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REMARKABLE GEOTECHNICAL STATE-OF-THE-PRACTICE APPLICATIONS OF STEELMAKING SLAGS IN BRAZIL

APLICAÇÕES GEOTÉCNICAS NOTÁVEIS DO ESTADO DA PRÁTICA COM ESCÓRIAS DE ACIARIA NO BRASIL

APLICACIONES GEOTÉCNICAS DESTACADAS DEL ESTADO DEL ARTE CON ESCORIAS DE ACERÍA EN BRASIL

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João Renato R. Prandina[1], Marcio Muniz de Farias[2]

ABSTRACT

Steelmaking slags, particularly Linz-Donawitz (LD) and, recently, Kambara Reactor (KR) slags, have emerged as valuable materials in geotechnical engineering due to their distinctive interaction with different soils, generally enhancing the quality of geotechnical applications, due to their physical, chemical, and mineralogical properties. Espírito Santo, a Brazilian state, has developed a vibrant environment for geotechnical applications of these slags, leveraging the most relevant aspect of steelmaking slags: these industrial byproducts exhibit high mechanical strength, durability, and chemical reactivity, enabling significant improvements in soil stabilization, pavement base layers, and other earth structures construction. Incorporation of slags into soils enhances key geotechnical parameters such as maximum dry density, California Bearing Ratio, resilient modulus, and unconfined compressive strength, while also reducing plasticity and mitigating swelling and shrinkage in fine-grained soils. The environmental and economic benefits include waste valorisation, reduction in natural resource consumption, with potential to lower greenhouse gas emissions compared to traditional stabilizers like Portland cement and lime. Challenges related to volumetric expansion and chemical variability are addressed through processing, aging, and quality control measures. Synergistic use with other industrial byproducts further optimizes mechanical performance and sustainability. Advances in testing, characterization, and life cycle assessment support the safe and effective application of these residues, aligning with circular economy principles and regulatory frameworks. Ongoing research focuses on mixture optimization, long-term durability, and innovative treatment methods to expand the applicability of slag-based geomaterials in sustainable infrastructure development.

Keywords: Steel Slag. Soil Stabilization. Resilient Modulus. Sustainable Pavement. MeDiNa Method.

RESUMO

As escórias de aciaria, particularmente as escórias Linz-Donawitz (LD) e, mais recentemente, as escórias do Reator Kambara (KR), têm se destacado como materiais valiosos na engenharia geotécnica devido à sua interação distintiva com diferentes solos,

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[1] Master's degree in Geotechnics. Universidade de Brasília (UnB). E-mail: renatoprandina@gmail.com
[2] Dr. in Numerical Analysis. Universidade de Brasília (UnB). E-mail: muniz@unb.br

melhorando, de modo geral, a qualidade das aplicações geotécnicas em função de suas propriedades físicas, químicas e mineralógicas. O estado do Espírito Santo, no Brasil, desenvolveu um ambiente dinâmico para aplicações geotécnicas dessas escórias, aproveitando o aspecto mais relevante das escórias siderúrgicas: esses subprodutos industriais apresentam elevada resistência mecânica, durabilidade e reatividade química, possibilitando melhorias significativas na estabilização de solos, nas camadas de base de pavimentos e em outras obras de terra. A incorporação das escórias aos solos melhora parâmetros geotécnicos essenciais, como a densidade seca máxima, o Índice de Suporte Califórnia (CBR), o módulo de resiliência e a resistência à compressão simples, além de reduzir a plasticidade e mitigar o potencial de expansão e retração em solos finos. Os benefícios ambientais e econômicos incluem a valorização de resíduos, a redução do consumo de recursos naturais e o potencial de diminuição das emissões de gases de efeito estufa em comparação com estabilizantes tradicionais, como o cimento Portland e a cal. Desafios relacionados à expansão volumétrica e à variabilidade química são tratados por meio de processamento, envelhecimento e controle de qualidade. O uso sinérgico com outros subprodutos industriais otimiza ainda mais o desempenho mecânico e a sustentabilidade. Avanços em ensaios, caracterização e avaliação do ciclo de vida sustentam o uso seguro e eficaz desses resíduos, alinhando-os aos princípios da economia circular e às normas regulatórias. As pesquisas em andamento focam a otimização de misturas, a durabilidade de longo prazo e métodos inovadores de tratamento para ampliar a aplicabilidade dos geomateriais à base de escória no desenvolvimento de infraestruturas sustentáveis.

Palavras-chave: Escória de Aciaria. Estabilização de Solos. Módulo de Resiliência. Pavimento Sustentável. Método MeDiNa.

RESUMEN

Las escorias siderúrgicas, particularmente las escorias Linz-Donawitz (LD) y, más recientemente, las escorias del Reactor Kambara (KR), han emergido como materiales valiosos en la ingeniería geotécnica debido a su interacción distintiva con diferentes suelos, mejorando en general la calidad de las aplicaciones geotécnicas gracias a sus propiedades físicas, químicas y mineralógicas. El estado de Espírito Santo, en Brasil, ha desarrollado un entorno dinámico para las aplicaciones geotécnicas de estas escorias, aprovechando su característica más relevante: estos subproductos industriales presentan alta resistencia mecánica, durabilidad y reactividad química, lo que permite mejoras significativas en la estabilización de suelos, capas base de pavimentos y otras obras de tierra. La incorporación de escorias en los suelos mejora parámetros geotécnicos esenciales, como la densidad seca máxima, el Índice de Soporte de California (CBR), el módulo resiliente y la resistencia a la compresión simple, además de reducir la plasticidad y mitigar la expansión y contracción en suelos finos. Los beneficios ambientales y económicos incluyen la valorización de residuos, la reducción del consumo de recursos naturales y el potencial de disminuir las emisiones de gases de efecto invernadero en comparación con estabilizantes tradicionales como el cemento Portland y la cal. Los desafíos relacionados con la expansión volumétrica y la variabilidad química se abordan mediante procesamiento, envejecimiento y medidas de control de calidad. El uso sinérgico con otros subproductos industriales optimiza aún más el rendimiento mecánico y la sostenibilidad. Los avances en ensayos, caracterización y análisis de ciclo de vida respaldan la aplicación segura y eficaz de estos residuos, alineándolos con los principios de la economía circular y los marcos regulatorios. La investigación actual se centra en la optimización de mezclas, la durabilidad a largo plazo y métodos innovadores de tratamiento para ampliar la aplicabilidad de los geomateriales a base de escoria en el desarrollo de infraestructuras sostenibles.

Palabras clave: Escoria Siderúrgica. Estabilización de Suelos. Módulo Resiliente.

Pavimento Sostenible. Método MeDiNa.

1 INTRODUCTION

Since 2006, roads under municipal and state jurisdiction in the small state of Espírito Santo, Brazil, have received more than 6 million tons of steelmaking slag (SS) for pavement applications. This large local applied volume targeted the improvement of the traffic conditions of approximately 2,000 kilometres of rural and secondary roads, covering about 5,000 roads in 60 municipalities across the state (ArcelorMittal, 2025). The initiative has shown a notable acceleration in recent years, with record donations of the different SS from the production units located in the state, amounting to 1.1 million tons in 2022 and 1.24 million tons in 2023 (SEAG, 2023) to be used in road infrastructure.

In Brazil, the road applications of SS date back to 1978 in the state of Minas Gerais, for the paving of the road access from the city of São Domingos do Prata to the federal highway BR-262/MG. In 1983, the state of Espírito Santo planned and executed a pioneering urban paving program, applying SS in the base layers of more than 105 kilometers of urban roads (DER, 2019) for bus traffic. In recent years, different private companies in many Brazilian states are studying, applying and monitoring SS addition in all pavement layers of their roadways.

The following Table 1 consolidates main milestones and case studies of slag applications in Brazilian roads, going from geotechnical applications of soft soil improvement in subgrades, primary surfacing with SS-soil mixtures of rural unpaved roads, to unbound base layers of highway pavements. The Table 1 offers a synoptic view of the journey of using steel slag aggregates in Brazilian paving.

Table 1

Main milestones and case studies of SS applications in Brazil

Location (City/State)	Associated Company/Institution	Slag Type	Application or Study Focus	Year/Period	Reference
São Domingos do Prata, MG	N/A	N/A	First paving application in Brazil	1978	Souza et al. (2017)
4 cities of ES	CST	Steel	105 km of urban paving (base/sub-base)	1983	DER-ES (2019)
Ipatinga, MG	Usiminas, DER-MG	Steel	"Caminhos do Vale" program, rural roads	2000, 2017, 2021	Rohde (2002)
Sapucaia do Sul, RS	UFRGS	Steel (Electric)	Study for base and sub-base	2002, 2013	Pinheiro Neto et al. (2015)
Maracanaú, CE	Gerdau, UFC	Steel (EAF)	Soil-slag mixtures (base); Asphalt mixtures	2003, 2004	
Santa Cruz, RJ	Gerdau-Cosigua	Steel	Study for triple surface treatment	2005	Lanzellotti et al. (2005)
Linhares, ES	Local Steel Mill	Blast Furnace (Raw)	Base and drainage layer on soft soil (5.6 km)	2007	Silva et al. (2007)
Cariacica, ES	ArcelorMittal, Kaeme Consulting, DER-ES	Steel (LD)	"Novos Caminhos" program in urban area, primary surface wearing course	2010	Mendonça & Rodrigues (2010)
Pindamonhangaba, SP	USP	Steel	Study for base and sub-base	2013	Pinheiro Neto et al. (2015)
Barro Alto, GO	Anglo American, Ecovias	Iron-Nickel	Test in base of federal highways (BR-153/414/080)	2022	Anglo American (2022)
Curvelo, MG	DER-MG	Steel	Recovery of unpaved highway (MG-164)	2022	SEINFRA (2025)
Eco 101 Highway, ES	ArcelorMittal, UFES	Steel (Sidercal®)	Use in sub-base for highway duplication	2013 - 2022	Teixeira, 2022

Source: prepared by the authors.

In the state of Espírito Santo, a historical sequence of SS relevant applications is presented by DER-ES (2019), using the previous technical name of the Linz-Donawitz steelmaking slag (LD-SS) byproduct as “Acerita” (ArcelorMittal, 2016), later named REVSOL (Mendonça & Rodrigues, 2010); several projects have already been carried out using it, including:

- LD-SS applied in 105.3 km (pavement base layer) of the Transcol Project/1983;
- LD-SS applied in 8.6 km (pavement base layer) TIMS/1995;
- LD-SS applied in 6.0 km (pavement base and HMA) in the Access to Praia Mole Port/2001;
- pavement 46.0 km (pavement base layer) in streets and avenues of the city of Vila Velha/1989;
- 80.0km (pavement base layer) in the streets and avenues of Serra/2006;
- Initial drainage layer in the duplication works of Rodovia do Sol (1999-2001);
- Pavement base layer in the Vitória Airport runway (2003-2015);
- Pavement sub-base layer and 20 cm base (90% Acerita and 10% clay) for the internal roads of the Serra Multimodal Industrial Terminal (2004);

- Subgrade reinforcement (50% acerita and 50% clay), 20 cm sub-base (Acerita), and 20 cm base (acerita) at the Steel Products Terminal – ArcelorMittal;
- Pavement base layer (70% acerita and 30% gravel), sub-base layer with 30% Acerita and 70% clayey sand base on highway ES-446, Colatina - *Acampamento* section, among others.

Even though the majority of the SS volume applied has been in soil mixtures for the purpose of surfacing layer of rural unpaved roads, called in the Brazilian technical terminology as primary surfacing, basically defined as an improved soil layer on the top of an unpaved road (DNIT, 2005) serving as wearing course, in recent years different SS has been researched and applied in this top layer (DNIT, 2023) and in the structural layers of rural and urban road, highway pavements, granting a more appropriate engineering use for a high strength geomaterial.

1.1 MOTIVATION HIGH-VALUE GEOTECHNICAL APPLICATIONS OF STEELMAKING SLAG (SS)

Traditional soil improvement methods, such as the use of chemical agents like lime and Portland cement, face growing challenges from high material costs and the diminishing availability of quality natural resources. This scenario compels engineers to investigate alternative industrial byproducts that are both economically and environmentally advantageous. Steelmaking slags (SS), particularly Linz-Donawitz (LD-SS) and Kambara Reactor (KR-SS) slags, emerge as promising candidates for sustainable soil stabilization due to their physical and chemical properties that enhance soil performance (Marin, 2022; Furieri, 2019). The incorporation of SS into geotechnical practices addresses the dual challenge of waste management and material scarcity, transforming an environmental burden into a valuable engineering resource (Medina, 2024; Marin, 2022).

The geotechnical value of SS derives from their granular structure, durability, and chemical reactivity, which enhance mechanical strength and particle interlock (Oliveira, 2016; Fardin, 2024; Gama & Rosa, 2016). Specifically, LD-SS provides cementitious properties via calcium silicates, while KR-SS offers hardness and stabilizing potential for clayey soils due to a high calcium oxide content (>40%) that enables cation exchange and cementation similar to Portland cement (Fardin, 2024; Oliveira et al., 2019; Medina, 2024; Furieri, 2019). These interactions consistently improve parameters such as Maximum Dry Density (MDD), Resilient Modulus (MR), and Unconfined Compressive Strength (UCS) (Gomes et al., 2021; Pires et al., 2019).

Notably, Pires et al. (2019) demonstrated that KR-SS mixtures achieved California Bearing Ratio (CBR) values far exceeding minimum requirements (Table 2), enhancing a clayey soil (S1) from 25.3% to 132% and a clayey sand (S2) from 49% to 116%.

Table 2

Mechanical characterization of soil-KR-SS mixtures

Soil	Mixture	Energy	OMC (%)	γ_{drymax} (kN/m³)	Exp. (%)	CBR (%)	MR (MPa)
S1 A-7-6	S1	Int.	17.0	17.520	0.02	22.7	—
		Mod.	16.3	18.080	0.00	25.3	—
	S1KR15%	Int.	18.0	17.720	0.00	47.8	2,212.6
		Mod.	16.1	18.490	0.04	132.0	2,211.6
	S1KR20%	Int.	17.4	18.040	0.01	81.2	1,491.9
		Mod.	15.5	18.530	0.03	103.2	1,107.9
	S1KR25%	Int.	18.0	18.770	0.00	69.5	—
		Mod.	15.5	18.860	0.02	118.6	—
S2 A-2-6	S2	Int.	10.6	19.200	0.00	49.9	—
		Mod.	10.3	20.090	0.00	89.1	—
	S2KR15%	Int.	12.2	19.220	0.00	107.8	—
		Mod.	11.2	20.250	0.00	164.5	322.3
	S2KR20%	Int.	12.5	19.520	0.00	116.4	—
		Mod.	12.2	19.750	0.00	162.6	399.0
	S2KR25%	Int.	12.8	19.440	0.00	95.4	—
		Mod.	11.5	19.960	0.00	112.5	—

Source: modified Pires et al., 2019.

This versatility allows for blends tailored to specific performance goals, such as optimal (ORC), maximum (MRC), or zero-residue equivalent (ZERO-E) contents as stated by Prandina & Farias (2025). Ultimately, SS utilization drives sustainability by offering a cost-effective, technically viable alternative to natural aggregates and conventional stabilizers without adverse environmental impacts (Oliveira, 2016; Freitas & Costa Jr., 2024; Marin, 2022; Fardin, 2024; Medina, 2024).

1.2 SCOPE AND STRUCTURE OF THE REVIEW

This review is structured to comprehensively synthesize and critically analyze the use of SS, particularly basic oxygen furnace (LD) and Kambara reactor (KR) slags, in geotechnical engineering contexts, focusing on both scientific findings and practical implications across laboratory and field applications. The scope encompasses an examination of the key physical and chemical properties of various SS used as soil stabilizers or ameliorants.

A core element addressed is the review of geotechnical improvements provided by SS amendments, with focus on metrics such as MDD of compacted mixtures, CBR, MR, and UCS. Attention is also given to the selection of relevant performance indicators in the context of mixture design and assessment. While CBR and UCS are widely adopted, the review underscores the complexities of achieving a sustainable optimum, suggesting that additional metrics such as expansion and durability must be factored into multi-criteria analyses (Gomes et al., 2021).

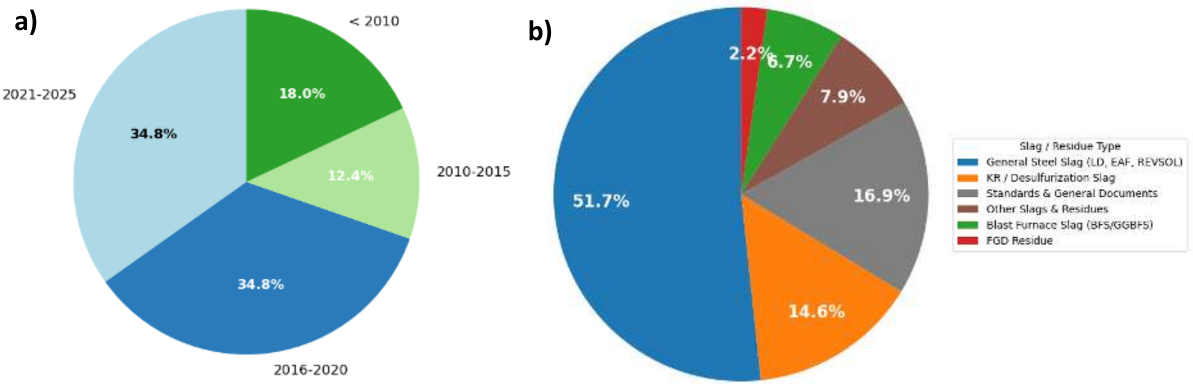
The discussion is anchored in the technical feasibility of using SS´s arising from diverse processes, LD, KR, blast furnace, and provides a classification of these byproducts with reference to their origin in the steel manufacturing supply chain (Marin, 2022; Resende, 2010). In mapping the landscape of current research, the review also integrates findings from studies employing advanced mixture design techniques, such as Monte Carlo simulation and multi-criteria optimization approaches. Figure 1 shows the number of relevant scientific references considered in this work.

These methods are examined for their practical applicability and replicability by road agencies. The chronological distribution of the 89 references highlights a current and comprehensive literature base, with 34.8% published between 2021 and 2025. This review intentionally prioritizes the inclusion of theses and dissertations to leverage their detailed, unabridged datasets. This methodological approach enables a deeper synthesis of primary research, accessing valuable data often excluded from space-limited publications.

Figure 1

a) Distribution of the 89 references by publication date;

b) Distribution of the first set of reference subjects by the types of SS



Source: prepared by the authors.

Finally, the review is structured to move systematically from the characterization of the slags, considering the types included in this work (Figure 1b), through their impacts on key engineering properties, to integrated case study analyses.

This structure allows for a nuanced discussion of the high-value and suitability of slag as a sustainable material for soil improvement, and highlights gaps in knowledge, practical barriers, and future research frontiers (Nunes, 2024; Pires et al., 2019). By collating diverse technical, scientific, and applied perspectives, especially the state of Espírito Santo experiences, the review aims to establish an authoritative synthesis that is relevant to researchers, engineers, and practitioners, which may collaborate to an environment of a vibrant specialized engineering state-of-the-practice leveling continuously to its state-of-the-art.

2 TYPES OF STEELMAKING SLAGS (SS) AND THEIR SOURCES

2.1 OVERVIEW OF SS PRODUCTION PROCESSES

SS production is intrinsically linked to the metallurgical processes of steel and iron manufacturing, where it emerges as a byproduct with distinct physical and chemical characteristics depending on the specific process and raw materials involved. The generation of SS occurs primarily during the separation of impurities from molten metal, with the resulting material comprising a complex mixture of oxides, silicates, and other compounds. The two most relevant types of SS for geotechnical applications are those derived from the basic oxygen furnace (LD - Linz-Donawitz process) and the KR (Kambara Reactor) process, each with unique production pathways and compositional profiles (Cunha, 2020; Bridi, 2020; Andrade, 2018).

2.2 *CLASSIFICATION OF SS BY INDUSTRIAL SOURCE*

2.2.1 Linz-Donawitz (LD) Slag

Linz-Donawitz slag (LD-SS), also known as Basic Oxygen Furnace (BOF) slag, is a byproduct generated during the steelmaking process, specifically in the refining stage where pig iron is converted into steel using oxygen blowing. Figure 2 shows a typical LD-SS.

The process involves several distinct steps, beginning with the appropriate positioning and inclination of the converter, followed by the loading of solid charge materials and subsequent addition of molten pig iron. These operational stages are fundamental to the generation of LD-SS, which accumulates as a result of the chemical reactions and phase separations occurring during steel refining (Izoton, 2020; Resende, 2010).

Figure 2

Full sample of a LD-SS from Espírito Santo industrial plant

Source: from Izoton, 2020.

The physical and chemical characteristics of LD-SS are shaped by the nature of the raw materials and the specific conditions of the steelmaking process. LD-SS is typically granular and exhibits a heterogeneous composition, containing oxides of calcium, silicon, iron, and magnesium, among others. Table 3 presents chemical compositions of LD-SS from different industrial plants in Brazil, with the updated current owner name.

Figure 3 shows the SEM images of the LD-SS. The images reveal the grains' porosity, their highly rough surface textures, angular shapes, and significant dimensional variability—characteristics that induce interlocking (Boldrini & Pacheco, 2022) and packing mechanisms when mixed with soils for engineering purposes.

The X-ray diffraction (XRD) analysis of the sample (Figure 4) revealed the crystalline peaks of $Ca(OH)_2$, CaO, MgO, and FeO within the LD-SS structure. One of the notable features of LD-SS is its potential for expansion, primarily due to the presence of free lime and periclase. This expansion behavior is a sensitive parameter when considering the LD-SS use as aggregates in construction and geotechnical works. The expansion can lead to volumetric instability if not properly managed, necessitating specific testing protocols such as autoclave expansion tests to assess the suitability of the LD-SS for engineering purposes (Resende, 2010; Raposo, 2005).

Table 3

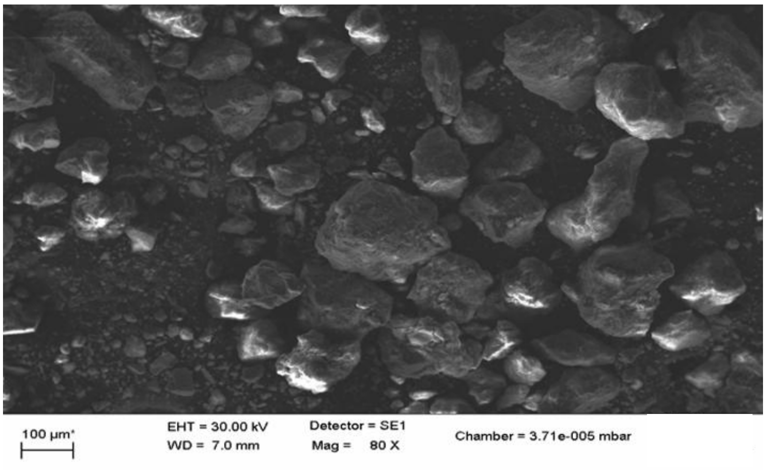
Chemical composition of LD-SS from Brazilian industrial plants

Plants	CaO	MgO	Al_2O_3	SiO_2	MnO	Fe (total)	S	P_2O_5
ArcelorMittal - Vitória	45.20	5.50	0.80	12.20	7.10	18.80	0.07	2.75
Aperam South America	44.81	7.32	2.42	15.47	02.09	14.06	0.06	1.18
ArcelorMittal - João Monlevade	47.00	8.00	1.50	15.00	3.00	19.00	-	-
Usiminas	41.40	6.20	1.40	11.00	6.30	22.00	-	1.80
Gerdau - Ouro Branco	45.58	9.48	0.75	12.01	6.59	16.71	-	2.23
Gedau - Cocais	36.20	12.50	0.93	15.40	5.80	21.00	0.04	01.01
Vallourec	43.00	7.00	0.80	15.00	3.00	22.00	0.20	1.60
CSN	35.00	6.00	4.00	15.00	3.50	19.70	0.34	0.70
Usiminas - Cubatão	38.69	9.76	1.29	11.17	6.42	22.29	0.06	1.44

Source: Adapted from Oliveira, 2016.

Figure 3

SEM image of the processed LD-SS sample

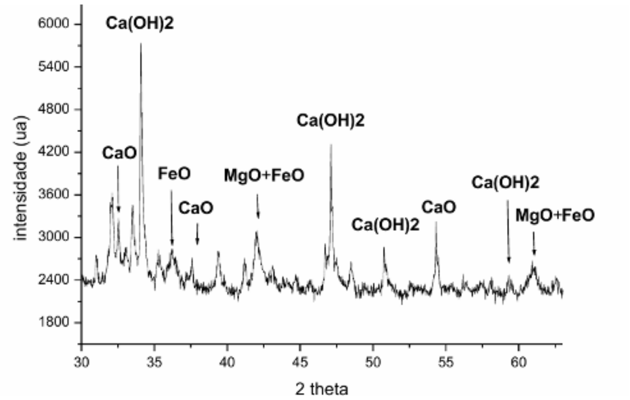


Source: from Boldrini & Pacheco, 2022.

The reduction of expansion is essential to ensure the long-term geotechnical performance and durability of infrastructure incorporating LD-SS. In the context of geotechnical engineering, LD-SS has been recognized for its beneficial properties when used as a soil stabilizer or as a component in pavement base and sub-base layers. Its granular nature and high angularity contribute to improved mechanical interlock and load distribution within soil mixtures.

Figure 4

XRD pattern for the LD-SS of Espírito Santo industrial plant



Source: from Boldrini & Pacheco, 2022.

2.2.2 *Kambara Reactor (KR) Slag*

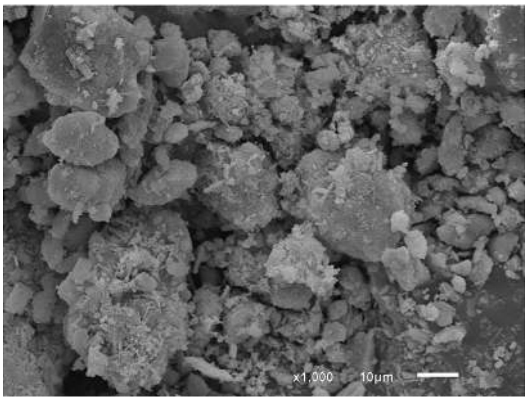
Kambara Reactor slag (KR-SS) is a byproduct generated from the desulfurization of hot metal (pig iron) in a Kambara Reactor. This slag is characterized by its unique chemical and mineralogical composition, which is influenced by the operational parameters of the Kambara Reactor and the raw materials used. The KR process involves the agitation of the molten iron with a desulfurizing agent to reduce impurities like sulfur, which results in the formation of the slag byproduct (Medina, 2024). KR-SS is distinct from other steelmaking slags such as LD-SS due to its unique chemical composition and mineralogical characteristics, which are a direct consequence of the desulfurization reactions and the specific fluxes employed in the process (Meneguete, 2018; Bridi, 2020).

The primary function of the slag-forming agents in the desulfurization process is to capture and remove sulfur from molten iron, typically through the addition of lime-based materials and other fluxes that promote the formation of stable sulfide phases. The chemical composition of desulfurization slag is characterized by elevated contents of CaO and, to a lesser extent, magnesium oxide (MgO), both of which are essential for the efficient removal of sulfur from the metal bath (Meneguete, 2018).

The physical properties of KR-SS, such as particle size distribution (Figure 5) and density, are crucial for its application in geotechnical engineering. The granulometric profile of KR-SS can be tailored through processing, and its particle size distribution often aligns closely with that of conventional granular materials used in pavement and sub-base layers. For instance, the granulometric curves of KR-SS and inert stone materials can be matched within a 5% variation, which facilitates its integration into existing construction specifications (Oliveira, 2018). This compatibility is significant for ensuring uniform compaction and mechanical performance when KR-SS is blended with soils or used as a standalone aggregate.

Figure 5

Scanning Electron Microscopy - SEM of a KR sample from Espírito Santo



Source: From Bridi (2020)

Chemically, KR-SS is predominantly composed of calcium oxide (CaO), silicon dioxide (SiO_2), and smaller amounts of magnesium oxide (MgO), iron oxides, and other minor constituents. The high CaO content imparts a certain degree of alkalinity, which can be beneficial for soil stabilization, as it promotes pozzolanic reactions when mixed with clayey soils or other siliceous ones (Oliveira, 2018).

Soil mixtures using different natural soils and SS, such as the KR-SS studied by Bridi (2020), showed in Figure 6, have been currently designed to optimize both the mechanical performance and the economic efficiency of pavement layers. The chemical and physical characterization of these materials ensures that the resulting mixtures meet the necessary requirements for stability and durability under traffic loading (Bridi, 2020). Laboratory analyses, such as X-ray diffraction and scanning electron microscopy (Figure 7), reveal that the presence of reactive phases in KR-SS can promote pozzolanic reactions when mixed with soils (Oliveira et al., 2019). These reactions contribute to the long-term strength gain and durability of the stabilized embankment material. However, the presence of free CaO and MgO in the final slag product can impart expansive properties, as these oxides may hydrate and expand upon exposure to moisture. This expansion potential is a critical consideration in geotechnical applications, as it can influence the long-term stability and durability of soil-slag mixtures (Santos, 2024).

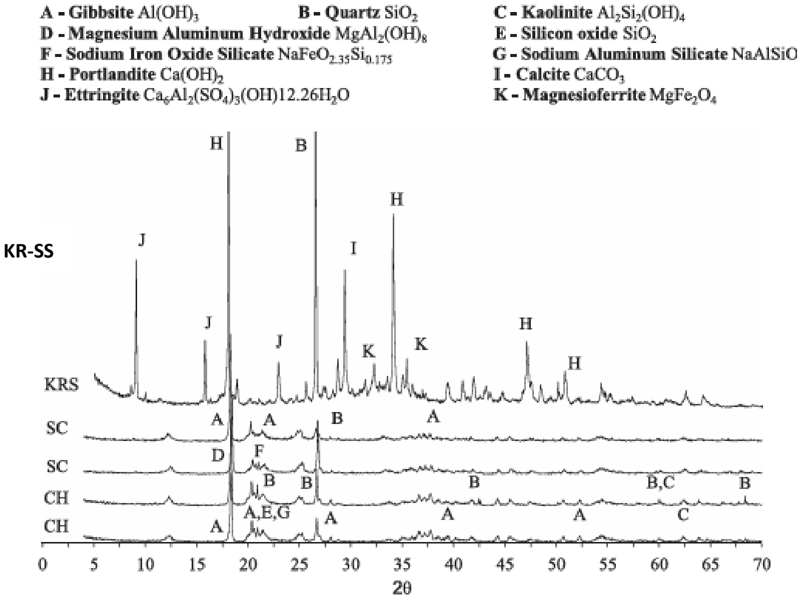
Figure 6

Natural sandy (A100) and clayey (Sa100) soils from Anchieta, Espírito Santo state, side by side with KR-SS (KR100), modified from Bridi (2020)


(a) A100 (b) Sa100 (c) KR100 (d) A100, Sa100 e KR100

Figure 7

XRD pattern for the CH and SC soils of Espírito Santo and KR-SS



Source: from Oliveira et al.,2019.

The mineralogical phases present in desulfurization slag often include dicalcium silicate, periclase, and various calcium sulfide compounds, which collectively contribute to its reactivity and engineering behavior (Meneguete, 2018).

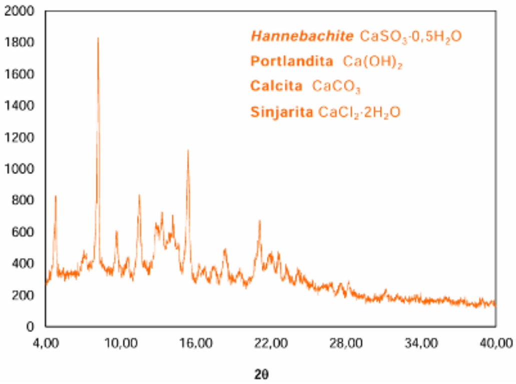
2.2.3 Flue Gas Desulfurization (FGD) residue

Flue Gas Desulfurization (FGD) is a mandatory process in many countries for removing pollutants from the combustion gases of coal-fired power plants. The technique functions by adsorbing not only SO_2 and SO_3, but also compounds like HCl and HF, in an alkaline medium such as lime, limestone, or calcium hydroxide. The captured compounds settle to form the resulting byproduct, FGD residue, which is a material rich in calcium oxide (CaO) and sulfur trioxide (SO_3) and exhibits physical and chemical characteristics similar to recycled gypsum (Wu et al., 2022). Visually, the raw FGD residue is a dark grayish, solid particulate with a fine grain size that tends to form lumps due to its hygroscopic nature (Moscon, 2024). In Figure 8, the XRD of the local FGD-SS and Figure 9 shows the residue itself.

In Espírito Santo, Brazil, SunCoke Energy generated 140,347.2 tons of FGD-SS in 2024 (IEMA-ES, 2024). In 2023, the Espírito Santo State Institute for Environment and Water Resources (IEMA-ES) launched the Sistema Estadual On-line de Manifesto de Transporte de Resíduos Sólidos (MTR-ES System).

Figure 8

XRD of the FGD-SS powder

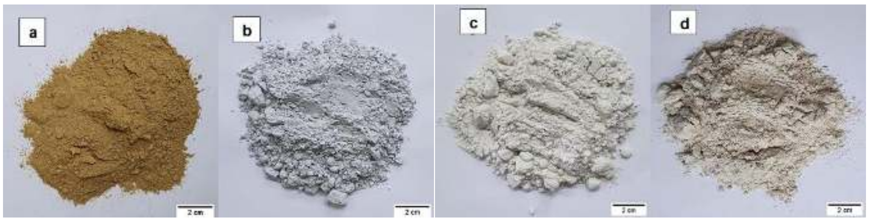


Source: from Picoli, 2020.

This mandatory, free-to-use digital platform functions as a cradle-to-grave tracking system for solid waste transported within the state. All generators, transporters, and final destinators subject to environmental licensing are required to use it (Espírito Santo, 2023).

Figure 9

Dried raw appearances of: a) Dried and disaggregated clay; b) FGD residue; c) Soda-lime glass polishing waste; and d) OSR (Ornamental stone residue



Source: from Moscon, 2024.

Due to the large volume of residue produced and the lack of widespread reuse options, industrial management of this waste still primarily involves disposal in industrial and sanitary landfills.

2.2.4 *Ground Granulated Blast Furnace (GGBF) Slag*

Granulated Blast Furnace Slag (GBF-SS) is a byproduct generated during the production of pig iron in blast furnaces, where iron ore is reduced to iron and the non-metallic components are separated as slag. The molten slag is rapidly quenched with water, resulting in a glassy, granular material that is subsequently dried and ground to a fine powder, turning it to a ground GBF-SS (Figure 10). When cooled directly in the air temperature, the steel industry refers as ABS (air-cooled furnace slag) and in this item is referred as ABF-SS.

This process imparts GGBFS with unique physical and chemical properties, making it a valuable material in geotechnical and civil engineering applications (Marin, 2022). Chemically, GGBFS is primarily composed of oxides such as SiO_2, CaO, Al_2O_3, and MgO, with minor constituents including Fe_2O_3 and other trace elements. This composition is responsible for its valuable pozzolanic and latent hydraulic properties, which are enhanced by the rapid cooling process.

Visually (Fig. 14), the ground GBF-SS consists of light-colored, sand-like particles. The Los Angeles abrasion test shows that the material is friable (83%), breaking down significantly under impact and generating a large portion of fine, powdery material from the original coarser grains. This physical breakdown contributes to its behavior when used in compacted pavement base layers. The predominance of silicates and aluminates, often in amorphous form, directly results from the rapid cooling process, which inhibits crystallization and enhances the material's latent hydraulic reactivity (Resende, 2010).

Figure 10

The effect of the Los Angeles abrasion test on the coarse fraction (>1.7 mm) of GBF-SS

Source: from Pinto, 2010.

2.2.5 Blends of Different SS

The Espírito Santo (ES) local industry (ArcelorMittal Tubarão) has evolved in recent years and have been offering different blend of SS, going from simple LD-SS to mixtures up to 4 different residues from the steelmaking process (Table 4). Figure 11 presents the XRD of 6 different SS, LD-SS compared LD-SS blended to KR-SS and GBF-SS, KR-SS, FGD-SS, GBF-SS, ABS-SS, and a Espírito Santo state soil. These blends alone reached 6 million tons applied in the ES state roads.

Table 4

Different blends of SS of the ES state local industry

Commercial Blend of SS	Composition	Primary Applications - Suggested by the Steelmaking Industry
Blend I	A 50/50 blend of LD-SS and KR-SS	Primary surfacing, yard paving, and grade elevation under clay layers.
Blend II	A blend of 1/3 LD-SS, 1/3 KR-SS, and 1/3 GBF-SS	Base and sub-base courses for asphalt and interlocking paver pavements.
Blend III	A blend of 70% GBF-SS and 30% KR-SS.	Base and sub-base courses for concrete and interlocking paver pavements.
Blend IV	An equal-part blend at 25% of GBF-SS, K-SS, LD-SS, and blast furnace sludge.	Base and sub-base courses for asphalt and interlocking paver pavements.

Source: modified Cunha, 2020.

3 TYPICAL GEOTECHNICAL APPLICATIONS OF STEELMAKING SLAGS (SS)

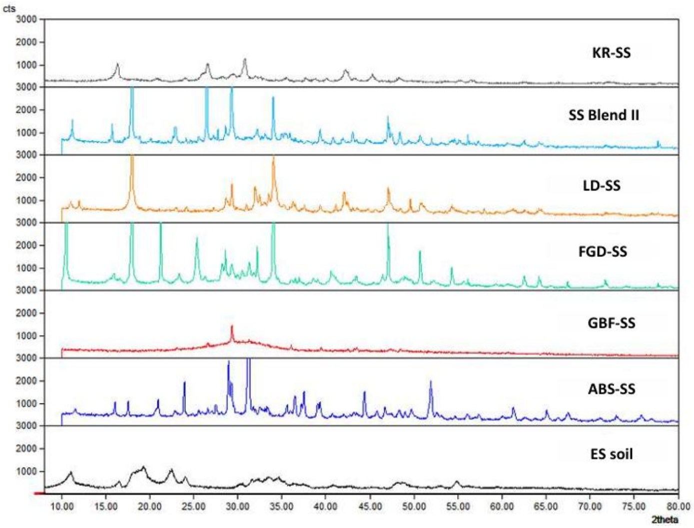
3.1 IMPROVEMENTS IN GEOTECHNICAL DEFORMATION PROPERTIES OF SUBGRADE SOILS

The integration of SS, particularly LD-SS and KR-SS, into subgrade soils has demonstrated significant improvements in geotechnical deformation properties. The original subgrade soils, often characterized by high clay content and suboptimal mechanical behavior, can be substantially enhanced through the addition of these industrial by-products (Gomes et al., 2021). The physical and chemical characteristics of SS, such as their granular structure and chemical reactivity, contribute to the modification of soil fabric and the development of cementitious bonds, which are the agents for improving deformation resistance (Cunha, 2020; Oliveira, 2016).

The SS incorporation into subgrade soils generating mixtures that can be designed, a notable increase will typically happen in MDD after compaction, CBR, both of which are essential indicators of soil improvement (Cunha, 2020; Pires et al., 2019). The improvement in MDD is attributed to the dense, angular particles of SS that fill and replace voids and soil-voids within the soil matrix, leading to a more compacted structure. This densification effect is further supported by the chemical reactivity of SS particles with the surrounding soil, which can induce secondary cementation reactions, especially in the presence of moisture and fine soil fractions (Pires et al., 2019; Oliveira, 2016).

Figure 11

XRD of different SS, LD-SS compared LD-SS blended to KR-SS and GBF-SS , KR-SS, FGD-SS, GBF-SS, ABS-SS, and a ES soil

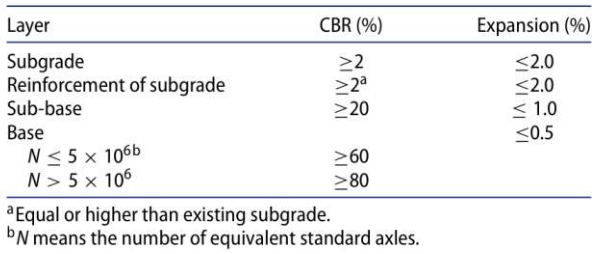


Source: modified Cunha, 2020.

The CBR values of soil-SS mixtures often surpass those of untreated soils, indicating enhanced resistance to penetration and deformation under load (Cunha, 2020). Table 5 shows the thresholds of Brazilian codes for different pavement layers, starting in the subgrade.

Table 5

Minimum thresholds of Brazilian codes for pavement layers



Layer	CBR (%)	Expansion (%)
Subgrade	≥ 2	≤ 2.0
Reinforcement of subgrade	$\geq 2^{a}$	≤ 2.0
Sub-base	≥ 20	≤ 1.0
Base		≤ 0.5
$N \leq 5 \times 10^{6b}$	≥ 60	
$N > 5 \times 10^{6}$	≥ 80	

[a] Equal or higher than existing subgrade.
[b] N means the number of equivalent standard axles.

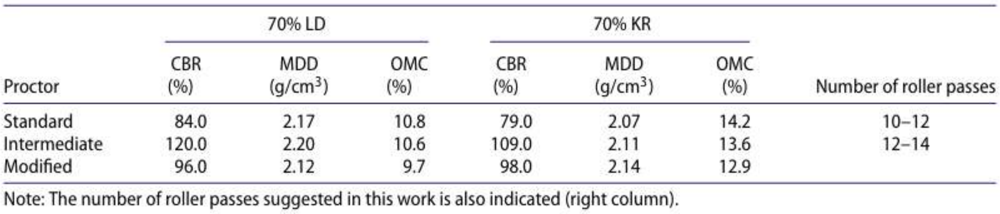
Source: from Magalhães et al., 2022.

Table 6 shows the LD-SS and KR-SS mixed with local soils surpassing by far these limits, indicating that an optimum residue content (ORC) and/or a maximum residue content (MRC) strategies might be used, according to Prandina & Farias (2025), to tailor specific mixtures for each pavement layer.

The MR, a parameter reflecting the elastic response of subgrade materials under repeated loading, also benefits from SS addition. The MR values of SS-treated soils are comparable to those achieved with traditional crushed stone aggregates, suggesting that SS can serve as effective alternatives in base and subbase layers of pavements. This similarity in resilient behavior is particularly advantageous for flexible pavement systems, where the ability to recover from traffic-induced stresses is critical for long-term performance (Cunha, 2020; Furieri, 2019).

Table 6

Comparison of the standard (top row), intermediate (middle row) and modified (bottom row) Proctor tests for 70% LD and 70% KR mixtures



	70% LD			70% KR			
Proctor	CBR (%)	MDD (g/cm³)	OMC (%)	CBR (%)	MDD (g/cm³)	OMC (%)	Number of roller passes
Standard	84.0	2.17	10.8	79.0	2.07	14.2	10–12
Intermediate	120.0	2.20	10.6	109.0	2.11	13.6	12–14
Modified	96.0	2.12	9.7	98.0	2.14	12.9	

Note: The number of roller passes suggested in this work is also indicated (right column).

Source: from Magalhães et al., 2022.

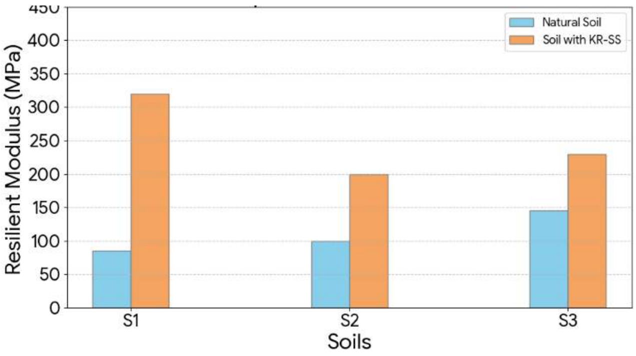
Laboratory studies confirm that the inclusion of SS in subgrades significantly increases UCS, driven by pozzolanic and hydraulic reactions that form cementitious compounds, rigidify the soil structure, and reduce plastic deformation (Pires et al., 2019; Ramos, 2018; Oliveira, 2016). This strengthening is particularly pronounced in clayey soils, where the interaction between fines and SS enhances mechanical integrity (Gomes et al., 2021). Although SS expansion is a design consideration, it is generally mitigated by the consolidation and strength gain of the stabilized matrix, provided that material selection adheres to established granulometric and expansion standards (Ramos, 2018; Santos, 2013). Consequently, proper characterization transforms marginal subgrade soils into competent structural layers, enhancing density and resilience while validating a sustainable solution for industrial by-product management (Cunha, 2020; Andrade, 2018; Furieri, 2019).

3.2 SOIL STABILIZATION FOR EMBANKMENTS

The integration of LD-SS and KR-SS into embankment soils significantly enhances mechanical performance (MDD, CBR, MR, UCS) due to their rich calcium-silicate composition (Fardin, 2024; Ramos, 2018). Notably, Fardin (2024) demonstrated that adding KR-SS to various clayey soils (A-2-7, A-7-6) yields substantial improvements, particularly in soils with lower initial Modulus of Resilience (MR), as illustrated in Figure 12.

Figure 12

Resilient modulus of natural soils and KR-SS



Source: modified Fardin, 2024.

This enhancement is attributed to matrix densification and the formation of cementitious bonds, which become more pronounced after a three-month curing period that also mitigates potential expansion (Santos, 2013). Furthermore, the non-plastic nature of crushed slag fines ensures water insensitivity, reducing volumetric instability risks critical for embankment durability (Raposo, 2005). However, careful selection is paramount; highly reactive slags with free lime may cause undesirable expansion, necessitating pre-treatment to ensure compatibility (Meneguete, 2018). Overall, proper slag utilization transforms marginal soils into robust, sustainable embankment materials (Santos, 2013; Raposo, 2005).

3.3 USE IN PAVEMENT BASES AND SUB-BASES

The application of LD-SS and KR-SS in pavement bases and sub-bases is supported by their compliance with national gradation standards (e.g., DNER ES-303/97, DNIT 031/2006-ES), ensuring adequate compaction and mechanical interlock (Raposo, 2005; Izoton, 2020). Physically, the high particle strength and sandy texture of these slags enhance load-bearing capacity compared to traditional sandy soils (Carvalho et al., 2022). Gomes et al. (2021) demonstrated that both KR-SS and LD-SS significantly improve geotechnical parameters when mixed with soil, yielding higher CBR values (Table 7), increased UCS, and improved MR, all critical for long-term durability.

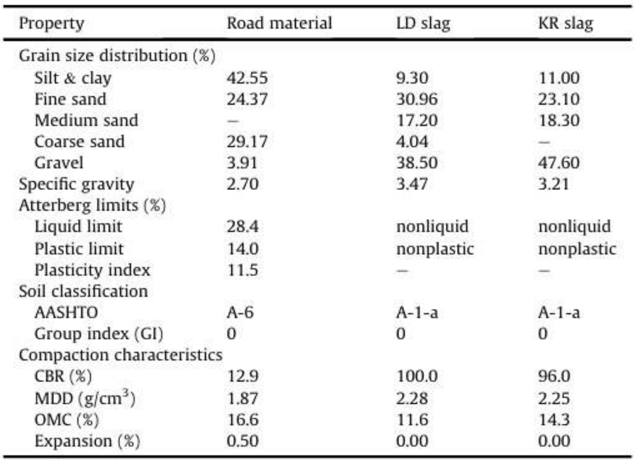
Field validation confirms these benefits; mechanistic retro-analyses of LD-SS base layers show satisfactory strength and durability under traffic, as illustrated in Figure 13 (Resende, 2010). Furthermore, industrial beneficiation produces specialized LD-SS byproducts (e.g., Revsol), tailored for primary surfacing and embankments, reinforcing the technical and environmental viability of substituting natural aggregates with slag in drainage and structural layers (Cunha, 2020; Gama & Rosa, 2016).

LD-SS and KR-SS are abundant local byproducts, exhibit consistent quality and are readily available for large-scale infrastructure projects allowing the adoption of different strategies seeking the ORC, the MRC or the ZERO-E proportions proposed by Prandina & Farias (2025) for sub-base applications. Valuable data on LD-SS behavior, distinct from international literature, is provided by Resende (2010), who performed compaction and CLTT tests under different energies as detailed in Table 8.

Expanding beyond slags, Carvalho et al. (2022) validated that iron ore tailings blends (e.g., 80/20) also meet DNIT sub-base thresholds (>20% ISC). For KR-SS and LD-SS, Gomes et al. (2021) indirectly identified the Optimal (ORC) and Maximum (MRC) Residue Contents that maximize UCS and CBR, as illustrated in Figure 14, thereby enhancing structural integrity.

Table 7

Typical properties of Espírito Santo soil, LD slag and KR

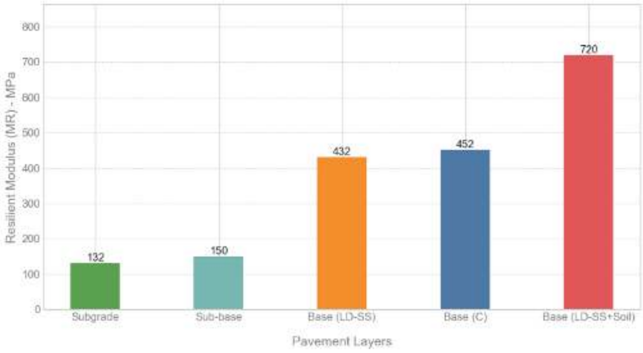


Property	Road material	LD slag	KR slag
Grain size distribution (%)			
Silt & clay	42.55	9.30	11.00
Fine sand	24.37	30.96	23.10
Medium sand	–	17.20	18.30
Coarse sand	29.17	4.04	–
Gravel	3.91	38.50	47.60
Specific gravity	2.70	3.47	3.21
Atterberg limits (%)			
Liquid limit	28.4	nonliquid	nonliquid
Plastic limit	14.0	nonplastic	nonplastic
Plasticity index	11.5	–	–
Soil classification			
AASHTO	A-6	A-1-a	A-1-a
Group index (GI)	0	0	0
Compaction characteristics			
CBR (%)	12.9	100.0	96.0
MDD (g/cm^3)	1.87	2.28	2.25
OMC (%)	16.6	11.6	14.3
Expansion (%)	0.50	0.00	0.00

Source: from Gomes et al., 2021.

Figure 13

Back analysis of different pavement layers and different base layers materials including a 80% LD-SS mixed with 20% clayey soil



Source: modified Resende, 2010.

This versatility highlights the dual functionality of SS as both aggregate and stabilizer, allowing for tailored solutions often combined with other binders like fly ash (Nepomuceno, 2019). Consequently, while technical compliance and environmental benefits are well-established, further standardization for determining optimal mixture ratios is necessary to fully leverage these sustainable geomaterials (Izoton, 2020; Gama & Rosa, 2016; Raposo, 2005).

3.4 ENHANCEMENT OF CONSTRUCTION MATERIAL PERFORMANCE

3.4.1 Reduction in Material Costs

The integration of SS, particularly LD-SS and KR-SS, into geotechnical applications has a direct influence on reducing material costs in construction projects. This cost reduction is primarily attributed to the replacement of conventional, often more expensive, natural aggregates with industrial byproducts that are readily available from steelmaking processes. Several steelmaking groups are actively investing in the development of products derived from the curing, crushing, and granulometric correction of slags generated in their steelworks, which not only adds value to what would otherwise be a waste product but also reduces the demand for virgin materials (Oliveira, 2016).

Table 8

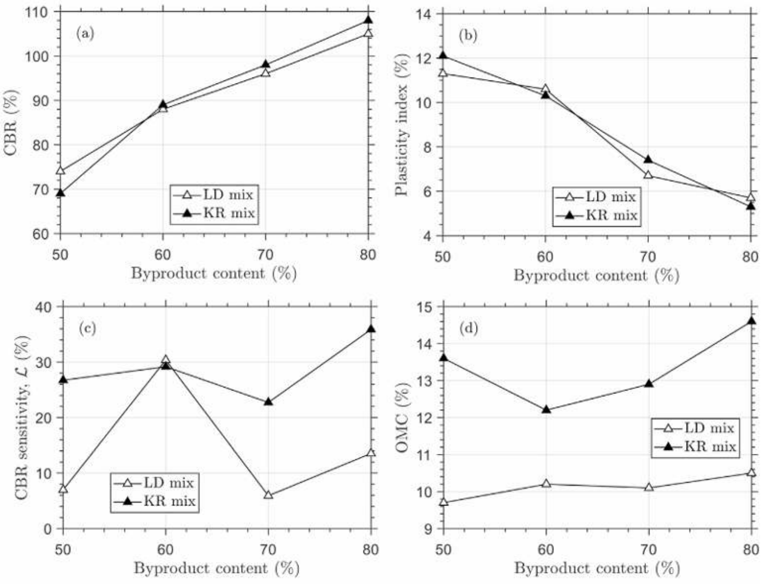
MG-232 road CBR test on classified construction materials

Location	Material / Layer	TRB	CBR (%)	EXP (%)
F1 - EST.: 9+12	LD-SS Base	A-1-a	240	-0,14
F2 - EST.: 109+19	80% LD-SS Base + 20% Clayey Soil	A-1-a	180	-0,17
F3 - EST.: 209+19	Natural gravel Base	A-1-b	109	-0,02
F4 - EST.: 309+19	Natural gravel Base	A-1-a	90	0,08
F5 - EST.: 410	80% LD-SS Base + 20% Clayey Soil	A-1-a	270	-0,04
F6 - EST.: 509+10	80% LD-SS Base + 20% Clayey Soil	A-1-a	192,8	-0,08
F7 - EST.: 609+09	LD-SS Base	A-1-a	205	0
F8 - EST.: 710+05	LD-SS Base	A-1-a	265	0,08
F9 - EST.: 810+01	Natural soil Base	A-2-6	60	0,05
F10 - EST.: 907+01	Natural soil Base	A-2-5	89	0,07
F11 - EST.: 998+19	Natural gravel Base	A-1-a	179,4	0,02

Source: apud Resende, 2010.

Figure 14

Performance indicators for ORC and MRC of soil/LD-SS and soil/KR-SS: variation of CBR (a), Plasticity index (b), CBR sensitivity to moisture (c), OMC (d), at different LD slag (LD-SS, open symbols) and KR slag (KR-SS, solid symbols) contents



Source: from Gomes et al., 2021.

The use of these byproducts as construction materials can significantly decrease the overall expenditure on raw materials, as SS are typically less costly than quarried aggregates. The granulometric correction of SS, as observed in the production of EGC (granulometrically corrected SS), results in a material with superior mechanical properties, such as a higher resilient modulus compared to conventional granular materials. This enhanced performance is attributed to the angular shape and rough surface texture of SS particles, which promote greater interlocking and mechanical stability within the mixture (Santos, 2013).

The improved mechanical behavior allows for the use of thinner pavement layers or reduced quantities of material to achieve the same or better structural performance, thereby lowering the total material volume required and, consequently, the associated costs. Incorporating SS into soil mixtures has also been shown to improve key geotechnical parameters, such as MDD and CBR. For instance, soil-SS mixtures exhibit higher MDD and lower optimum moisture content compared to mixtures with natural aggregates or pure soil.

The increase in the support capacity considering the CBR for soil-SS mixtures is, on average, three times greater than that of pure soil and about twice that of soil-gravel mixtures (Oliveira, 2016). This substantial improvement in load-bearing capacity means that less material may be needed to achieve the required structural integrity, further reducing costs.

3.4.2 Extension of Service Life

The extension of service life in geotechnical applications is a direct consequence of the improved durability and mechanical performance imparted by the incorporation of SS, particularly LD-SS and KR-SS, into construction materials. The use of these SS as stabilizing agents or partial replacements for traditional binders and aggregates has demonstrated a significant enhancement in the longevity of geotechnical structures, such as pavements and embankments, due to their unique physical and chemical properties (Medina, 2024; Marin, 2022; Raposo, 2005).

One of the primary mechanisms by which SS contribute to service life extension is through the stabilization of expansive or weak soils. When mixed with soils, SS can increase the MDD and CBR, both of which are critical parameters for the load-bearing capacity and deformation resistance of subgrades and base layers (Fardin, 2024; Freitas & Costa Jr., 2024; Oliveira, 2018). The improved compaction characteristics and higher CBR values translate into a more robust foundation that is less susceptible to rutting, settlement, and other forms of distress under repeated traffic loading.

4 PHYSICAL AND CHEMICAL PROPERTIES OF SLAGS

4.1 CHEMICAL ELEMENTS AND MINERALOGICAL COMPOSITION

The mineralogical composition of slags is a fundamental aspect that influences their behavior and suitability for geotechnical applications. LD-SS and KR-SS are characterized by a complex assemblage of mineral phases, each contributing distinct physical and chemical properties to the material.

The primary mineral constituents typically include dicalcium silicate (larnite, Ca_2SiO_4), calcium ferrite, free lime (CaO), iron oxides (FeO), periclase (MgO), portlandite ($Ca(OH)_2$), and calcite, among other minor phases. These minerals are formed as a result of high-temperature reactions during the steelmaking process, and their proportions can vary depending on the raw materials and operational parameters employed in the production of the SS. The presence of dicalcium silicate and calcium ferrite is particularly significant, as these phases are known to impart hydraulic and pozzolanic reactivity to the SS. This reactivity is crucial for the development of strength and durability when SS are used as binders or stabilizing agents in soil improvement.

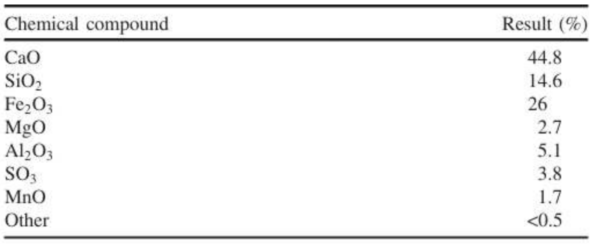
CaO, another abundant phase, plays a dual role: it can contribute to the alkalinity of the system, promoting the dissolution and subsequent precipitation of secondary minerals, but it may also pose challenges related to volumetric stability if present in excessive amounts. The hydration of free lime leads to the formation of portlandite ($Ca(OH)_2$), which further reacts with atmospheric CO_2 to form calcite ($CaCO_3$), thus influencing the long-term stability and leaching behavior of the material (Oliveira, 2016). A KR-SS sample of Meneguete (2018) is shown in the Figure 15, with finds of portlandite, calcite, quartz, and larnite (Ca_2SiO_4).

The chemical composition of ground GBFS, typically reveals a dominance of CaO, with significant amounts of MgO, Fe_2O_3, and minor oxides such as K_2O, Na_2O, and Mn_2O_3. KR-SS, with the chemical composition presented in the Table 9, does not fall far from the general rule of high presence of free lime.

The high CaO content, often exceeding 40%, is a key factor in the SS's reactivity and its ability to participate in cementitious reactions when mixed with soils or other binders (Sant'ana, 2003). The fineness of the SS particles also plays a role in accelerating these reactions, as finer particles provide a greater surface area for dissolution and subsequent mineral transformations. From a mineralogical perspective, the solubility and reactivity of these phases are influenced by the alkaline environment typically encountered in geotechnical applications.

Table 9

Chemical composition of KR-SS



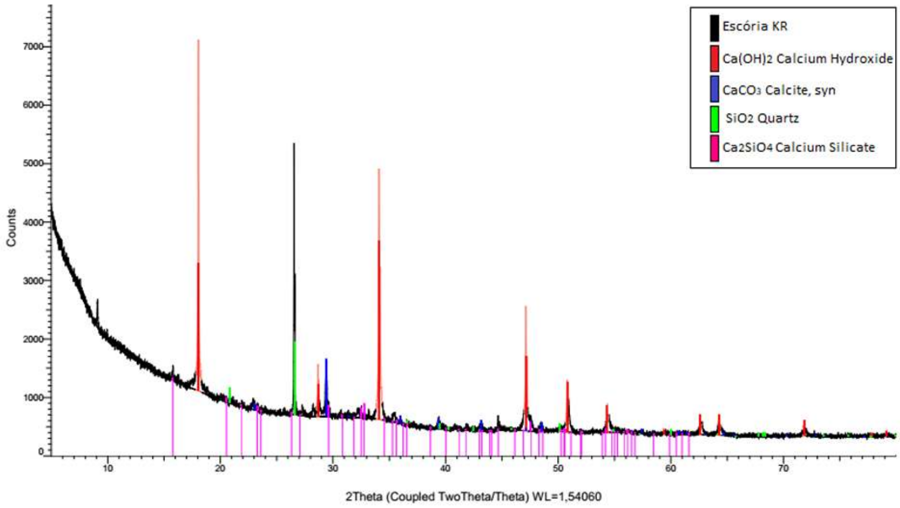
Chemical compound	Result (%)
CaO	44.8
SiO_2	14.6
Fe_2O_3	26
MgO	2.7
Al_2O_3	5.1
SO_3	3.8
MnO	1.7
Other	<0.5

Source: from Pires et al., 2019.

The presence of sulfates or other activators can further accelerate the dissolution of reactive phases, leading to the formation of stable hydration products that enhance the mechanical properties of the treated soils (Velten et al., 2006).

Figure 15

XRD of KR-SS



Source: from Meneguete, 2018.

The mineralogical diversity of SS, therefore, underpins their versatility as soil stabilizers, allowing for tailored engineering solutions based on the specific requirements of a project. It is also important to note that the mineralogical composition of SS is not static; it evolves over time due to ongoing hydration, carbonation, and other geochemical processes. This dynamic behavior can result in the gradual transformation of less stable phases, such as free lime, into more stable minerals like calcite, thereby reducing potential environmental risks associated with leaching or expansion (Oliveira, 2016; Sant'ana, 2003).

Santos (2013) indicates that advanced characterization techniques, including X-ray diffraction and electron microscopy, are essential for accurately identifying and quantifying the mineral phases present in SS, which in turn informs their optimal use in geotechnical engineering. In summary, the mineralogical composition of SS is marked by a rich assemblage of calcium silicates, ferrites, oxides, and hydroxides, each contributing to the material's reactivity, stability, and performance in soil stabilization. The interplay between these phases, modulated by environmental conditions and processing history, determines the long-term behavior and sustainability of SS-based geotechnical solutions (Oliveira, 2016; Santos, 2013; Velten et al., 2006; Sant'ana, 2003).

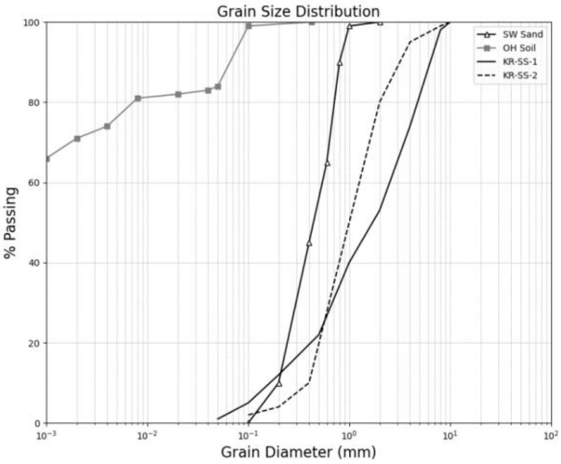
From a chemical perspective, the reactivity of SS as a stabilizing agent is highly dependent on its physical and chemical properties (Bridi, 2020). The ability of certain SS, such as KR powder, to act as hydraulic binders under alkaline stimulation further enhances their value as cost-effective alternatives to traditional cementitious materials (Nunes, 2024).

4.2 PARTICLE SIZE DISTRIBUTION AND TEXTURE

The granulometric distribution (GD) of LD-SS and KR-SS, is characterized by a predominance of coarse fractions after appropriate processing and curing. These coarse fractions exhibit high hardness, favorable surface friction, and low porosity, which are desirable attributes for road infrastructure applications such as embankment bodies and pavement layers (Resende, 2010). The GD of KR-SS available for geotechnical use is typically controlled during processing, with commercial products being offered in specific GD intervals, for example, from 0 to $12.7\ mm$ and from $12.7\ to\ 63.5\ mm$ (Fig. 16).

Figure 16

SW sand, OH clay and KR-SS-1 (Ramos, 2018) and KR-SS-2



Source: Oliveira et al., 2017.

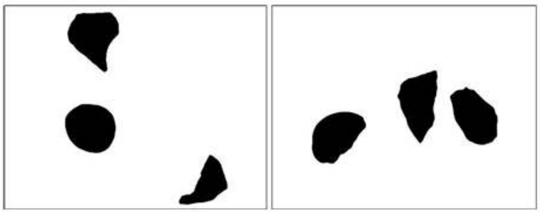
This controlled gradation ensures that the expansion potential of the SS is minimized, thereby allowing its safe incorporation into pavement layers without risk of deleterious volumetric changes (Ramos et al., 2009). The texture of SS particles is another critical property.

SS, especially after weathering and stabilization, tend to have angular shapes and rough surfaces, which enhance interparticle friction and mechanical interlock within soil mixtures. This morphological characteristic is advantageous for improving the shear strength and stiffness of the composite material. The reduced porosity of the coarse SS fraction further contributes to its suitability as a high-quality aggregate, as it limits water absorption and potential degradation under cyclic loading (Resende, 2010).

The angularity and surface roughness of iron-nickel slags, for instance, (Figure 17) have been confirmed through advanced imaging techniques such as the Aggregate Imaging System (AIMS), which quantitatively assesses aggregate shape and texture (Santos, 2013).

Figure 17

AIMS Image of the iron-nickel slag aggregate: slag angularity #50



Source: (from Santos, 2013)

When SS are blended with soils, the resulting particle size distribution is significantly altered, depending on the type and proportion of SS added. For example, the addition of granulated or raw blast furnace SS to silty soils can shift the soil classification towards a more granular material, such as clayey sand, by increasing the coarse fraction content. This modification in gradation not only affects the soil's classification but also enhances its compaction characteristics and load-bearing capacity.

In contrast, the incorporation of certain byproducts, such as FGD (flue gas desulfurization) residues or Revsol, may not substantially change the original soil classification, indicating that the effect on particle size distribution is highly dependent on the specific type of SS or byproduct used (Cunha, 2020). The original subgrade materials in many geotechnical projects, particularly in regions like Brazil, are often composed predominantly of silt and clay particles, as classified by the AASHTO system (e.g., A-6 soils with a liquid limit of approximately 28.4% and a plasticity index of 14.0%), as observed by Gomes et al. (2021).

The introduction of LD-SS and KR-SS, with their coarser and more angular particles, can thus significantly improve the gradation of these fine-grained soils, leading to better compaction and mechanical performance. The improved gradation is directly linked to enhancements in maximum dry density (MDD), California Bearing Ratio (CBR), resilient modulus (MR), and unconfined compressive strength (UCS), as the coarse SS particles fill voids and provide a stable skeleton within the soil matrix (Bastos, 2022; Gomes et al., 2021). The variability in the chemical composition of LD-SS, as observed across different steel plants, can also influence the physical properties, including particle size distribution and texture, due to differences in crystallization and cooling processes (Raposo, 2005). However, the general trend remains that SS, when properly processed and aged, offer a consistent and beneficial particle size distribution for geotechnical applications (Ramos et al., 2009; Raposo, 2005).

In summary, the integration of SS into soil systems for geotechnical engineering is strongly governed by their particle size distribution and surface texture. The coarse, angular, and low-porosity nature of processed SS enhances the mechanical interlock and load transfer within stabilized soils, while controlled gradation ensures compatibility with engineering specifications for pavement and embankment construction (Gomes et al., 2021; Cunha, 2020; Santos, 2013; Resende, 2010; Ramos et al., 2009).

4.3 BULK DENSITY AND POROSITY

Bulk density and porosity are fundamental physical properties that directly influence the geotechnical performance of SS when used as soil improvement agents. The bulk density of a material, defined as the mass per unit volume including the pore spaces, is a critical parameter for understanding compaction behavior and the load-bearing capacity of SS-soil mixtures.

Porosity, on the other hand, quantifies the proportion of void spaces within the material, affecting permeability, compressibility, and the potential for water retention. The physical characteristics of SS, such as those derived from steelmaking processes (including both LD-SS and KR-SS), are shaped by their mineralogical composition and the cooling regime during production. For instance, the granular structure of blast furnace slag, a byproduct of pig iron manufacturing, results in a relatively high bulk density compared to many natural soils, which can be advantageous for increasing the maximum dry density (MDD) of soil mixtures (Sant'ana, 2003).

Santos (2013) pointed that iron-nickel slags, when analyzed by scanning electron microscopy, exhibits a dense microstructure with limited interconnected porosity, which contributes to its high bulk density and low water absorption capacity. When SS are incorporated into soils, the resulting mixtures often display an increase in bulk density, particularly when the SS particles are well-graded and angular.

4.4 CHEMICAL STABILITY AND REACTIVITY

Chemical stability and reactivity are fundamental for SS in geotechnical applications, influencing performance. The stability of SS (like LD-SS and KR-SS) is linked to mineralogy and cooling. For instance, Brazilian GBF-SS is up to 95% vitreous due to rapid cooling, increasing its chemical reactivity (Sant'ana, 2003).

Reactivity is also influenced by variable chemical composition (raw materials, production, cooling), which affects hydration reactions and cation exchange in iron-nickel slags (Santos, 2013). Reactive phases, especially in fine fractions, enhance the pozzolanic and hydraulic reactions essential for strength development (Fardin, 2024).

Geotechnically, stability must prevent deleterious expansion or the release of hazardous substances. One study found that even when LD-SS exceeded 3% expansion limits for pavement use, its volumetric and mechanical properties were unaffected, suggesting adequate stability (Izoton, 2020). However, environmental classification is crucial, as some SS may contain elevated aluminum, phenols, or fluorides (Oliveira, 2018).

SS reactivity, demonstrated by cation exchange and hydration, is more pronounced in finer fractions; these reactions form cementitious compounds, enhancing the soil-SS mixture's mechanical properties (Fardin, 2024). Adding other agents, like FGD (flue gas desulfurization) powder, can modulate reactivity, significantly increasing UCS, though it may also introduce expansion issues (Picoli, 2020).

5 GEOTECHNICAL PERFORMANCE GAINS WITH STEELMAKING SLAG-SOIL MIXTURES (SS-SM)

5.1 MAXIMUM DRY DENSITY (MDD)

The maximum dry density (MDD) is a fundamental parameter in geotechnical engineering, as it directly influences the compaction quality and mechanical performance of soils in unbound layers. However, when slags, such as LD-SS and KR-SS, are incorporated into soil matrices, notable changes in MDD can be observed, which are closely linked to the physical and chemical characteristics of both the slag addition percentage and the host soil chemical interaction.

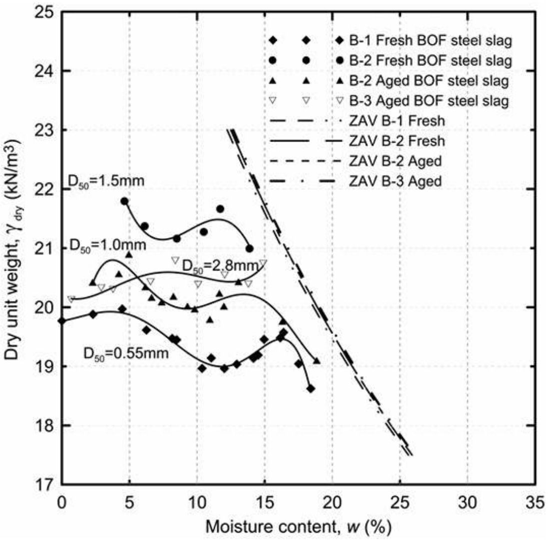
The granular nature and particle size distribution of SS, especially when processed through crushing, allow them to act as effective substitutes for natural aggregates in geotechnical applications, including concrete, pavement, and railway ballast. This substitution is possible due to the solidness and the inert characteristic available in the material, which ensures compatibility with a wide range of granular soils (Oliveira, 2018). Figure 18 shows typical data of LD-SS compaction curves, showing MDD and OMC of LD-SS.

Nonetheless, the SS have the characteristic to chemically interact with soils, especially fine-grained soils. Therefore, MDD may become a secondary parameter when chemical interaction is present. Experimental studies have demonstrated that the addition of SS to soils can modify the compaction curve, often resulting in an increase in the MDD of the mixture. For instance, Sant’ana (2003) present data for a mixture of clayey soil (ETA) with 10% iron-nikel slag, showing a clear relationship between OMC and MDD. The compaction curve for this mixture indicates that the presence of slag can enhance the packing of soil particles, leading to a higher MDD compared to the natural soil alone (Sant’ana, 2003). This effect is attributed to the angularity and rough surface texture of slag particles, which facilitate better interlocking and reduce the void ratio within the compacted mass.

The influence of SS on MDD is not uniform across all soil types. The response depends on the granulometry and mineralogical composition of the soil. Soils with a high content of fines, such as clays and silts, may exhibit different compaction behaviors compared to sandy or granular soils when mixed with SS.

Figure 18

BOF steel slag (LD-SS) compaction curves



Source: from Yildirim et al., 2015.

Fardin (2024) observes that mixtures with similar SS content can display varying MDD values, a phenomenon linked to the type of soil stabilized. Soils with elevated fines content tend to chemically interact more strongly with the KR-SS than the physical interaction which leads to denser packing and higher MDD, as shown in Figure 19. The KR-SS mixed with sandy or silty soils may not benefit to the same extent.

The physical characterization of KR-SS, as outlined by Andrade is a prerequisite for achieving optimal compaction and, consequently, desirable MDD values (Andrade, 2018). The particle size distribution, specific gravity, and angularity of the SS are critical factors that determine its compaction behavior when blended with soils.

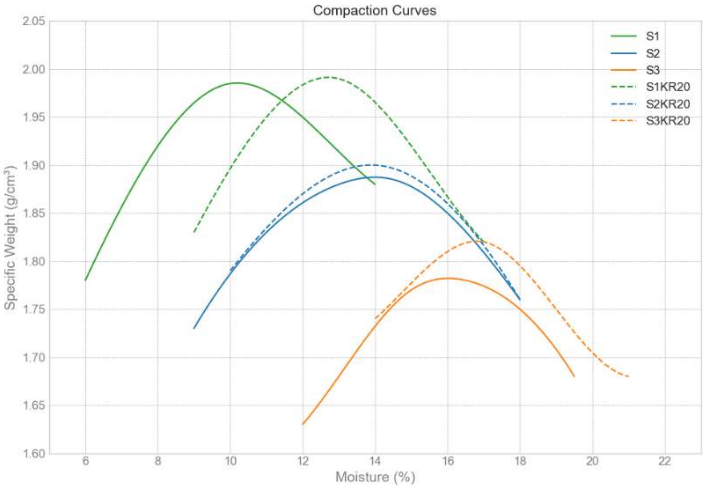
The process by which blast furnace slag is rapidly cooled, such as by water quenching, inhibits crystallization and results in a material with unique physical properties. This amorphous structure can contribute to improved compaction characteristics, as the non-crystalline slag particles can fill voids more efficiently within the soil matrix, thereby increasing the MDD (Oliveira, 2018).

The interaction between SS and soil during compaction is further influenced by the moisture content at which maximum dry density is achieved. The OMC may shift depending on the proportion and type of SS added, as well as the nature of the soil. The restructuring of particles and the potential for cementitious or pozzolanic reactions, especially when Portland cement is present, can further enhance the compaction characteristics, leading to higher MDD and improved mechanical properties (Pires et al., 2019).

Laboratory analyses, such as those reported by Medeiros (2019), demonstrate that specific ratios of SS to soil, for example, 70% SS and 30% clay, can yield favorable compaction characteristics and mechanical indices. These findings are supported by Picoli (2020), who review the improvement of soils using industrial by-products, emphasizing the importance of understanding the interaction between SS type, soil characteristics, and additive content.

Figure 19

Compaction curves of 3 different soils mixed with 20% of KR-SS



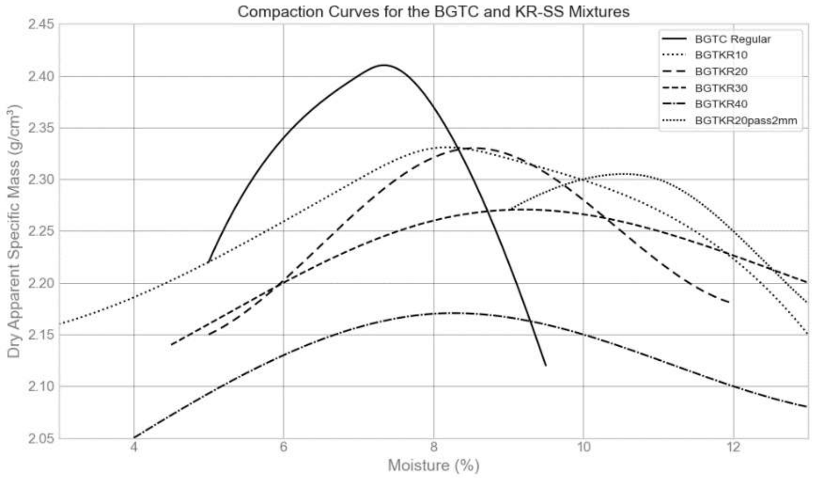
Source: from Fardin, 2024.

The high-value of SS as a sustainable material for soil stabilization is underscored by its ability to improve key geotechnical properties, including MDD, while simultaneously addressing environmental concerns related to industrial waste management (Medeiros, 2019). The use of SS in geotechnical engineering generally enhances the performance of soil mixtures compared to the natural compacted soil.

Andrade (2018) studied the replacement of cement in chemical stabilized natural gravels by KR-SS and Figure 20 shows different KR-SS and soil proportions from 10 up to 40%, showing best results for MDD in somewhere in the middle of the range. The main objective: to verify the mechanical performance of the blends with KR-SS compared to cement treated base with natural materials.

Figure 20

Compaction Curves for the BGTC and KR-SS Mixtures



Source: modified Andrade, 2018.

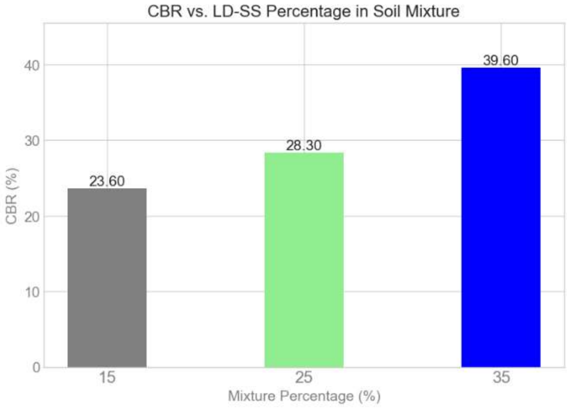
The literature highlights the necessity of tailored mix designs and thorough laboratory testing to optimize the benefits of SS incorporation in geotechnical applications (Fardin, 2024; Andrade, 2018; Oliveira, 2018; Sant'ana, 2003).

5.2 CALIFORNIA BEARING RATIO (CBR)

The California Bearing Ratio (CBR) remains a pivotal parameter for assessing pavement material suitability. The incorporation of LD-SS and KR-SS has demonstrated substantial improvements in CBR values, attributed to a synergy of physical and chemical mechanisms. Physically, the granular nature and angularity of slag particles enhance mechanical interlocking and densification during compaction. This effect is distinctively illustrated in the compaction curves shown in Figure 21, which evidence the superior packing density achieved by the mixtures compared to natural soils (Andrade, 2018; Oliveira, 2018; Fardin, 2024).

Figure 21

A4 Soil CBR as a Function of LD-SS Percentage

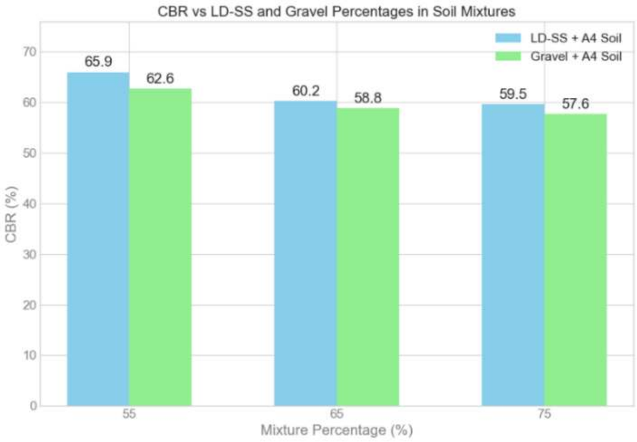


Source: modified Silva et al., 2021.

Consequently, the mechanical performance improves drastically. Experimental investigations reveal that adding 5% to 20% of slag can elevate CBR from values as low as 19% (A-7-6 clay) to over 110%, with optimized mixtures reaching up to 279%, confirming their viability for base layers as presented in Figure 22 (Silva et al., 2022; Nepomuceno, 2019; Gomes et al., 2021).

Figure 22

A4 Soil CBR as a Function of LD-SS Percentage



Source: modified Santos, 2024.

Chemically, the calcium-silicate composition of the slags facilitates the development of cementitious bonds through hydration and latent pozzolanic activity, especially when mechanically activated (Figure 23), thereby reinforcing the soil matrix and enhancing long-term durability (Raposo, 2005; Ramos, 2018; Sant'ana, 2003).

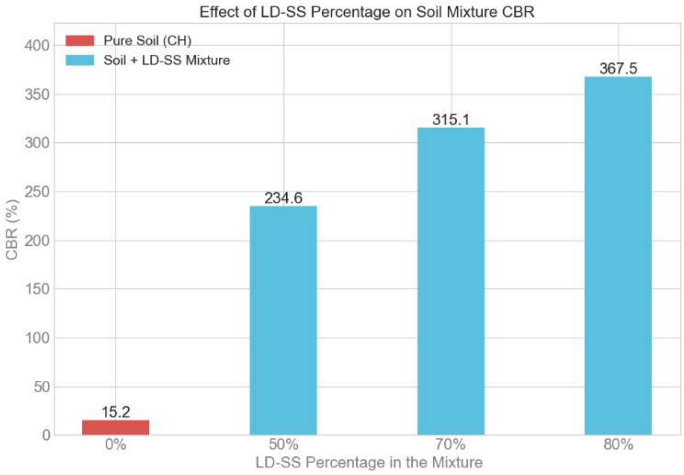
5.3 RESILIENT MODULUS (MR)

The resilient modulus (MR) is a fundamental parameter in geotechnical engineering, representing the elastic response of soil or soil-aggregate mixtures under repeated loading. When SS, particularly LD-SS and KR-SS, are incorporated into soil matrices, notable changes in MR have been observed, reflecting the potential of these industrial by-products to enhance pavement performance and durability.

Medeiros (2019) highlights that the integration of iron ore tailings mixed with blast furnace slag (BFS) can improve the overall mechanical behavior of road materials, leading to better qualitative field performance. This general improvement in mechanical behavior is often reflected in specific parameters like the Resilient Modulus (MR). Studies by other authors have shown that the angularity and hardness of SS particles contribute to a denser packing and more efficient load transfer, resulting in higher MR values.

Figure 23

A-7-6 Soil CBR as a Function of LD-SS Percentage



Source: modified Boldrini &Pacheco, 2022.

The findings from Oliveira (2018) further support the beneficial impact of SS on geotechnical properties, including MR. Research at the UFES, UFMG and others has demonstrated that SS can act as effective stabilizing agents for low-consistency cohesive soils, leading to improved load-bearing capacity and elastic response. These improvements are particularly relevant for pavement layers, where repeated traffic loading demands materials with high resilience to minimize rutting and surface deformation. In addition to the direct mechanical effects, the granulometric compatibility between slag and soil is crucial for optimizing MR.

The particle size distribution of LD-SS can be tailored to match that of the host soil, ensuring a well-graded mixture that maximizes packing density and stiffness (Prandina &

Farias, 2025; Oliveira, 2016). This tailored approach allows for the design of SS-SM with superior resilient properties, as the interlocking of particles and reduction in void ratio contribute to a stiffer, more elastic composite. The broader context of using industrial by-products like SS for soil improvement is also addressed by (Resende, 2010), who outlines the versatility of slags in various geotechnical applications, including as base and sub-base layers in pavements. The improved MR observed in SS-SM translates directly to enhanced pavement performance, as higher resilience reduces the risk of fatigue cracking and extends service life under dynamic loading conditions. Sant'ana (2003) provides additional insight into the mechanical behavior of slag-stabilized soils, reporting increased UCS alongside improvements in MR.

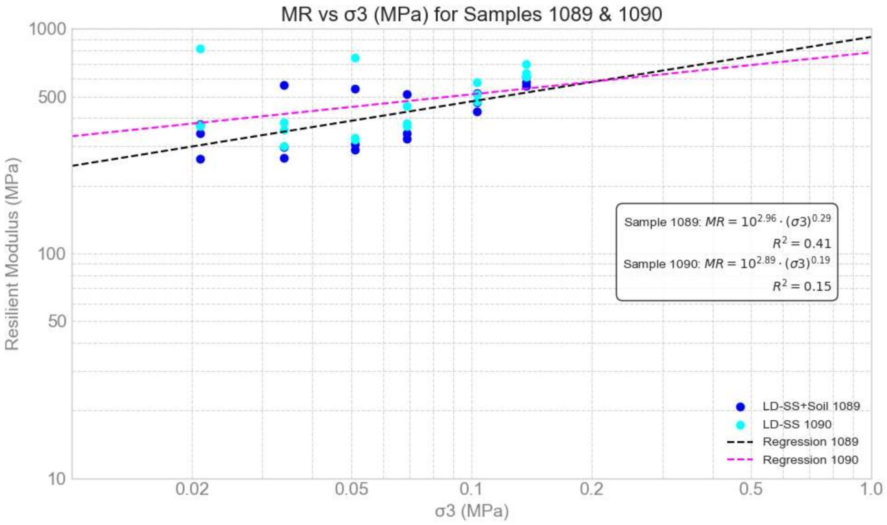
The synergy between strength and resilience is particularly advantageous for geotechnical applications where both parameters are critical for long-term stability and performance. The sustainability aspect of using slags is emphasized by Ramos (2018), who advocates for the valorization of materials that would otherwise be discarded. By incorporating SS into soil improvement strategies, geotechnical properties such as MR generally enhances.

LD-SS have shown great CBR values alone and its potential to improve CBR values for soils mixtures with clayey soil; nonetheless, Resende (2010) have also verified the impact of LD-SS on MR which findings shown that the great positive difference of LD-SS CBR and LD-SS soil mixtures disappears when testing at CLTT to obtain MR for these 2 types of materials (Figure 24).

The 1089 sample was located at the EST 509+10, therefore a LD-SS mixture with local soil by the proportion of 80/20 (LD-SS/soil), and the 1090 sample was located at the EST 70+05, a LD-SS pure initially unbound one-material layer. The CBR of the 1089 sample, a LD-SS/soil mixture, is 192,8% and for the 1090 sample, the CBR is 265%, a difference of 37%. Figure 25 shows the trend lines of the samples, which account for less than this difference after s_3 of 2 kPa (0,02 MPa), at the level of 30%, reducing to around 10% at s_3 of 5 kPa.

Figure 24

MR of LD-SS (1089) and LD-SS / soil mixture (1090)



Source: modified Resende, 2010.

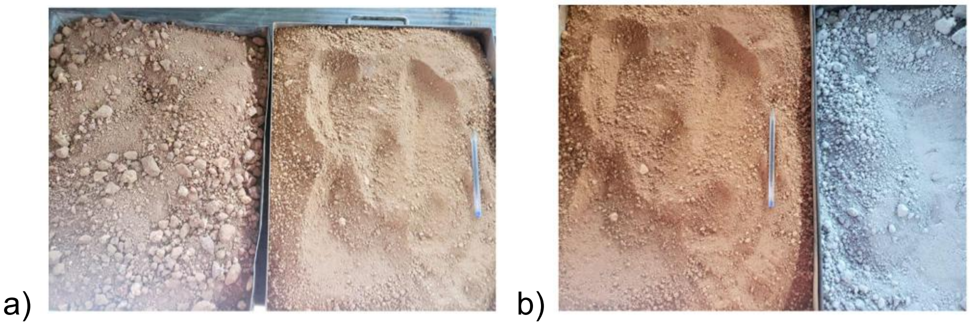
KR-SS, in particular, has been studied for its effect on the resilient modulus of clayey soils. Bastos (2022) state that the addition of KR-SS to clayey soils results in a measurable increase in MR. This enhancement is attributed to the physical stabilization provided by the SS particles, which reinforce the soil matrix and limit permanent deformation under cyclic loading. Interestingly, the same authors note that while the initial increase in MR is significant, extending the curing time does not necessarily yield further improvements in modulus. This suggests that the primary mechanism is mechanical rather than chemical stabilization, as the interaction between SS and soil is dominated by particle rearrangement and densification rather than pozzolanic or cementitious reactions.

Bastos (2022) studied different KR-SS mixtures with tropical lateritic clayey soil and clayey sand soil, seen side-by-side in Figure 30. The soils used are the ones close to the main federal roads which crosses the Espírito Santo state.

Figure 25

a) A-2-6 (CL, IG =8) and A-7-6 (CL, IG = 6) Espírito Santo lateritic soils

b) A-7-6 soil and the KR-SS



Source: modified Bastos, 2022.

The MR versus the deviator stress graph of the soils and a KR-SS-soil mixture is presented in Figure 26 and shows the excellent results of the addition of KR-SS, transforming positively the performance of the soil in respect to the MR.

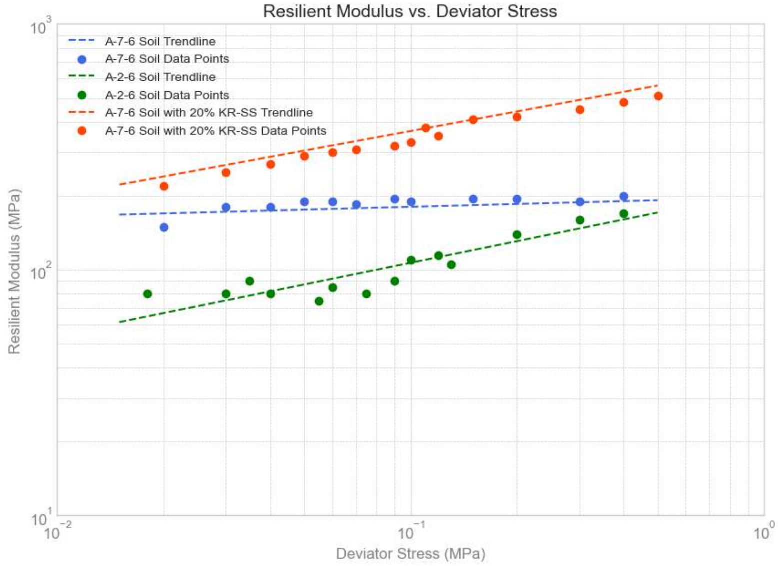
The use of KR-SS has the potential to stabilize a locally available, poor-quality cohesive soil (A-7-6) creating a material that outperforms even a standard, untreated granular fill (A-2-6). This has significant economic and logistical advantages, as it can reduce the need to haul in more expensive quarry materials. The stabilization has not only made the soil mixture greater in strength; it fundamentally transformed its mechanical behavior from that of a low-quality clay into a high-performance, stress-hardening material suitable for robust pavement structures.

Investigating the dynamic behavior of SS-SM, Bona et al. (2022) studied a mixture of 70% low-plasticity clayey soil (A-4) and 30% LD-SS for use in sub-base layers. The mixture exhibited high MR and low permanent deformation under cyclic loading, and the authors noted that the potential for volumetric expansion did not negatively interfere with the material's excellent dynamic performance.

In summary, the integration of LD-SS and KR-SS into soil matrices leads to significant gains in modulus of resilience, primarily through mechanical stabilization mechanisms. The resulting mixtures exhibit improved elastic response under repeated loading, making them suitable for demanding geotechnical applications such as pavement layers. The optimization of particle size distribution and the selection of appropriate SS types further enhance these benefits, positioning slags as high-value and sustainable materials for soil improvement in geotechnical engineering (Bastos, 2022; Medeiros, 2019; Oliveira, 2018; Ramos, 2018; Resende, 2010; Sant'ana, 2003).

Figure 26

MR of A-2-6 (CL, IG =8) and A-7-6 (CL, IG = 6) Espírito Santo lateritic soils and A-7-6 soil mixed with KR-SS



Source: prepared by the authors.

5.4 UNCONFINED COMPRESSIVE STRENGTH (UCS)

The determination of UCS serves as a cost-effective benchmark for evaluating the mechanical efficacy of soil-SS mixtures. The incorporation of LD-SS and KR-SS significantly enhances load-bearing capacity, often exceeding critical pavement thresholds. Notably, mixtures containing KR-SS have surpassed 3.5 MPa after 28 days, rivaling the performance of traditional soil-cement stabilization (Andrade, 2018). This strengthening is particularly effective in fine-grained (clayey and silty) soils due to superior interaction between the slag particles and the soil matrix (Fardin, 2024).

Mechanistically, this improvement stems from chemical interactions—specifically the formation of hydrated products identified via XRD—where the unique reactive oxide composition of KR-SS can provide strength gains superior to equivalent cement dosages in certain environments (Nunes, 2024). Crucially, this performance is time-dependent; prolonged curing periods facilitate ongoing hydration and pozzolanic reactions, resulting in progressive strength gains from 10 to 90 days that correlate linearly with increases in undrained shear strength (USS), as studied by Ramos and Andrade (2018).

5.5 BEHAVIOR IN FINE-GRAINED SOILS: PLASTICITY MODIFICATION AND STRENGTH ENHANCEMENT

The incorporation of LD-SS and KR-SS into fine-grained soils significantly enhances their engineering performance by simultaneously altering plasticity and increasing mechanical strength. The primary stabilization mechanism involves cation exchange, where calcium ions (Ca^{2+}) released by the slag replace monovalent ions on clay surfaces, promoting flocculation-agglomeration and compressing the diffuse double layer (Fardin, 2024; Meneguete, 2018; Andrade, 2018). This physicochemical alteration typically reduces the Liquid Limit and increases the Plastic Limit, leading to a marked decrease in the Plasticity Index and swell potential. Consequently, the soil becomes more workable and easier to compact, facilitating the achievement of target densities (Sant'ana, 2003; Rohde et al., 2003; Zumrawi & Eltayeb, 2016; Phanikumar & Sharma, 2004; Wild et al., 1996; Kinuthia et al., 1999).

These microstructural changes directly translate into macrostructural improvements in Shear Strength (S_u) and Unconfined Compressive Strength (UCS). The gain in strength is attributed to the combined effects of increased internal friction, provided by the rough texture of slag particles, and the development of cohesion through the formation of cementitious gels (C-S-H and C-A-H) from pozzolanic reactions (Ramos, 2018; Fardin, 2024; Nunes, 2024; Oliveira et al., 2019; Shen et al., 2009; Yi et al., 2015). Notably, experimental data indicates a strong linear correlation between the increases in UCS and *Su*, confirming that the chemical stabilization and physical densification effectively reinforce the soil matrix against structural failure (Ramos, 2018).

5.6 BEHAVIOR OF SS IN COARSE SOILS: STABILITY, DURABILITY, AND MECHANISTIC PERFORMANCE

The integration of LD-SS and KR-SS—residues available in Espírito Santo—into coarse-grained soils (sands and gravels) results in significant geotechnical improvements driven by physical and chemical mechanisms. Physically, the high specific gravity and angular particle shape of these slags promote enhanced packing density and mechanical interlocking when blended with granular soils. This interaction reduces void ratios and increases the MDD, directly improving the material's ability to resist deformation under load (Ramos, 2018; Oliveira, 2016, 2018; Resende, 2010). Optimization procedures often guide the proportion of SS to fill interstitial spaces, balancing mechanical performance with economic and logistical viability (Gomes et al., 2021; Carvalho et al., 2022). Consequently, these mixtures exhibit gains in UCS and CBR, although the improvement magnitude in coarse soils may differ from fine-grained soils (Sant'ana, 2003).

From a chemical perspective, the durability and long-term strength of SS-soil mixtures are governed by the reactivity of the SS. The presence of reactive oxides in finely ground KR-SS and GBFS facilitates cation exchange and pozzolanic reactions, particularly when activated by lime or cement (Andrade, 2018; Meneguete, 2018). Mineralogical analyses identify the formation of secondary cementitious products, such as calcium silicate hydrates and ettringite (Furieri, 2019; Nunes, 2024). Microstructural studies (SEM) confirm that these gels densify the matrix, enhancing cohesion, resistance to moisture-induced damage, and long-term mechanical performance (UCS, MR, CBR) due to ongoing reactions (Oliveira et al., 2019; Sant'ana, 2003; Fardin, 2024).

This enhanced physical and chemical stability is critical for the mechanistic-empirical assessment of pavement layers required by the Brazilian MeDiNa method, which has been gaining traction with different studies in other countries. Reflecting the increased M_R observed in laboratory testing (Ramos, 2018), the evaluation of long-term structural performance has evolved beyond empirical indices like CBR to explicitly include the prediction of Permanent Deformation (PD) (Souza et al., 2022). The national standard model (Guimarães, 2009), standardized by DNIT 179/2018-IE, correlates accumulated plastic strain (εp) with stress states and load cycles using specific regression parameters (ψ_1-ψ_1). This mechanistic approach allows for the identification of "Shakedown" behavior (Type A vs. Type C,), validating the use of alternative materials like steel slag mixtures. These materials often demonstrate superior resistance to rutting and stable plastic accommodation in field applications, even when their conventional index properties might suggest otherwise (Cabral, 2021; Bona & Guimarães, 2021). Table 10 summarizes the permanent deformation parameters and performance results for the studied mixtures.

Table 10

Summary of Mechanical Characterization and Mechanistic Performance Parameters for Granular and Stabilized Materials

Soil Type / Material	Classification / Origin	Conventional Properties	Resilient Modulus (MR)	Permanent Deformation (PD)	Relevant Observations	Source
Stabilized Soils of Espírito Santo State						
Clayey Soil + 20% KR Slag (S1KR20%)	Original Soil: A-7-6 (Low-quality clay). Origin: BR-101/ES.	CBR (Mod.): 103.2% | Expansion: 0.03%	Avg MR: 1107.9 MPa	Excellent field performance (HVS), with low final deformation.	Transformed a poor soil into a high-performance material, superior to cement solutions in terms of stiffness (MR).	Pires et al. (2019)
Sandy Soil + 3% Cement (S2PC3%)	Original Soil: A-2-6 (Good quality sand). Origin: BR-101/ES.	CBR (Mod.): 128.1% | Expansion: N/A	Avg MR: 587 MPa	Control parameter in the field (HVS): excellent performance and low deformation.	Conventional high-performance solution used as a reference for the slag mixture.	
Tropical Soils - Case Studies						
Laterita from BR-163/PA	A-7-6 (Clayey gravel).	CBR: 62.8% | Expansion: 0.24%	Avg MR: 522 MPa. Model (Pezo): k1=6.79, k2=0.48, k3=-0.31.	Max PD: 1.7 mm (in 200 mm specimen). Shakedown behavior (Type A) in all tests.	Excellent mechanical behavior, despite CBR being lower than the normative minimum (80%), validating the mechanistic	Bona & Guimarães (2021)
Sandy Soil (Soil 02 - Pernambuco)	MCT: LA' | AASHTO: A-4 | USCS: SM.	CBR: 30.0% | Expansion: 0.00%	Avg MR: 488 MPa. Model (Compound): k1=601.39, k2=0.36, k3=-0.36.	Total DP : 0,7 mm (σ3=120 kPa / σd=360 kPa). (Guimarães Model): Ψ_1=0.076, Ψ_2=0.043, Ψ_3=0.912, Ψ_4=0.047.	Model (Guimarães, 2009):Meets sub-base criteria by CBR and presents excellent resistance to PD.	Sousa et al. (2024)
Clayey Soil (Soil 01 - Pernambuco)	MCT: LG' | AASHTO: A-6 | USCS: ML.	CBR: 12.8% | Expansion: 30.0%	Avg MR: 438 MPa. Model (Compound): k1=354.12, k2=0.33, k3=-0.52.	DP Total: 6,5 mm (sob σ3=120 kPa / σd=360 kPa). Modelo (Guimarães): Ψ_1=0.209, Ψ_2=-0.45, Ψ_3=1.73, Ψ_4=0.056.	Despite low CBR and very high expansion, the MCT classification indicates potential for use. Presents high plastic deformability.	
Granular Soils (Mossoró, state capital of Rio Grande do Norte, Brazil)						
Soil AB	A-2-4.	CBR: 41.9% | Expansion: 0.00%	Model (Pezo): k1=590.8, k2=0.22, k3=0.14.	Guimarães Model: Ψ_1=0.72, Ψ_2=0.18, Ψ_3=-0.21, Ψ_4=0.09.	Good performance, with low PD accumulation and good shakedown behavior. Indicated for sub-base.	Cabral (2021)
Mixture (Soil AB + Crushed Stone)	Mixture 50% soil AB + 50% granitic crushed stone.	CBR: 69.3% | Expansion: 0.00%	Model (Pezo): k1=935.8, k2=0.33, k3=-0.02.	Guimarães Model: Ψ_1=1.15, Ψ_2=0.25, Ψ_3=-0.15, Ψ_4=0.02.	High resistance to PD with rapid accommodation. Indicated for base layer.	
Soil SM	A-3 (fine sand).	CBR: 9.8% | Expansion: 0.10%	Model (GuimarÃ£es): k1=260.2, k2=1.09, k3=-0.98, k4=0.01.	Guimarães Model: Ψ_1=0.17, Ψ_2=-0.25, Ψ_3=0.72, Ψ_4=0.23.	Excessive rutting in tests, indicating low stiffness and tendency to rupture under higher stresses.	

6 BARRIERS AND OPPORTUNITIES FOR WIDER ADOPTION

Primary barriers to wider LD-SS and KR-SS use include variability in physical and chemical properties, leading to inconsistent performance and non-characteristic compaction curves that complicate MDD and OMC prediction (Raposo, 2005). Another challenge is expansive behavior from free lime and periclase, causing volumetric instability and limiting applications requiring dimensional stability (Cunha, 2020; Raposo, 2005).

From a policy perspective, Brazilian codes exist (DNIT 113/2009; 114/2009; 115/2009; 406/2017; 407/2017; NBR 16.364/2015), mostly for LD-SS (Prandina, 2018), but this regulatory system is considered poor as it fails to cover all SS types and blends.

Opportunities are reinforced by studies showing SS viability. Almeida (2014) found SS has hydraulic conductivity similar to coarse sand and low leaching potential. As evidence grows, the perception of SS as a resource, not waste, strengthens, paving the way for broader adoption (Ribeiro et al., 2018; Santos, 2013).

7 SYNERGIES WITH OTHER INDUSTRIAL BY-PRODUCTS

7.1 COMBINED USE WITH FLY ASH

Combining SS-soil mixtures with fly ash leverages the pozzolanic activity of fly ash and the cementitious properties of SS. This interaction enhances the formation of calcium silicate hydrates (C-S-H), the primary binding phase (Nunes, 2024; ANDRADE, 2018). This synergy improves UCS and durability. SS variability is crucial (Raposo, 2005); LD-SS (high CaO, SiO) works well with fly ash. Fardin (2024) notes that KR-SS feasibility is enhanced when combined with other by-products, addressing material shortages. Further research on long-term behavior is needed (Nunes, 2024; Fardin, 2024).

7.2 ADVANCES IN MATERIAL PROCESSING TECHNOLOGIES

Processing advances allow precise control over SS granulometry and chemical composition (Fardin, 2024). Using KR-SS in sub-bases can reduce the carbon footprint (Medina, 2024). The regulatory landscape is adapting (Motta & Portela, 2023), as seen in Espírito Santo, where over 6 million tons of SS have been applied (ArcelorMittal, 2025). Continued refinement and supportive regulations, especially for the private sector, are needed to drive innovation (Fardin, 2024; Medina, 2024; Nunes, 2024; Motta & Portela, 2023; Carvalho et al., 2022; Marin, 2022; Picoli, 2020; Pires et al., 2019).

The review of the international literature robustly supports and validates the categorization of soil-slag interactions (specifically utilizing LD and KR slags) into four distinct models. These mechanisms often occur simultaneously but can be distinguished by their physicochemical nature and temporal evolution:

- Chemical Cementation (Model 1): This model is validated by microstructural investigations, including Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD). These studies confirm the formation of Calcium Silicate Hydrates (C-S-H), Calcium Aluminate Hydrates (C-A-H), and ettringite resulting from long-term pozzolanic reactions between the calcium-rich slag and soil aluminosilicates (Jha et al., 2019; Poh et al., 2016). This is widely considered the primary mechanism for long-term compressive strength gain in stabilized soils.
- Physicochemical Modification (Model 2): Validated by plasticity and swelling potential tests, this model demonstrates an immediate improvement in cohesive soils. The mechanism is driven by cation exchange (Ca^{2+} from the slag substituting Na^{+} on clay surfaces) and subsequent flocculation-agglomeration of clay particles, which reduces the thickness of the diffuse double layer (Ouf, 2017; Yildirim & Prezzi, 2011).

- Particle Size Stabilization (Model 3): Validated by Proctor compaction tests, this physical model demonstrates that blending the distinct particle size distributions of the soil and the slag optimizes the packing density. This results in an increased Maximum Dry Density (MDD) and a reduction in the Optimal Moisture Content (OMC) of the mixture (Motz & Geiseler, 2001).
- Granular Reinforcement (Model 4): Validated by advanced mechanical testing, specifically the Resilient Modulus (RM) and cyclic triaxial tests. The high hardness, rough texture, and angularity of steel slag particles form a high-stiffness interlocked granular skeleton. This skeleton efficiently distributes stresses, making the mixture ideal for pavement base and subbase applications (Magalhães et al., 2017; Yi et al., 2012).

The integration of these findings allows for the construction of a "Unified Theory of Slag Stabilization," which structures these models chronologically:

1. Phase I (Immediate): Physicochemical Modification and Granular Improvement. Immediately upon mixing, cation exchange reduces soil plasticity, while the physical addition of SS improves the GD curve. The soil becomes more workable and denser (Wu et al., 2019; Freitas & Costa, 2024).
2. Phase II (Short Term): Nucleation and Skeleton Formation. In the early days of curing, the nucleation of ettringite begins within the voids, alongside the physical interlocking of the granular slag skeleton. The material gains its initial stiffness and structural integrity (Nunes, 2024; Ribeiro et al., 2019).
3. Phase III (Long Term): Silicate Cementation and Consolidation. Over extended curing periods (28 days and beyond), the slow-reacting silicates form C-S-H gels, potentially accompanied by carbonation effects. This phase consolidates the material's final strength and ensures long-term durability (Shen et al., 2019; Aldeed et al., 2020).

8 FUTURE DIRECTIONS IN RESEARCH AND PRACTICE

SS application for soil improvement—a high-volume use—is evolving, driven by natural material scarcity and the re-evaluation of SS as secondary commodities (Fardin, 2024; Ribeiro et al., 2018). A key trend is using SS to replace Portland cement; KR-SS stabilizes organic soils while reducing CO_2 (Nunes, 2024). Research also focuses on minimizing LD-SS expansion effects to ensure longevity (Izoton, 2020).

SS is highly adaptable, combining with other byproducts like ornamental stone residues (Prandina & Farias, 2025) and working in various soils (Bridi, 2020). This versatility and economic viability position SS as key for sustainable construction (Fardin, 2024), especially for Brazil's highway network (Raposo, 2005).

Future research must explore slag-soil interaction mechanisms and develop standardized testing protocols (Ramos, 2018). The trajectory requires interdisciplinary collaboration, shifting toward sustainability and optimization (Fardin, 2024; Nunes, 2024; Ribeiro et al., 2018; Izoton, 2020; Picoli, 2020; Bridi, 2020; Andrade, 2018; Medeiros, 2019; Ramos, 2018; Raposo, 2005).

9 CONCLUSION

The extensive examination of steelmaking slags, particularly Linz-Donawitz (LD) and Kambara Reactor (KR) slags, underscores their distinguished role as sustainable and effective materials in geotechnical engineering. Their unique chemical and mineralogical compositions, characterized by high calcium oxide content and reactive phases, confer significant hydraulic and pozzolanic properties that enhance soil stabilization and improvement. These attributes, combined with favorable physical characteristics such as angular particle shape, high specific gravity, and controlled granulometry, contribute to notable improvements in key geotechnical parameters including maximum dry density, California bearing ratio, resilient modulus, unconfined compressive strength, and shear strength of the geomaterial obtained from SS-soil proportions compared to the ones of natural soils traditionally adopted.

The integration of SS into soil matrices not only addresses mechanical deficiencies of marginal soils such the ones with higher plasticity, but also offers environmental and economic advantages by valorizing industrial byproducts, with great potential to reduce reliance on natural aggregates, and lowering greenhouse gas emissions associated with traditional binders like Portland cement. The capacity of slags to improve load-bearing capacity, reduce plasticity, and mitigate swelling and shrinkage in fine-grained soils further expands their applicability across diverse geotechnical scenarios, from embankments to pavement bases and sub-bases.

Despite their promising potential, challenges such as volumetric expansion due to free lime and periclase, variability in chemical and physical properties, and environmental considerations related to leachability necessitate rigorous characterization, quality control, and appropriate pre-treatment strategies. Advances in testing methodologies, including mineralogical, chemical, and mechanical assessments, have enhanced the ability to predict and optimize slag performance, ensuring compliance with regulatory standards and long-term durability.

The synergistic use of SS with other industrial by-products, such as fly ash, flue gas desulfurization residues, ornamental stone residues has the potential for further improvements in mechanical strength and durability, supporting the development of innovative composite materials that align with circular economy principles. Material processing technologies have evolved to tailor SS properties, enabling their effective combination with diverse waste streams and facilitating their acceptance in infrastructure projects.

Global practices reveal regional variations influenced by material availability, regulatory frameworks, and environmental priorities, highlighting the importance of context-specific research and adaptation of best practices. The integration of SS into circular economy models exemplifies a strategic approach to sustainable infrastructure development, promoting resource efficiency, waste reduction, and environmental stewardship.

Future directions emphasize the optimization of mixture designs through advanced statistical and analytical techniques, the refinement of treatment methods to control expansion and enhance reactivity, and the incorporation of comprehensive sustainability metrics such as life cycle assessment. Continued interdisciplinary collaboration and long-term field monitoring are essential to validate laboratory findings, address knowledge gaps, and support the broader adoption of slags in geotechnical engineering.

In summary, steelmaking slags represent high-value materials with the capacity to transform geotechnical practices in pavement engineering and earthworks by delivering enhanced mechanical performance, environmental benefits, and economic efficiencies. Their responsible and innovative utilization holds significant promise for advancing sustainable infrastructure development and addressing the challenges of resource scarcity and industrial waste management in the construction sector.

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