].

5.5. Long-Term Sustainability and Future Prospects

The advantages of SS for sustainability extend beyond addressing present environmental issues. With further technological advancements and innovative applications, SS can be converted into high-value products. For example, it is already utilized as a catalyst material in the chemical industry, demonstrating its broad potential. In this respect, SS can contribute not only to sustainable practices in construction but also to various other sectors [63].

To conclude, incorporating SS into sustainable practices is a strategy that not only reduces environmental harm but also offers economic benefits, conserves natural resources, and efficiently manages industrial by-products. Promoting this practice globally will enhance environmental sustainability while improving industrial productivity.

6. REVIEW OF STEEL SLAG APPLICATIONS IN ROAD BASE AND SUBBASE LAYERS

There are numerous scientific studies in the literature evaluating the recycling potential of steel industry slags in various fields. These studies demonstrate that steel slag offers significant advantages over traditional materials and can serve as a sustainable alternative in road infrastructure projects. Revealing that this material not only enhances engineering performance but also provides substantial benefits in terms of waste management and resource conservation, research on the structural properties, durability, and environmental impacts of SS shows. Helping reduce environmental impacts, lower material costs, and expedite construction processes, SS in road base and sub-base layers can be highly beneficial [64]. The pavement structure is primarily composed of three layers: bituminous surfacing (surface course), road base (base course), and subbase, as illustrated in Figure 4 [65].

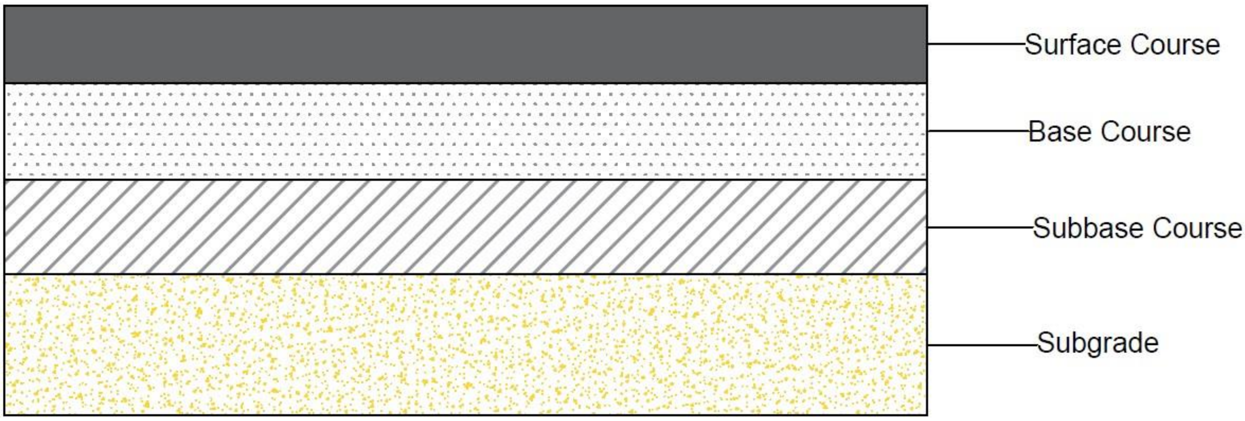

***Figure 4**. Usual flexible pavement configuration (redrawn from [65])*

These reviews thoroughly explore the potential applications of SS in various road infrastructure projects, while also highlighting the technical and environmental challenges that may arise. With the growing demand for sustainable construction practices, these studies promoting the use of SS have gained increasing importance. Confirming that SS can serve as an alternative aggregate in road base and subbase layers, several studies highlight its physical and mechanical properties, such as high density, high strength, and excellent abrasion resistance, which support these findings. Below are some examples from the research on this topic

To assess the viability of using steel slag-fly ash and steel slag-blast furnace slag mixtures as alternatives to lime for subgrade stabilization, an experimental study was carried out by Yıldırım et al. [66]. The research involved investigating mixtures of soil with 5% steel slag and 5% fly ash, 7% steel slag and 3% fly ash, 8% steel slag and 2% fly ash, and 7% steel slag and 3% blast furnace slag as potential subgrade materials. Before stabilization, the clayey subsoil from the target application site was analyzed through various tests, including specific gravity, Atterberg limits, particle size distribution, compaction, CBR swelling, and unconfined compressive strength tests. The mechanical behavior of mixtures combining soil with steel slag and fly ash, as well as soil with steel slag and blast furnace slag, was examined through compression and unconfined compression tests. Moreover, CBR swelling tests were conducted to evaluate the swelling characteristics of the soil-steel slag blends. Based on the experimental findings, it was recommended that a 7% steel slag-3% fly ash mixture be used as the stabilizing agent. The selected mixture was then applied at the 109th Street and I-65 intersection near Crown Point, Indiana. The 7% steel slag-3% fly ash mixture was utilized to stabilize the in-situ subgrade soils in sections of the I-65 ramps located in the southwest (SW) and northwest (NW) quadrants of the 109th Street and I-65 interchange. Nuclear gauge tests were used for field compaction quality control. The subgrade was monitored for any cracks or signs of distress, but no issues were detected before the base course and concrete were placed. The stabilized subgrade performed well. To ensure successful implementation, it is essential to continuously monitor the long-term performance of pavements constructed over the stabilized subgrade and evaluate the immediate and long-lasting environmental impacts of slag-fly ash blends as stabilizing agents. Additionally, further laboratory tests on high plasticity clay-steel slag-fly ash combinations with varying ratios of steel slag and fly ash are recommended to confirm the efficacy of steel slag-fly ash blends as stabilizers.

Putra [67] assessed the effectiveness of using slag and cement as reinforcing agents to enhance the performance of expansive soil for use as subgrade material in road pavements. Various laboratory tests were performed to analyze the properties and behavior of the expansive soil. These included grain size distribution, standard Proctor compaction, specific gravity, Atterberg limits, free swelling, acidity and alkalinity measurements, and permeability tests. The performance of the soil was evaluated through CBR, UCS, and repeated load triaxial (RLT) tests. The stabilizer ratio was determined based on the UCS test results, which needed to meet the required standards for subgrade performance. The study concluded that the optimal stabilizer ratio for the soil was 13.5% slag and 1.5% cement after 28 days of curing. An eight-fold increase in UCS strength compared to the untreated soil was achieved by this mixture. The CBR values were also found to be four times higher than the minimum required for road pavement design. Moreover, the modulus of elasticity of the stabilized soil, as determined by the RLT test, was found to be influenced by deviator stress. The best-fitting model to the deviator stress data was identified as the hyperbolic correlation model, with a coefficient of determination of $R^2 = 0.96$. The study's results confirm that slag, as a by-product, effectively enhances the strength of subgrade soils and contributes to environmental pollution reduction.

Maghool et al. [68] conducted a range of engineering and environmental tests to assess the potential use of Electric Arc Furnace (EAF) and Ladle Furnace (LF) slags in road construction. The evaluations included parameters such as particle size, specific gravity, water absorption, pH, CBR, and abrasion resistance. Environmental tests focused on the leaching of heavy metals. The results indicated that both slag types are environmentally safe, and particularly, LF slag exhibited high CBR values and favorable technical performance. These findings suggest that EAF and LF slags can be effectively utilized in road base and subbase layers. As for EAF, which showed a lower CBR value, it was deemed suitable mainly for pavement sub-bases and engineering fills. By utilizing SS aggregates in road construction, a sustainable solution is provided for the end-of-life phase of these materials, offering an effective means of diverting large quantities of waste from landfills.

A study conducted by Aldeeky et al. [69] aimed at evaluating the impact of fine SS aggregate (Ferrous Steel Slag Aggregate) on enhancing the geotechnical properties of highly plastic subgrade soil. Initially, both the mechanical and engineering properties of the soil and fine SS were assessed. FSSA was then mixed with the soil samples at dry weight ratios of 0%, 5%, 10%, 15%, 20%, and 25%, and the mixtures were prepared. Improvements in consistency limits, compaction, free swelling, unconfined compressive strength, and CBR were used to assess the performance of FSSA. The results indicated that the addition of 20% FSSA led to a 26.3% reduction in the plasticity index and a 58.3% decrease in free swelling. Moreover, the mixture with 20% FSSA enhanced unconfined compressive strength by 100%, increased maximum dry density by 6.9%, and boosted the CBR value by 154%. These results demonstrate that FSSA significantly improves the geotechnical properties of the soil, offering a sustainable solution for waste disposal while simultaneously enhancing the performance of the subsoil.

Exploring the potential of secondary SS (SSS) as a material for subsoil treatment, Gu et al. [70] mixed SSS with lime in varying proportions and evaluated the performance of these mixtures in terms of compressibility, strength, and expansion ratio. The optimal treatment was achieved with a mixture consisting of 50% SSS, 45% soil, and 5% lime. To examine the strength development of the lime-treated SSS, a scanning electron microscope (SEM) analysis was performed. Further improvement in performance was achieved by enhancing the SSS components with lime and metakaolin, per the oxide compositions and ratios commonly found in Portland cement. After 28 days, the unconfined compressive strength (UCS) of the treated SSS increased from 0.73 MPa to 4.09 MPa. Additionally, the activation of SSS with NaOH, NaCl, and Na2SO4 was tested to boost its reactivity. For samples activated at 5%, the UCS values for NaCl and Na2SO4-treated samples were 8.02 MPa and 10.88 MPa, respectively. Concluding that the regeneration and activation of SSS were effective strategies, the study confirmed its enhanced performance in subgrade treatments.

In Karadağ et al.'s [71] studies, the potential of steel mill slag as a base and subbase material in the road superstructure was evaluated. A road section consisting of crushed stone base and crushed stone subbase material was analyzed as a control section. Steel mill slag was used both together and separately in the base and subbase layers. Axisymmetric analyses were performed on four different road sections using the two-dimensional finite element method, with 20,111 cyclic loadings under 400 kPa load. Resonant column experiments determined the dynamic shear modulus of the slag. The results indicated that steel mill slag could replace natural aggregate in the road base and subbase layers. Particularly, the KC section, where slag was used in the subbase, exhibited the best performance in terms of vertical deformations.

Dang et al. [72] investigated the potential use of steelmaking slag as a mineral aggregate in the base and sub-base layers of road pavements. The mechanical properties of the slag were evaluated using testing procedures defined by Vietnamese standards, and a volume stability test was conducted in accordance with JIS A 5015-2018 (Japanese Industrial Standard for road construction materials). The findings revealed that the steel slag met all mechanical and stability requirements set by both standards. These results indicate that the material is technically reliable and suitable for use in road construction. Notably, its compliance with multiple international standards highlights its potential for broader application. Furthermore, when steelmaking slag was used in the base or sub-base courses, the elastic modulus was found to be higher than that of conventional graded aggregates made from mineral materials. Consequently, they concluded that the use of steelmaking slag could reduce both the required coating thickness and construction costs.

In the study by Dayıoglu et al. [73], the mechanical properties of SS as an unbound aggregate for road construction were examined and compared with those of conventional graded aggregate base (GAB) materials. Three SS samples with different aging characteristics, as well as five aggregate samples from various quarries, were tested to evaluate their behaviors. The results showed that the aging process had no effect on the final swelling of the SSs, a finding that contrasted with the conclusions of previous studies.

Özsoy et al. [74] stated that in the research, the total vertical deformation changes of the road using SS in the road base and subbase layers was examined comparatively with the sections using natural aggregate. The road superstructure constructed with a 30 cm thick granular base, 40 cm thick subbase layers and carrier natural soil consisting of clay under the 10 cm thick asphalt coating layer was subjected to numerical analysis using the 3D finite element method. The dynamic and static analysis results of the 3D model made by taking into account the tire layout plan of the selected vehicle type show that road performance can be increased with appropriate model design and correct material selection. The findings obtained reveal that the vertical deformation values decrease in dynamic analyzes performed under cyclic traffic loads when SS is used in the road base and subbase layers. In addition, increases in the safe carrying load values of sections using SS were observed in the range of 10-70% depending on the number of geogrid reinforcement layers and the location of the settlement. This situation shows that thanks to the use of geogrid reinforcements between the road layers, the traffic loads are distributed to a wider area, the tensile strength of the road is increased and the safe carrying load is increased. By using SS as aggregate in road construction, the need for disposal of waste in regular storage areas is reduced; thus, it is stated that a sustainable system is provided by using natural resources more efficiently and recycling waste materials.

Panda et al. [75] investigated the use of SS, a by-product from a local integrated steel plant that is abundant in the area, as a material for pavement sub-base construction. Their approach not only helped reduce construction costs and address solid waste disposal issues, but also mitigated environmental concerns while conserving natural stone resources for other applications. Their experimental program involved grading the SS and regular aggregates, mixing them to achieve the desired grade, and performing compaction tests to determine the optimal moisture content. Additionally, they evaluated the potential hazards associated with using slag in the sub-base, including its expansion potential and California bearing ratio (CBR). The results showed that using aged SS significantly improved performance properties while meeting environmental standards, providing an effective, sustainable solution for pavement construction in areas near steel plants. Trinidad et al. [76] emphasized the challenges related to the disposal of EAF SS, a waste by-product from steel production, and the environmental concerns associated with it. Their research showed that this slag could serve as a replacement for sand and limestone aggregates in road surface construction, thereby helping to mitigate these environmental issues. Crucial in determining the mixture's mechanical properties and suitability for engineering applications is the interaction between asphalt materials and mineral aggregates. However, because the chemical compositions of asphalt materials vary across sources, generalizing the properties of such mixtures is not feasible. In their study, they examined the impact of incorporating EAF SS (0-20% by weight of ¾ inch aggregates) on Marshall stability to find the optimal slag content. The findings revealed that 15% SS by mass (equivalent to 2.25% of the total aggregate mass) provided the best Marshall stability and air voids within acceptable limits. Not only did the use of SS improve pavement performance, but it also offered an environmentally sustainable method for managing these waste materials.

Sab et al. [77] focused on assessing the impact of SS aggregates on improving the engineering properties of locally produced asphalt concrete (AC) mixtures. They began by assessing the toxicity, chemical composition, and physical properties of SS. In the AC mixtures, SS was used as a replacement for conventional aggregates. The evaluation focused on various performance parameters such as indirect tensile strength, flexural modulus, rut resistance, fatigue life, creep modulus, and stripping resistance. As the proportion of SS in the mixture increased, the ductility of the bitumen initially rose, but then decreased. The findings demonstrated that SS plays a significant role as a binder when combined with bitumen, enhancing the overall performance of the mixture.

Li et al. [78] investigated the potential use of steel slag (SS) in semi-rigid base layers, focusing on its performance and interaction with various stabilizers. The study evaluated how SS behaved when combined with three different binders: cement, lime–fly ash, and cement–fly ash. It also examined how varying slag content influenced the strength and stability of the base layer. Relationships between curing time and unconfined compressive strength, as well as the impact of drying shrinkage and thermal contraction, were analyzed. Key performance aspects such as freeze–thaw durability, rutting resistance, and crack development were assessed using advanced modeling tools including the finite element method (FEM), discrete element method (DEM), and molecular dynamics simulations. Although SS-based foundations may emit slightly more CO_2 than conventional macadam due to production, transportation, and compaction processes, the material demonstrates clear advantages in terms of mechanical strength, cost-effectiveness, and environmental benefit. These results suggest that SS is a highly promising alternative for semi-rigid base courses. Moreover, the study highlights how proper binder selection can enhance SS performance, and it recommends further research to fully explore its application potential.

Aziz et al. [79] conducted an investigation into the physical, mechanical, and chemical characteristics of SSs and assessed their potential for use in road pavement construction. The study highlights current challenges and emphasizes the need for further research to fully explore SS's potential as a building material. Its hydrophobic properties promote strong adhesion with bitumen binders, improving resistance to stripping and other pavement-related issues. Consequently, SS supports the development of cost-effective and sustainable green pavement solutions within the road construction industry.

Bhushan et al. [80] carried out a detailed review of the use of ferrochrome slag as a material for embankments and pavements. Their research assesses the physical, chemical, and mechanical properties of ferrochrome slag and explores its potential applications in civil engineering. The study presents ferrochrome slag as a sustainable and environmentally friendly alternative to conventional construction materials, emphasizing both its benefits and the challenges involved. Furthermore, the authors highlight the potential of ferrochrome slag in terms of stability, durability, and cost-efficiency, while calling for additional research and the establishment of standards to optimize its use.

Al-Shamsi et al. [81] investigated the potential of replacing traditional aggregates with slag in road construction, specifically in the base and subbase layers. The authors conducted an in-depth evaluation of the technical properties, performance, and suitability of slag as an alternative to conventional aggregates. Their findings indicate that slag can improve the durability and load-bearing capacity of road structures, while also providing environmental benefits. However, the study also highlights the challenges associated with the utilization of slag, including potential variability in its properties and the necessity for meticulous processing. The authors underscore the necessity for additional research, encompassing both laboratory experiments and field trials, to thoroughly investigate the long-term performance and environmental implications of slag. The conclusion highlights that, beyond standard practices, project-specific design and implementation strategies are essential for the effective use of slag in road construction. This underlines the need for a holistic approach to fully realize the material’s potential.

Gökalp et al. [82] offer a technical and environmental evaluation of metallurgical slags (Electric Arc Furnace-EAF, and Ferrochromium slags) as aggregates for sustainable pavement layers. The research examines the physical, chemical, and mechanical characteristics of slags, exploring their feasibility as a substitute for traditional aggregates. The study reveals that metallurgical slags positively influence performance characteristics such as durability, friction resistance, and load-bearing capacity. From an environmental perspective, the recycling of slags can reduce waste and conserve natural resources. The paper concludes that the use of metallurgical slags in pavement materials offers both economic and environmental benefits, yet further research is required to develop standards and improve application techniques.

Shen et al. [83] explored the use of a solidified material, created by combining SS, fly ash, and phosphogypsum, as a material for road base construction. The authors conducted a detailed analysis to determine the potential use of the material as a road base. The study demonstrates that the combination of SS, fly ash, and phosphogypsum improves properties such as durability, load-bearing capacity, and water resistance. Additionally, it highlights the environmental benefits of this mixture, as it facilitates the recycling of waste materials and reduces the use of natural resources. The paper concludes that such materials offer sustainable economic and environmental alternatives for road construction; however, further laboratory tests and field trials are necessary.

7. CONCLUSION

Failure to properly dispose of steel slag, along with challenges in its transportation and storage, can lead to environmental pollution. To mitigate these issues and conserve natural resources, steel slag generated during steel production can be effectively utilized in various applications. It is widely employed in road construction, including hot mix asphalt, cement concrete mixtures, anti-slip layers, and base and sub-base layers. The overall performance and durability of roads are significantly influenced by the properties of steel slag.

Based on the literature review presented above, the following conclusions can be drawn:

- Steel slag can serve as a sustainable alternative to natural aggregates in road construction, particularly in regions where aggregate resources are limited. Due to its high wear resistance, it enhances the durability of pavement structures. Additionally, its high friction coefficient improves vehicle traction, thereby enhancing driving safety. Its strong binding properties also contribute to reducing rutting and deformation in asphalt layers under elevated temperatures.

- The use of SS with additives like fly ash and blast furnace slag has been studied to improve strength and long-term stability. These combinations have shown the potential to improve binding capacity, mitigate expansion-related concerns, and increase the overall durability of pavement structures.

- The use of steel slag as railway ballast has been validated through experimental studies, demonstrating superior wear resistance and hardness compared to natural ballast materials. Additionally, steel slag has been effectively utilized as a filling material in coastal and waterway applications to prevent erosion.
- Both standalone steel slag and its combinations with stabilizing agents exhibit superior performance indicators when used in road structure layers. Notably, improvements in service life, particularly within the first five years, contribute to enhanced pavement durability, reduced construction costs, and an extended construction season.

- The economic and environmental advantages of utilizing steel slag are substantial. Incorporating steel slag and its blends with industrial by-products into construction practices reduces material costs, minimizes environmental impact, and supports sustainable development initiatives. Furthermore, this approach promotes job creation in local industries and contributes to the advancement of a circular economy.

To ensure the reliable performance of these alternative materials in transportation infrastructure, the development of new design parameters is essential. This requires a comprehensive evaluation of the mechanical and environmental properties of steel slag and its various combinations through both laboratory investigations and field studies.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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