Review

The Use of Steel Slags in Asphalt Pavements: A State-of-the-Art Review

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Abstract: Steel slag is a by-product obtained through the separation of molten steel from impurities in steel-making furnaces. It can be produced by different types of furnaces (blast, basic oxygen, electric arc, ladle furnaces). The reuse of metallurgical slags in road pavements can pursue aims of recycling and environmental sustainability. Based on the extensive literature, the paper presents a state-of-the-art review concerning the use of slags in asphalt pavements, discussing the main controversial literature findings. Slag manufacturing processes, chemical, morphological, and physical characteristics, affect its contribution to the asphalt mixture, when it partially or fully substitutes natural aggregates. Legislative state-of-the-art environmental issues, weathering, and leaching aspects are also discussed. The main mechanical and durability properties of pavements containing different types of slags are analyzed based on laboratory and field studies. Generally, the higher mechanical properties of steel slag suggest that its inclusion in asphalt mixtures can provide high-performance pavement layers (excellent strength and stiffness, superior rutting and fatigue resistance, low moisture susceptibility). However, several research gaps still exist (e.g., mix design and seasoning procedure, bitumen-aggregate affinity, low-temperature behavior, brittleness); they are discussed to direct possible future study efforts to clarify specific technical aspects, such as, for example, the effect of slag morphology and physical properties on the final mix properties and the development of specific mix design guidelines.

Keywords: steel slag; road pavement; asphalt mixture; recycling; steel-making; by-product; circular economy

1. Introduction

Steel slag is a waste product obtained through the separation of molten steel from impurities in steel-making furnaces during metallurgical manufacturing. Although the wide utilization of slags is rather recent, the use of iron wastes dates back to the origin of the first metallurgical materials and melting production processes. Among the earliest reports of slag utilization, one is from the Greek physician Aristotele in the field of medicine; the Roman Empire, more than 2000 years ago, firstly utilized slag from crude iron-making forges to build road bases [1]. During the following centuries, several examples exist concerning slag utilization: cannon ball production in Germany at the end of the 1500s, masonry works developed in the 1700s across various European countries, the first road building in England in the early 1800s, and even military road construction during World War I. The amount of steel slag by-products derived from steel-making increased significantly with the rapid development of the steel industry in the last century, resulting in growing needs for effective recycling, also in civil engineering [2–5] and road constructions [6–9]. As an example, Figures 1 and 2 summarize slag reuse in 2018 in Europe (Belgium, BE—Bosnia-Herzegovina, BA—Bulgaria, BG—Czech Republic, CZ—Finland, FI—France, FR—Germany, DE—Greece, GR—Italy, IT—Luxembourg, LU—Netherlands,
Accordingly, half of the produced slags are of the BOF type (52.3% of the total); most slags are utilized in the road construction sector (70.6%).

**Figure 1.** Steel slag field utilizations in European countries in 2018 [10].

The literature reports that worldwide steel production in 2005 was about 1100 million tons, with approximately 21 million tons of steel slag obtained, for instance, each year in the United States [11] (commercial value exceeding 140 million dollars [12]). It is estimated...
that 15–40% of those slags are initially stockpiled in steel plants before being sent to slag disposal sites [13]. Generally, it is possible to categorize four main slag types, based on the corresponding furnace used: Blast Furnace Slag (BFS), Basic Oxygen Furnace Slag (BOFS), Electric Arc Furnace Slag (EAFS), and Ladle Furnace Slag (LFS), which is also called refining slag [14]. For instance, the United States produces 14 million tons of BFS annually [15] (220–370 kg per ton of iron produced) [16], although EAF steel-making is becoming competitive and is beginning to dominate the American steel industry (55% of total steel production in 2006) [17].

China's crude steel output was 808.1 million tons in 2016, and steel slag production exceeded 100 million tons [18]. As examples for Europe, the United Kingdom stockpiles about 4 million tons of slags (98% are reused as aggregates in concrete and asphalt mixtures in 2002) [19], continuing to provide 1 million tons each year. Additionally, 97% of BOF slags are recycled in the same way in Germany [20]. The total annual BOF steel production in Spain is 16 million tons, while 4.5 million tons of BFS, 1.5 million tons of EAFS, and 0.33 million tons of LFS are produced each year in that country [21]. French EAF steel production is about 12 million tons (with 100–200 kg of BOFS per ton of steel, depending on the raw material). In Italy, most of the slags produced every year are EAFS (3 million tons) [22].

As expected, the huge amounts of steel by-products lead to an urgent need for recycling, which could also be a promising way to save natural resources [23] since the availability of raw mineral materials is decreasing rapidly [24]. Conversion and reutilization of wastes can be a successful practice to tackle awareness of the environment, pollution reduction, and cost control. In this regard, a recent study demonstrates that the incorporation of EAF by-products and RA (50%) in warm wearing courses could lead to quantifiable environmental benefits, referred to as the “cradle-to-gate” approach, which are mostly related to the preservation of raw materials rather than the reduction in paving temperatures [25]. Therefore, slag’s reuse in road construction nowadays constitutes a promising way to accomplish the above-mentioned aims [26].

In this regard, metallurgical wastes are reported to be marginally utilized as aggregates in bases, sub-bases [27–29], and subgrades [30]. As examples, Rhode et al. (2003) [9] studied the effects of steel slag replacing traditional dense graded crushed sound rocks in unbound low-volume roads, similarly to Akbarnejad et al. (2012) [31], who evaluated the possibility of sub-base stabilization with slags to enhance pavement strength and reduce maintenance needs. More recently, Yildirim and Prezzi (2020) [32] performed soil stabilization using steel slags; through unconfined strength tests, they demonstrated that EAF by-products were able to hinder the swelling behavior of in-situ clayey soils thanks to their enhanced strength-gain characteristics. On the other hand, it was demonstrated that a porous asphalt mixture containing steel slag aggregate could be used as a foundation for high-quality pavement layers [33].

Despite the variety of possible steel slag applications in roads, the recycling of metallurgical by-products in asphalt mixtures is prevalent. In this sense, the rough texture, high angularity, and superior mechanical properties of steel slags suggest the partial or full substitution of natural aggregates in bituminous mixtures to improve their mechanical and functional properties [34,35]. The early studies concerning steel slag in asphalt mixtures date back to the beginning of the 1970s [36]; since then, studies have been conducted worldwide to characterize steel slag-based materials for both high traffic [37] and secondary roads [38]. In recent years, steel slag has been tested to assess its suitability with non-conventional materials such as foamed [39], polymer-modified (elastomeric or plastomeric), and additive-modified asphalt mixes (warm and cold) [40–42], thin bituminous overlays (LFS with porous asphalt) [43], or in combination with additional recycled materials as Reclaimed Asphalt (RA) [44,45] and Asphalt Rubber (AR) [46,47].

2. State-of-the-Art Objectives

Given the introduction, the paper presents a state-of-the-art review about steel slag utilization in road construction, specifically dealing with asphalt mixtures manufactured for
the surface layers of flexible road pavements. The manuscript aims to give a comprehensive overview of the sector, reporting an extended literature review on the most recent research experiences worldwide. A highly-detailed look is taken at the specific field of asphalt materials to give an innovative overview of the existing state-of-the-art concerning the recycling of steel slags in civil and road constructions. In this sense, the contents can represent a useful tool for the asphalt industry and the practitioners given the specific topics schematized and discussed, for which a flowchart is shown in Figure 3. In general, the research approach aimed at providing a comprehensive review of specific technical aspects. A further innovative aspect concerns the section giving a description of the steel slag production processes since they influence the morphological properties and subsequent characteristics of the by-products obtained, which affect the final mechanical performances of asphalt mixes.

Figure 3. State-of-the-art review flowchart.
3. Steel Slag Production and Stabilization

The wide utilization of steel slags in civil constructions is mainly due to the great diversity of materials deriving from steel-making production, substantially differing in origin and formation, and thus in characteristics and suitability. The differences in iron and steel wastes are, predictably, affected by the associated production procedures.

This section is included in the state-of-the-art study since the mechanical behaviors of slag-based asphalt mixes are strongly affected by the chemical characteristics of each by-product (strictly related to the composition and impurities of all materials involved in treatments). Specifically, the following sub-sections deal with the production processes of blast furnace iron slags, basic oxygen furnace steel slags, electric arc furnace steel slags, and ladle furnace steel slags (representative schemes were inspired by the Euroslag organization [48]).

3.1. Production Process

3.1.1. Blast Furnace Iron Slags

Blast furnace slag (BFS) is a co-product, formed in the process of making iron or steel, that differs in structure depending on the cooling method applied to the molten slag derived from the iron ore’s reduction to molten iron (used to form iron products or, most commonly, as feedstock for steel production). The combustion processes (up to 1650 °C) involve a coke-fueled blast furnace containing iron ore, iron scrap, and fluxing agents (dolomite or limestone) utilized to produce the carbon monoxide needed for the reduction (Figure 4).

![Figure 4. Blast furnace slag production process.](image)

Air-Cooled Blast Furnace Slag (ACBFS) is characterized by a crystalline structure developed with slow cooling under ambient conditions of liquid slag poured and laid into “beds”; subsequent crushing provides a hard, rough, and angular material, with external porous fractures determining water absorption values even higher than 6% (but not preventing effective drying processes) [49]. Processed ACBFS generally shows good mechanical properties for being used as aggregate, including satisfactory abrasion resistance and strength, even if there can be considerable variability in the physical and mechanical properties of blast furnace slag depending on the iron production process. Many agencies consider ACBFS as a conventional aggregate for extensive uses in granular base, hot mix asphalt, and Portland cement concrete applications. Specific quality controls may assess properties such as gradation, density, and absorption [49]. ACBFS is the slag most commonly employed as aggregate material, with respect to other BFS types [50].

Expanded or foamed blast furnace slags are produced through cooling and solidifying the waste material by the addition of a controlled quantity of water, air, or steam, which causes expansions and foaming processes; these types of slags are characterized by relatively low bulk density (approximately 70% of that of air-cooled slag), rougher external texture, and higher porosity than ACBFS aggregates. Typical loose bulk density for expanded BFS ranges from 800 kg/m³ to 1040 kg/m³ [51].
Pelletized blast furnace slag is obtained through air and water quenching; controlling the cooling process, it is possible to determine the resulting internal structure influencing the crystallization or glassy phenomena (slow quenching leads to greater crystallization and less vitrification, which is desirable for aggregate to be used in road construction applications). Unlike air-cooled and expanded blast furnace slag, pelletized blast furnace slag has a smooth texture and rounded shape, with lower porosity than those of ACBFS. Typical grain size ranges from 0.1 to 13 mm, with a loose bulk density of about 840 kg/m$^3$ \cite{52}.

Finally, granulated blast furnace slag derives from water cooling and rapid solidification to a glassy state without crystallization; this commonly results in sand-sized fragments, the properties of which depend on the chemical composition and production method.

### 3.1.2. Basic Oxygen Furnace Steel Slags

Basic oxygen furnace steel slag (BOFS) is a waste product derived from steel-making processes in a basic oxygen furnace (Figure 5), where the molten iron produced in the blast furnace is joined with ferroalloys, steel scraps, and limestone (as fluxes). Here, the presence of steel scraps plays a key role in cooling down the furnace and keeping the temperature at approximately 1600 °C (the temperature required for chemical reactions of coke and iron ore). Conventionally, the proper basic oxygen furnace charge consists of 80–90% molten iron and 10–20% steel scraps, with a limited amount of ferroalloys and fluxes \cite{53}. Through molten iron pouring (from the furnace top) and pure oxygen blowing, the impurities of the charge are removed by oxidation phenomena, and the carbon monoxide formation can develop; fluxes act as purifiers, reducing all unwanted chemical elements of the melt (limestone can react to form oxides of silicon, phosphorus, sulfur, and manganese) \cite{54}.

![Figure 5. Basic oxygen furnace slag production process.](image)

The blowing cycle stops when the desired chemical composition is achieved. Slag derived from this steel-making process floats on top of the molten steel, and it can be separated thanks to the difference in material density. If further secondary refining procedures are not planned, BOFS results in a solid product obtained with cooling processes. It can assume various shapes (blooms, billets, or slabs) and characteristics \cite{13}. Commonly, this type of slag is characterized by prismatic angles and high hardness. Final chemical composition of the basic oxygen furnace slag is strongly affected by the chemical reactions that take place during the removal of impurities provided by fluxes.

### 3.1.3. Electric Arc Furnace Steel Slags

The electric arc technology is utilized in furnaces electrically supplying high temperatures to melt steel scraps and provide high quality steel conversion (Figure 6). After the insertion of the various types of steel scraps (based on size, density, and chemistry to ensure a homogenous product) in the furnace \cite{55}, the presence of an arc allows the
electricity to flow through graphite electrodes and the subsequent heat generation. The total melting of the charge can be achieved with the progressive lowering of electrodes on the succeeding layer of melted scraps. Oxygen injection can also be used to reduce scraps to smaller sizes; similarly to the steel-making process carried out in a basic oxygen furnace, oxygen also contributes to developing the reaction between fluxes (initially charged) and scrap impurities, promoting the CaO combination (in the form of lime or dolomite) and the oxidation of aluminum, silicon, manganese, phosphorus, and carbon.

![Electric arc furnace slag production process](image)

**Figure 6.** Electric arc furnace slag production process.

The possible addition of carbon powder on the surface of the melting steel can also lead to the formation of carbon monoxide (due to the slag foaming), with beneficial effects on the thermal energy transition efficiency. Once the desired composition is reached, the furnace can be tilted to pour the melted material into ladles, splitting steel and slags. Final EAFS are treated with cooling (from approximately 1300 °C to room temperature, with possible water sprinkling to accelerate the process) and crushing (to obtain the desired particle size). EAFS consists of irregularly shaped, rough, and porous grains with high particle density. There is residual free lime in the final slag, so it could potentially be subjected to hydration and carbonation (with consequent inhomogeneous expansion and segregation); thus, monitoring the chemical composition throughout the entire process (seasoning included) is crucial.

3.1.4. Ladle Furnace Steel Slags

Ladle furnace slag (LFS) comes from secondary steel-making operations (i.e., refining processes applied to basic steel derived from electric arc or basic oxygen furnace production) used to obtain specific chemical compositions (Figure 7). The morphological characteristics of refined steel are strongly affected by secondary refining mechanisms that consist of the removal of impurities (oxygen, hydrogen, and nitrogen), desulfurization, and decarburization [56]. Ladle furnaces are also characterized by the presence of graphite electrodes connected to an arc utilized for the heating process, whereas controlled argon gas can be injected from the bottom of the charge to stir and homogenize the melted steel. The chemical composition required is also achieved by adding alloy to the charge during the refinement. At the end of the treatment, liquid steel is conveyed in casting machines that separate ladle slag; during further cooling and solidification (24 h), expansive behavior can occur (a volume increase even higher than 12% and fine powder dispersion). The final process consists of by-product hydration, forming a steam that contains a certain amount of calcium oxide powder [57]. The main use of LFS is its reintroduction into the steel production processes [58], in both basic oxygen [59] and electric arc [60,61] furnaces, with appreciable cost benefits and useful effects concerning the resulting steel and slags [62,63]. However, since it is known that the presence of CaO and MgO can lead to dimensional instabilities due to hydration and carbonation (related to the high porosity of this type of
slag), practical applications in the construction sectors have been carefully evaluated while exploiting LFS hydraulic reactivity [64].

![Figure 7. Ladle furnace slag production process.](image)

### 3.2. Steel Slag Stabilization Process

The use of steel slags can be affected by several concerns connected to their chemical and physical properties; for example, slags can be subjected to volume instability and expansion phenomena, during the hydration processes, due to the presence of specific chemical compounds. Thus, developing a way to guarantee proper waste stabilization is a crucial aspect to yield slags suitable for the planned recycling. Volumetric expansions, caused by the hydration of calcium and magnesium oxides in steel slags, are reported in several studies [65–67], and they even occur after a certain period of time [68]. The common stabilization approach adopted to avoid these issues consists of expansion inhibitions obtained by limiting the CaO and MgO oxide amounts.

With this aim, adequate BOFS volumetric stability can be guaranteed when treating slags with: (i) the HBM (Hot-stage BOF slag Modification) method, i.e., introducing silica sand into the molten slag, for reactions with CaO and MgO to form stable minerals of calcium silicates and ferrites, and maintaining the molten state of BOFS for the reaction progression [69–71]; (ii) injecting oxygen and silica, as well as autoclaving [72]; (iii) weathering solid slags outside the slag pits [53].

Furthermore, EAFS must be properly seasoned (stockpiled for some months, even outdoors), during which stabilization of the unbound calcium and magnesium oxide fractions can occur naturally. In order to prevent the swelling behavior, the free lime content should be 2–3% at most. In the case of oxidizing EAFS (resulting from oxidation refining), potential expansion can be eliminated, ensuring a CaO/SiO₂ ratio of 2 at most (i.e., CaO weight content less than 0.3%). On the other hand, reducing EAFS (derived from reduction refining) are subjected to an incomplete conversion of CaO; this could cause potential expansion up to almost twice the initial volume (in this case, by-products are considered unsuitable as construction materials) [73]. Similarly, ladle furnace slags manifest hydraulic reactivity due to the persistent free lime portion [74].

Therefore, specific attention must be paid to the definition of seasoning protocols to determine periods and techniques able to control the free lime content, porosity, and microporosity of slags: several researchers [75–77] suggested weathering such materials for a period of at least 2 months (for natural stabilization of the CaO fraction). Usually, the weathering time is calibrated as a function of the swelling test results obtained to describe the specific expansion evolution on granular slags (e.g., EN 1744-1 [78] or ASTM D4792M-13 [79]).

In this regard, most of the literature reports that the expansion values of steel slags comply with the limits imposed by the international regulation [24,76,80,81]. For instance, Autelitano and Giuliani (2015) [7] found EAFS expansion values matching the reference
technical requirements in the case of both fresh and aged materials. Otherwise, they recorded worse results with untreated (unseasoned) slags, thus confirming the dependency of the final swelling on the preliminary exposure and on different physical factors such as particle size, distribution, and air void content. Kandhal and Hoffman (1997) [82] registered average expansion values within the specification criteria, with expansion of less than 1.5% (after 6 months of weathering) mainly due to the fine fraction of steel slags. Rohde et al. (2003) [9] reported slag expansion of less than 0.5% after 4 months of seasoning in stockpiles, which was still complying with specifications. Similarly, Sorlini et al. (2012) [83] indicated expansion of 0.6% even with tests conducted on fresh slag (with only 15 days aging). Given the heterogeneity of proposed methodologies and related findings, also taking into account the significance of this aspect in view of a successful use of slags in asphalt mixtures, further refinements are encouraged in this regard.

4. Steel Slag Characterization

Although the chemical composition of all slags may vary due to the original material (molten iron and steel scraps), common chemical–physical attributes can be distinguished depending on the steel-making production technique.

4.1. Chemical and Mineralogical Characteristics

X-ray Diffraction (XRD), X-ray Fluorescence (XRF), and Scanning Electron Microscope (SEM) are generally used to assess the chemical–morphological properties of all steel slags. Depending on the specific production process, most slags are composed of lime and silica; therefore, calcium (CaO) and silica (SiO₂) oxides are their primary components [84], whereas alumina and magnesium oxides (Al₂O₃ and MgO) are present in lower proportions [85]. Tricalcium silicate (C₃S) can be another principal constituent [86]. The iron content (Fe) is definitely affected by the refining processes, as it is much higher in the case of slags generated with oxidizing methods. In BFS, for example, it is generally lower than 0.5% by weight (depending on reduction procedures).

The mineral composition of blast furnace slags generally comprises melilitite (Ca₂MgSi₂O₇-Ca₂Al₂SiO₇) and merwinite (Ca₃MgSi₂O₈).

On the contrary, BOFSs are principally formed by iron oxide (FeO), while also containing CaO, MgO, and SiO₂, which define the CaO-MgO-SiO₂-FeO quaternary system [87]. Thus, the main BOFS components consist of dicalcium silicate (Ca₂SiO₄), dicalcium ferrite (Ca₂Fe₂O₅), and wuestite (FeO).

EAFSs partially differ from BOFSs because of the free magnesia content influenced by the steel-making production process, the quality of limes used as fluxes [88], and in some cases, the lower content of free calcium oxide [89]; however, EAFSs exhibit less expansion aptitude if compared with BOFS [90]. Generally, the conventional mineral components of electric arc furnace steel slags are Fe₂O₃, CaO, SiO₂, and Al₂O₃.

LFSs are made up of magnesium and calcium basic oxides with other silicon, aluminum, manganese, and titanium oxides, as well as iron, sulfur, and calcium fluoride [13]. In general, these have been shown to be crucial in developing the adhesiveness with bituminous binders, since steel slags increase the concentration of asphalt components on the mineral surface (resins and asphaltenes), even when subjected to water erosion [86].

Asphaltenes and resins were also found to perform a greater diffusion in the presence of steel slag because of their polarity and enhanced electrostatic attractiveness given by the slag [91].

As an example, Table 1 summarizes some typical compositions of iron and steel slags taken from surveys conducted within several EU countries (ranges were indicative of the intrinsic variability of composition due to geographical origin and raw materials used).
Table 1. Typical composition of iron and steel slags [92].

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Iron Slag 1</th>
<th>Steel Slag 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>35–42%</td>
<td>35–45%</td>
</tr>
<tr>
<td>SiO₂</td>
<td>33–38%</td>
<td>11–17%</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>10–15%</td>
<td>1–6%</td>
</tr>
<tr>
<td>MgO</td>
<td>7–12%</td>
<td>2–9%</td>
</tr>
<tr>
<td>FeO</td>
<td>≤1.0%</td>
<td>16–26%</td>
</tr>
<tr>
<td>MnO</td>
<td>≤1.0%</td>
<td>2–6%</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>not available</td>
<td>1–2%</td>
</tr>
<tr>
<td>S</td>
<td>1–1.5%</td>
<td>≤0.2%</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>≤0.1%</td>
<td>0.5–2%</td>
</tr>
</tbody>
</table>

1 percentages by weight.

4.2. Physiscal Characteristics

The physical properties of steel and iron slags are strictly dependent on both the chemistry and production process; moreover, the speed of the cooling technique determines a crystalline or vitreous structure [93]. BOFS presents fairly variable surface tissue, rough texture, high angularity, and good mechanical properties [94]. The presence of aluminum oxide and metallic components, especially in EAFS, strongly contributes to high polishing resistance—a property useful for providing material suitable for civil constructions. Given that significant contents of CaO, as well as SiO₂ and MgO, can cause hydration, expansion, and stability issues, several slag processing methods (crushing, screening, etc.) are executed to guarantee that aggregates and mixtures comply with the requirements given by reference standards and regulations. Thus, adequate slag materials must show similar results to natural rock aggregates, which are characterized by high density, high compressive strength, good polishing, and freeze/thaw resistance. It is acknowledged that the properties of aggregates used in road materials directly influence final pavement performance [95,96], so several literature studies focused on the analysis of methods able to univocally determine the physical–mechanical slag parameters [96,97]. Conventionally, good characteristics of oxidizing steel slags (BOFS or EAFS) make these by-products useful for several construction fields [11], whereas LFS are suitable for many applications related to agriculture (soil acidity correction), environmental engineering (water depuration) [98], aquaculture (fishing block development) [99], the cement industry (clinker fabrication) [100,101], masonry mortars [102], and soil stabilization [103]. From the physical point of view, coarse and fine slags typically present a rough surface with numerous micro-pores and uniform angularity distribution [104]. These features, together with a larger specific surface area, increase the contact area with asphalt and, thus, promote the adhesion phenomena [105], improving the bonding with bitumen [106]. In this regard, Liu et al. (2022) [107] demonstrated that the interlocking of the lithic skeleton could be significantly promoted when traditional coarse aggregates are entirely replaced with steel slags. Moreover, steel slag is reported to have a strong crushing resistance thanks to its physical properties (comparable with that of conventional basalt aggregate), which reflects in reduced risks of particle breaking during the field compaction of the asphalt mixes [108].

As an example, Table 2 lists some of the tests generally performed to evaluate the physical characteristics of slags, comparing these properties with some traditional natural rocks. Steel slags are generally characterized by superior performance. However, the higher bulk density can limit their extensive use in road construction because of the subsequent higher transportation costs involved [109]. Specific studies investigating the chemo–physical affinity between steel slags and bituminous binders are also encouraged since only a few pieces of literature directly address this aspect so far.
Table 2. Typical physical properties of iron slags, steel slags, and natural rocks [92].

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard</th>
<th>Unit</th>
<th>Iron Slag</th>
<th>Steel Slag</th>
<th>Basalt</th>
<th>Greywacke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact value</td>
<td>EN 1097-2 [110]</td>
<td>%</td>
<td>27</td>
<td>17</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td>Particle density</td>
<td>EN 1097-6 [111]</td>
<td>g/cm³</td>
<td>2.4</td>
<td>3.6</td>
<td>3.0</td>
<td>2.7</td>
</tr>
<tr>
<td>Water absorption</td>
<td>EN 1097-6 [111]</td>
<td>%</td>
<td>2</td>
<td>1</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Polishing resistance</td>
<td>EN 1097-8 [112]</td>
<td>PSV</td>
<td>50</td>
<td>57</td>
<td>50</td>
<td>56</td>
</tr>
<tr>
<td>Freeze/thaw resistance</td>
<td>EN 13467-5 [113]</td>
<td>%</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
</tr>
</tbody>
</table>

4.3. Basic Legislation and Technical Standards

Over the last 30 years, the legislation concerning standard requirements and regulations did not treat slags, by-products, or wastes; since 2008, after the Waste Framework Directive—WFD revision (2008/98/EC) [114], European countries have stated clear definitions of by-products, intended as wastes that are finally useful in further productions, otherwise omitting archetypal characterizing criteria. Thus, slag classification in Europe is not yet uniform, with some countries considering slag as a by-product and implementing specialized regulations and others still treating steel-making slag as simple waste. The standard approach used by the metallurgical companies’ policies, when interested in steel slag manufacturing, must be focused on the achievement of the “end of waste” status that makes the slag a by-product instead of a waste. Iron and steel slag valorizations are also widely considered in the Best Available Techniques Reference (BREF) document, i.e., the European technical paper that, according to regulations regarding environmental integrated protection and prevention control, delineates the best available eco-friendly techniques for each industrial sector. Representing the final effort of a technical working group coordinated by the European Integrated Prevention Pollution and Control Bureau (EIPPC), BREF summarizes the standard treatments to which the steel-making by-products must be subjected in order to allow their reutilizations as aggregate in civil constructions, including road pavements. European standards directly addressed to steel slags’ utilization in civil engineering have also been published in the last decade: EN 14227-12 [115] describes regulations concerning soils treated by slag for roads, airfields, and other trafficked areas, and it specifies the requirements for their constituents, composition, and laboratory performance classification. In this standard, ground or partially ground blast furnace slag specifications are given, which also comply with EN 14227-2 [116]. Since 2013, EN 13043 [117] has specified the properties of aggregates and filler aggregates obtained by processing natural, manufactured (including steel slag), or recycled materials for use in bituminous mixtures and surface treatments for roads, airfields, and other areas (providing information about the determination of slag volume stability). Similarly, EN 13242 [118] defines the properties of aggregates and fillers obtained by processing natural, manufactured, or recycled materials, for use in hydraulically bound and unbound materials, for civil engineering works and road construction (while also defining the constituents that affect the volume stability of blast furnaces and steel slags). Such standards consider steel slag aggregates as a possible source of aggregates and fillers for the road pavement layers subjected to the CE marking and labeling procedure. The American Society for Testing and Materials International also regulates the use of steel slag aggregate in bituminous paving mixtures (ASTM D5106-15 [119]), with a particular emphasis on specific toxicological tests when aggregates exhibit a potential to produce leachates.

5. Environmental Issues

5.1. Generalities

As anticipated, special attention is given to environmental issues deriving from steel slag manufacturing and utilization as raw material in road constructions. In fact, the disposal and reuse of marginal materials in embankments, subgrades, or unbound layers can cause issues connected to the possible infiltration of dangerous compounds in soils; specific environmental regulations are, thus, generally desired. On the other hand, metal-
Surgical waste reuse can be seen as an environmentally-friendly technique since it allows for savings in natural resources. The most relevant possible polluting substances connected to steel slags are heavy metals (e.g., Pb, Hg, Cd, As, Ni, Cu, Mn, Zn) [120] that could be involved in the leaching and percolation processes to which metallurgical by-products can be subjected. The pollution severity is influenced by the characteristics of the waste mass, especially those of the finest fraction, i.e., the physical–chemical properties, pH, and redox potential.

Indeed, specific regulations vary locally, with some being stricter or more tolerant across different states that are even located in the same area. Given this background, the literature considers some environmental analyses to determine the environmental impacts of steel slag use as construction material. In this regard, the Life Cycle Assessment (LCA) methodology [121–123] consists of a complex sequence of unitary operations, with information exchange between them and with the environment, through inputs and outputs (standard ISO 14004 [124]). After the first phase (the definition of the objective, scope of the study, the functional unit, and the system limit), the methodology considers the development of the Life Cycle Inventory (LCI) to gain all the required data and calculation routines necessary to quantify system input and output. The computation of potential environmental impacts is performed through the data collected in the inventory phase, and it permits further interpretation of the results, conclusions, and recommendations for the improvement of the environmental performance of the system under study. As an example, Ferreira et al. (2015) [121] proposed environmental evaluations of two case studies with the use of natural aggregates and steel slags in bituminous mixtures, showing that the bitumen consumption caused the highest impact in both cases. In particular, 75% of the natural aggregates were substituted by EAF slags. With respect to impacts (abiotic depletion, acidification, freshwater eutrophication and ecotoxicity, global warming, ozone layer depletion, human toxicity, terrestrial ecotoxicity, photochemical oxidation), a 10% global reduction was promisingly obtained when using EAFS, both in the base and the surface layers of the asphalt pavement. Similarly, Pasetto et al. (2016) [125] used the LCA to demonstrate the beneficial use of steel slags as partial replacements for natural aggregate; impacts concerning energy and water consumption, carbon dioxide, particulate matter, hazardous waste generated, human toxicity potential of cancer, and the generation of CO2, CO, NOx, SO2, Pb, and Hg were evaluated. The use of steel slags played a key role in costs and environmental impacts (for instance, about 5% of reductions were found for the energy and water consumption, the generated hazardous waste, and the human toxicity potential of cancer). Moreover, materials production had a marginal weight in the life cycle of pavement with respect to the transport processes (20% of the total impact). Analogously, Mladenović et al. (2015) [126] certified lower environmental impacts in several categories (acidification, eutrophication, photochemical ozone creation, human toxicity, and global warming) using the steel slag aggregate (impacts of the alternative scenario were reduced by about 20% in comparison with those related to the virgin material). More recently, an environmental analysis was done considering calculations about electricity usage, diesel consumption, transportation, and the use of explosives for aggregate supply to determine the carbon footprint of asphalt pavements made with EAF steel slags. The calculated amount of greenhouse gases (e.g., carbon dioxide, etc.) showed that the produced asphalt wearing courses were less impactful when using such a slag (about 30% lower impacts), if the transportation costs were included (by-products available near the construction sites) [127].

5.2. Leaching

The composition of leaching elements, including pollutants, obviously depends on the component amounts in the original metallurgical wastes. Toxicological characteristics can be assessed to determine the typical slag leachates, generally represented by chromium and vanadium, molybdenum, copper, zinc, nitrates, chlorides, and fluorides [85,128,129]. Some literature focuses on the behavior of vanadium, as it is recognized to be one of the most
important polluters: EAFS leaching tests were able to explain that vanadium is concentrated, preferentially, in mixed non-stoichiometric phases, including the majority of oxides that form the slag. It has also been demonstrated that a higher tricalcium silicate formation temperature (during slag cooling) definitely lowers the vanadium content that is leached, suggesting a successful way to strongly reduce its percolation and promote the formation of tricalcium silicate (i.e., slag modification with higher CaO activity) [130]. Chromium leaching, however, does not seem to be preventable by a rapid cooling process [93,131], even if it has been shown that leaching decreases with road aging and outdoor storage [132]. European specifications about leaching are given in the EN 12457-2 [133] regulation that concerns the waste characterization and leaching test methodology related to granular materials and sludges. Several studies evaluating slag leaching aptitudes affirm that steel slag leaching of heavy metals and pollutants is in low percentages, within the prescribed legal limit of the local environmental regulations [75,76,83,93]. For instance, based on the Toxicity Characteristic Leaching Procedure (TCLP) (an analytical method to simulate leaching through a landfill using an acetic acid solution at pH = 4), Hasita et al. (2021) [134] detected acceptable heavy metal concentrations within coarse steel slag. Moreover, in most of the analyzed cases, the preparation of steel slag asphalt mixtures did not present toxicological problems since the bitumen film further inhibited leaching phenomena [80]. In this sense, Gan et al. (2022) [135] demonstrated that steel slag leachate concentrations in asphalt mixes can be affected by bitumen content, asphalt grading, and in-service temperature, even if a structured (well-covered) asphalt is a key factor to reduce the leaching risk.

In general, it can be quite difficult to establish typical leachates, as well as other possible environmental issues, for each slag type, which are largely variable depending on the original waste characteristics. Despite the heterogeneity of local regulations, the identification of potential hazardous concerns and related risks for the environment, in the presence of steel slags, can be assessed by examining Table 3 (extracted by [136]).

<table>
<thead>
<tr>
<th>Property</th>
<th>Potential Hazard</th>
<th>Environmental Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leachable (or soluble) trace metals</td>
<td>Presence of As, Cd, Cu, Cr, Hg, Pb, Zn</td>
<td>Groundwater and surface water pollution</td>
</tr>
<tr>
<td>Soluble solids</td>
<td>Presence of soluble and mobile salts</td>
<td>Contamination of groundwater and sensitive freshwater ecosystems</td>
</tr>
<tr>
<td>Total and respirable dust</td>
<td>Presence of fine particulate matter</td>
<td>Respiratory diseases (particles also susceptible to airborne migration)</td>
</tr>
<tr>
<td>Volatile metals</td>
<td>Presence of volatile metals such as As, Hg, Cd, Pb, and Zn</td>
<td>Worker health issues (particles released at high temperatures)</td>
</tr>
</tbody>
</table>

### 6. Steel Slags in Asphalt Pavements

#### 6.1. Laboratory Studies

#### 6.1.1. Mix Design

The most frequently used mix design procedure for asphalt mixtures with steel slag is the well-known Marshall method. In order to evaluate the effect of aggregate substitution, experimental studies involving steel slag are usually performed through a comparison with traditional asphalt mixtures, constituted by natural aggregates only (such as limestone, granite, or basalt). It is generally observed that the addition of steel slags increases the Optimum Bitumen Content (OBC) as a result of the porous surface of slags. Typical higher porosity, clearly demonstrated by SEM analysis [137,138], is determined by the steel-making production processes originating the slags when microscopic air bubbles are trapped in the melted mass during the rapid cooling procedures to which the oxidized and superficial liquid phase are subjected [139,140]. Such porosity could also be detected at the filler-scale, as reported by Tao et al. (2019) [105], who found diffused micro-pores with a size order of 0.5–5 µm while analyzing slag fillers through SEM.
In particular, higher OBC can be quantified in the presence of electric arc furnace [76,137,141] and basic oxygen furnace slags [142]. Generally, this is found regardless of the bitumen type (both traditional and polymer modified binders) [76], or it is found, together, with the partial addition of recycled concrete aggregate from construction and demolition (C&D) procedures [143]. Other studies, with the total substitution of natural aggregates, attributed the highest optimum bitumen content to the high void space of the mixture [144]. However, other studies did not record significant OBC differences, despite the presence of EAFS [145], probably because of a mix design with lower content of the slag fine fraction.

As far as mix design parameters are concerned, the Marshall Quotient (MQ) is reported to increase significantly with the progressive substitution of natural aggregates by slags [35,75,137,143,145–149], depending on binder characteristics [76,145]. This is due to the higher Marshall stability and lower Marshall flow [24,82,87,143,145] that are generally collected in the cases of lithic matrixes characterized by aggregates with higher sharpness, angularity, and internal friction angles that guarantee a better aggregate interlock [137]. Similar trends are also reported with the introduction of steel slag in stone mastic asphalt (SMA) mixtures [75,150]. However, some studies showed quite similar, or even higher, Marshall flows in the case of asphalt mixes with steel slags [83,137]; this could be due to non-negligible variations in the volumetric proportions of mixtures. In this sense, voids in mineral aggregate (VMA) and void content (V) values are sometimes in contrast when also using EAFS [24], BOFS [151], or LFS [67]: VMA and V increase or decrease depending on the aggregate gradations and bitumen contents [152,153]. With respect to the Marshall mix design, Luan et al. (2022) [154] proposed a modified method for considering steel slag (iron and steel types) within the bituminous mixture, including the concept of a nominal asphalt–aggregate ratio for both dense-graded and SMA mixes.

Fewer studies involved the use of the Superpave mix design [155] procedure through the use of a shear gyratory compactor [156–158]. In general, an increase in OBC was, again, observed when adding steel slags to asphalt mixtures (for instance, the absorbed bitumen of an EAFS mixture was found to be 0.3–0.4% higher with respect to a control mixture [159]).

The mix design Bailey method [160] was selected by some authors [161], showing that SSA mixes, having significant differences in the specific gravity between aggregate fractions, can be produced with similar VMA with respect to reference mixtures.

Overall, the literature review seems to demonstrate that, to carefully develop a correct mix design, the granulometric distribution, as well as the bitumen content, must be chosen according to the volumetric proportions of the constituent materials; this is particularly true when natural aggregates are replaced by porous heavy steel slags (a proper volumetric design should lead to similar VMA and residual voids).

As a conclusion, Table 4 summarizes the main findings about mix design identified in the literature, where it is demonstrated that higher mechanical properties (i.e., Marshall Stability and Quotient), along with lower voids, could be achieved thanks to the use of slags, provided that a slightly higher bitumen content is designed in the mix recipe. A relationship between the amount of slags and performance increases, both detailed in the Table, cannot be clearly established due to the high variability in the mix design characteristics among the different studies (e.g., bitumen type, aggregate mineralogy and physical properties, mix gradation, etc.).
Table 4. Summary of the main findings about mix design.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Slag Type (Content)</th>
<th>Method</th>
<th>OBC 1</th>
<th>MQ</th>
<th>Flow</th>
<th>Voids</th>
</tr>
</thead>
<tbody>
<tr>
<td>[24]</td>
<td>EAFS ( \geq 90% )</td>
<td>Marshall</td>
<td>( \geq +1% ) [L]</td>
<td>( \geq +50% )</td>
<td>( \geq -5% )</td>
<td>Fixed</td>
</tr>
<tr>
<td>[35]</td>
<td>EAFS ( \geq 90% )</td>
<td>Marshall</td>
<td>n.a. [L]</td>
<td>( \geq +25% )</td>
<td>( \geq -20% )</td>
<td>( \geq -10% )</td>
</tr>
<tr>
<td>[76]</td>
<td>EAFS ( \geq 50% )</td>
<td>Marshall</td>
<td>( \geq +0.1% ) [L]</td>
<td>n.a.</td>
<td>n.a.</td>
<td>( \geq -15% )</td>
</tr>
<tr>
<td>[137]</td>
<td>EAFS ( \geq 50% )</td>
<td>Marshall</td>
<td>( \geq +0.05% ) [L]</td>
<td>( \geq +5% )</td>
<td>+14%</td>
<td>( \geq -20% )</td>
</tr>
<tr>
<td>[141]</td>
<td>EAFS ( \geq 90% )</td>
<td>Marshall</td>
<td>( \geq +0.5% ) [L]</td>
<td>n.a.</td>
<td>n.a.</td>
<td>( \geq -30% )</td>
</tr>
<tr>
<td>[142]</td>
<td>BOFS ( \geq 70% )</td>
<td>Marshall</td>
<td>( \geq +0.2% ) [L]</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>[143]</td>
<td>n.a. ( \geq 50% )</td>
<td>Marshall</td>
<td>( \geq +0.4% ) [D]</td>
<td>( \geq +40% )</td>
<td>( \geq -15% )</td>
<td>( \geq +15% )</td>
</tr>
<tr>
<td>[144]</td>
<td>n.a. ( \geq 50% )</td>
<td>Marshall</td>
<td>( \geq +1% ) [GA]</td>
<td>( \geq +35% )</td>
<td>( \geq -10% )</td>
<td>( \geq -20% )</td>
</tr>
<tr>
<td>[145]</td>
<td>EAFS ( \geq 70% )</td>
<td>Marshall</td>
<td>( \geq 0% ) [GR]</td>
<td>( \geq +30% )</td>
<td>( \geq -25% )</td>
<td>( \geq -15% )</td>
</tr>
<tr>
<td>[146]</td>
<td>EAFS ( \geq 90% )</td>
<td>Marshall</td>
<td>( \geq +0.2% ) [GR]</td>
<td>( \geq +30% )</td>
<td>( \geq -25% )</td>
<td>( \geq -30% )</td>
</tr>
<tr>
<td>[147]</td>
<td>n.a. ( \geq 90% )</td>
<td>Marshall</td>
<td>( \geq +0.5% ) [L]</td>
<td>( \geq +50% )</td>
<td>( \geq -30% )</td>
<td>( \geq +20% )</td>
</tr>
<tr>
<td>[148]</td>
<td>EAFS ( \geq 90% )</td>
<td>Marshall</td>
<td>( \geq +0.35% ) [L]</td>
<td>( \geq +50% )</td>
<td>( \geq -10% )</td>
<td>Fixed</td>
</tr>
<tr>
<td>[149]</td>
<td>n.a. ( \geq 90% )</td>
<td>Marshall</td>
<td>( \geq +0.8% ) [L]</td>
<td>( \geq +20% )</td>
<td>( \geq -25% )</td>
<td>( \geq -15% )</td>
</tr>
<tr>
<td>[150]</td>
<td>EAFS ( \geq 20% )</td>
<td>Superpave</td>
<td>( \geq +0.4% ) [S]</td>
<td>n.a.</td>
<td>n.a.</td>
<td>( \geq +5% )</td>
</tr>
<tr>
<td>[151]</td>
<td>BOFS ( \geq 60% )</td>
<td>Marshall</td>
<td>( \geq -0.4% )</td>
<td>( \geq +45% )</td>
<td>( \geq -15% )</td>
<td>( \geq -20% )</td>
</tr>
<tr>
<td>[152]</td>
<td>BOFS ( \geq 90% )</td>
<td>Marshall</td>
<td>( \geq -0.4% ) [L]</td>
<td>( \geq 0% )</td>
<td>( \geq -5% )</td>
<td>Fixed</td>
</tr>
</tbody>
</table>

1 by aggregate weight, with respect to control mixes with: [L = limestone; GR = granite; S = sandstone; D = dacite; GA = gabbro]; OBC: Optimum Bitumen Content; MQ: Marshall Quotient; n.a.: non available data.

6.1.2. Indirect Tensile Strength

Although the test is not directly simulative of a field response, the Indirect Tensile Strength (ITS) is a widely utilized parameter in bituminous mixture characterization and acceptance (EN 12697-23 [162]) since there is vast experience correlating ITS and field behavior [137,163]. ITS values are reported to be influenced by several factors, such as the aggregate surface textures and the void content of the mixture [149,150], as well as the bituminous film thickness (providing high adhesive forces and binder-particle interlocking abilities) and binder properties [67].

Thus, better cohesive strength, and subsequently higher ITS, can be achieved with the utilization of highly abrasive, rough textured, highly angular aggregates such as steel slag. In this sense, Ahmedzade and Sengoz (2009) [149] found higher ITS results with mixtures containing only steel slag coarse aggregates (with respect to limestone-based control mixes) in agreement with Hosseinzadeh et al. (2016) [35], Behnood and Ameri (2012) [150] (replacing crushed stones with EAFS), and Lin et al. (2015) [151]. However, Ameri et al. (2013) [137] found higher tensile strengths for hot mix asphalt specimens prepared with limestone only, and they explained this result on the basis of the different aggregate–binder affinity (lower EAF slag alkalinity, i.e., the ratio between CaO and SiO2).

A related literature summary is reported in Table 5.

6.1.3. Stiffness Characteristics

A wide variety of literature determines the stiffness modulus through the non-destructive Indirect Tensile Stiffness Modulus (ITSM) test (EN 12697-26 [164]); although regulations do not generally specify any acceptance limit for bituminous mixtures, the stiffness parameter is considered a key indicator for analyzing the performance of mixes for asphalt layers in terms of structural bearing capacity [148,149]. Commonly, the progressive steel slag introduction, as a replacement for natural aggregate, leads to a higher stiffness modulus as a function of the bitumen type (unmodified or SBS polymer modified) and test temperature [77,149,165–167]. The test temperature seems to directly affect the stiffness increase in the case of steel slag mixes, with it being more significant at higher temperature [76,148]. Similar trends have been reported with the simultaneous inclusion of recycled concrete aggregate, and they have mainly been attributed to the high angularity of such aggregates [143]. In the case of stone mastic asphalt, better mechanical properties can be ascribed to both the integration of the steel aggregates in the lithic skeleton and the high filler–bitumen ratio of asphalt mastic [72]. Such a stiffening effect is documented when
including steel slags in both the coarse [44] and fine [105] fractions. Other studies used the resilient modulus to characterize the asphalt surface, base, and subgrade layers of flexible pavements, providing a more representative description of their mechanical properties [137]. ASTM D7369-11 [168] can be used for the determination of the resilient modulus of asphalt mixes by repeated-load indirect tension tests, which are conducted through repetitive applications of compressive loads in a haversine waveform. Such a stiffness modulus is expressed as the ratio of the repeated axial deviator stress to the recoverable axial strain [169]. Again, many studies report that resilient moduli are sensibly increased in steel slag mixtures with respect to the control ones [170]. An increase in the resilient modulus is also mentioned in the case of recycled concrete fine aggregates, steel slag coarse aggregates [143], or stone mastic asphalts [150]. Evaluating the temperature effect on the resilient modulus, Jain et al. (2015) [171] analyzed ACBFS-based and conventional mixes, demonstrating that resilient modulus increases were not affected by a test temperature in the range between 25 and 45 °C; comparable findings were also found by Ameri et al. (2013) [137], Lin et al. (2015) [151], and Hainin et al. (2014) [170] using laboratory or field specimens. On the other hand, some studies [172,173] documented an increase in resilient moduli, until a slag replacement was used, of up to 70%. A sudden decrease in the resilient modulus was found for higher slag content, probably, because of poor interlocking between slag aggregate particles. Increasing stiffness trends were also detected with stress or strain-controlled laboratory dynamic tests (e.g., with sinusoidal loads) developed at different temperatures and frequency ranges in Four Point Bending—4PB [166], compression [172], or tension–compression [174] configurations. For instance, Abulkhair et al. (2020) [175] tested EAFS mixtures using axial compression haversine loads and observed that steel slag-based materials exhibited higher complex stiffness moduli with respect to conventional asphalt concretes; moreover, they concluded that this finding highlights a beneficial aspect that is useful to reduce asphalt layer thicknesses during pavement design. A steel slag filler was employed by Awed et al. (2020) [176] on dense-graded asphalt mixtures and led to similar stiffness behaviors, with respect to control mixes, under continuous sinusoidal loadings.

Stiffness characteristics can also be investigated through an assessment of the rheological properties of mastics, analyzing the material responses at a lower scale [37,177–180]. In this sense, Pasetto et al. (2016) [181] evaluated the stiffness complex modulus of EAFS mastics and control mastics (limestone-based) with frequency sweep tests performed through a dynamic shear rheometer, recording increasing stiffness with the total replacement of limestone filler with slags, particularly in the presence of a warm chemical additive (probably because of enhanced bitumen–particle interactions). Accordingly, Wang et al. (2011) [182] found a noticeably higher stiffness modulus for slag mastic, again highlighting the role of bitumen type (addition/modification) and, hence, the importance of binder–filler interactions. According to Chen et al. (2022) [183] and Zhang et al. (2022) [184], stable bonding interaction between asphalt and steel slag powder can be achieved thanks to its high alkalinity, as well as rich convex and corrugated morphologies. In other words, steel slag seems to increase the concentration of each asphalt component on the mineral surface; this is often found even with water erosion (peak concentrations of resin and asphaltene are higher using steel slag) [86].

From this perspective, consolidated literature links such findings with the above-mentioned superior physical characteristics of slags that are able to enhance the bitumen–aggregate affinity and binder adhesiveness [105]. EAF steel slags in different fractions were also tested by Preti et al. (2019) [165] in terms of stiffness characteristics: at mixture-scale, open-graded asphalt mixes did not seem to be particularly influenced by the slag presence; analogously, slags neither improved nor worsened the overall behavior of dense-graded mixtures. Actually, the effectiveness of slag introduction must always be evaluated depending on its specific composition affected by the raw material origin, production, treating, and seasoning processes [176].
A related literature summary is reported in Table 5. It is worth noting that all the cited literature studies reported an increase in stiffness, regardless of the slag type, content, and mineralogy of the control aggregates. In this sense, it is crucial to remember that an excessive increase in stiffness could lead to a brittle material, which could be subjected to cracking failures. Thus, specific studies aimed at verifying the cracking resistance of slag-based mixes are needed in case of significant increases in stiffness.

6.1.4. Rutting Potential

Rutting resistance of asphalt pavements is defined as the resistance to permanent deformation under traffic loading, occurring predominantly at elevated temperatures/low traffic speed and dependent on the magnitude of the loads and the relative strength of the pavement layers. Surface rutting performance is reported to be mainly connected to the layer resistance to plastic flow, rather than to densification and volume changes [185]. The susceptibility of bituminous mixtures to permanent deformation can be analyzed with several methods, i.e., dynamic, cyclic, or repeated stress tests that try to simulate the loading action of vehicles.

Typically, the inclusion of steel slag in asphalt mixture structures involves a clear improvement in permanent deformation resistance [138,186–189], with creep modulus (i.e., the ratio between applied stress and final cumulative axial strain) increments up to about 50% [148] or clear increased flow number (i.e., the cycle at which a tertiary strain flow starts) [175] in the case of EAFS-integrated asphalt mixtures. The literature also mentions lower creep rates (i.e., the slope of the quasi-constant part of the creep curve) using BOFS by-products [190], as the steel slag coarse portion in SMA mixtures [150,191], or with the simultaneous inclusion of recycled concrete aggregate [143,192].

Analogously, other studies found similar results through the Repeated Load Axial Test (RLAT), according to BS DD 226 reference standard, with creep modulus increases of 40% in the case of EAFS [76] and 49% when testing SMA mixtures [75]. Similarly, Pasetto et al. (2016) [42] observed that the presence of steel slag, in partial substitution for limestone, did not compromise permanent deformation resistance. On the contrary, Ameri et al. (2013) [137] recorded a decrease in rutting resistances in hot asphalt mixes when steel slag was used within the fine fraction, whereas higher performance was found if only the coarse fraction was replaced.

The permanent deformation behavior of bituminous mixtures can be also determined, with the wheel tracking devices performing simulative tests (EN 12697-22 [193]) able to correlate laboratory results with in-service pavement performance through rutting depth analysis. Once again, steel slag materials (for instance, EAFS and ACBFS) generally showed reduced rut depths [171] for different types of mixtures (dense-graded, porous asphalt, SMA).

Hence, high angularity, rough texture, and polyhedral shapes of steel slags seem to guarantee a better performance, in terms of rutting resistance, since they promote high internal frictions and aggregate interlocks, as well as ensure better densification [194]. Among different steel slag types, EAF asphalt mixture (100% of slag) was found to exhibit higher rutting resistance with respect to conventional HMA (Hot Mix Asphalt) and BOF asphalt concrete with 100% slag [195].

As anticipated, important information regarding bituminous mixture performance can also be derived from the rheological analysis at mastic and mortar-scale: elastic and plastic material behaviors, affecting recoverable and permanent deformations, are generally examined through the Multiple Stress Creep Recovery (MSCR) test, according to the EN 16659 [196] standard, where creep–recovery cycles at high temperatures are provided. Comparing limestone and EAFS mastics, Pasetto et al. (2016) [181] and Alnadish et al. (2021) [197] verified a significant anti-rutting effect when fillers or coarse EAFS were combined with chemical warm-modified binders. Other studies [182,198] presented a multiple regression analysis through a stepwise procedure to consider the effect of filler properties on the mastic and rutting potential of mixtures (with the utilization of steel...
slags); they mainly showed a poor correlation between mixture rutting potential and filler properties when the data were grouped for all binder types and aggregate gradations (thus, they demonstrated that asphalt binder type and aggregate gradation dominate the mechanical properties of asphalt mixtures). Analogous results were found at the mastic-scale by Pasetto et al. (2023) [199]. The anti-rutting effect, due to the presence of steel slag fractions, was demonstrated by Preti et al. (2019) [165] and Pasetto et al. (2023) [200], who included fine or coarse EAFS in different asphalt mixes.

A related literature summary is reported in Table 5.

6.1.5. Fatigue Resistance

The cracking of asphalt pavements related to fatigue phenomena is an unavoidable problem, caused by the repetitive tensile stresses induced by traffic [201], which leads to progressive crack propagation and causes the gradual weakening of the structures. The complete fracture of the road pavement represents the final step of fatigue cracking: a distress typically occurring at low and mid-range in-service temperatures. Fatigue resistance is reported to be mainly influenced by the bitumen content and its rheological properties, as well as by the compaction degree of the mixtures.

In order to evaluate the fatigue performance of bituminous mixes, various experimental protocols have been developed. According to EN 12697-24 [202], asphalt mixtures can be tested by applying sinusoidal, or other controlled dynamic loading, with different configurations (for example, the Four Point Bending—4PB—and Indirect Tensile Fatigue—ITF—configurations). Regardless of the stress or strain-controlled mode, the fatigue life could be clearly represented by the physical failure of the specimens when cracks evolve until complete failure; otherwise, many studies consider the classical approach based on a 50% reduction in the initial stiffness of the mixtures [203,204]. More advanced fatigue energy approaches can also be used [205,206]. The literature about mixture fatigue analysis is vast, and it also concerns steel slag asphalt mixes, for which ITF results are widely available. In this perspective, Pasetto and Baldo (2012) [75] highlighted that the mixes with slags presented higher fatigue resistance than those with natural aggregates. Moreover, enhanced fatigue performance has also been demonstrated to belong to the slag inclusion in SMA. Similar results have been found by Aziz et al. (2020) [37], Pasetto and Baldo (2010, 2011) [76,148], Arabani and Azarhoosh (2012) [143], Qazizadeh et al. (2018) [207], and Groenniger and Wistuba (2017) [208] when testing very different materials, including EAFS and LFS. These findings seem to be ascribable to the rough surface and high angularity of steel slag, regardless of the utilized fraction. Similar results were obtained with three-point bending tests (3PBT) by Xue et al. (2006) [190], who showed good fatigue resistances using three aggregate types with similar gradation. In the four-point bending configuration, Pasetto and Baldo (2013) [80] detected good fatigue performance of different mixes containing EAFS. The study also highlighted the importance of binder type (and the role of polymer modification), according to Kavussi and Qazizadeh (2014) [24], who recorded fatigue life improvement with EAFS mixes, along with a higher initial stiffness. Evaluating the influence of steel slag types, BOF asphalt mixture (100% of slag) was found to exhibit superior fatigue life performance with respect to conventional hot mix asphalt and EAF asphalt concrete with 100% slag [195]. Since it is widely recognized that a crack’s behavior is mainly related to the bituminous mastic properties, as well as to the bitumen–filler interaction, the literature also mentions an experimental analysis on the fatigue performance of mastics. Bahia et al. (2010) [198] reported laboratory protocols to consider the variability of fatigue-representative parameters $G^* \sin \delta$, depending on the filler type, even if they observed no consistent patterns in the effect of the filler source nor in the slag-based mastic cases.

Few literature studies reported slightly lower fatigue resistance when using steel slags, at least in comparative terms, with respect to mixtures prepared with natural aggregates. For instance, under specific experimental conditions, some authors reported worse fatigue performance when using EAFS [175] or BOFS [207], instead of limestone or gabbro aggre-
gate, within dense-graded hot mix asphalts. This finding could be ascribed to the greater stiffness documented for many slag-based asphalt mixes that could lead to increased brittleness [209]. As an example, Tao et al. (2019) [105], trying to evaluate the influence of slag filler in hot mix asphalt, found slightly lower cycles to fatigue failure that were caused by a higher complex shear modulus of the asphalt mortar. Again, the lower fatigue performance of warm mixtures containing EAF steel slag was shown by Pasetto et al. (2017) [166], and it was reasonably related to the higher stiffening effect and embrittlement provided by the manufactured fine fraction.

A related literature summary is reported in Table 5.

6.1.6. Low-Temperature Behavior

Generally, bitumen characteristics are considered to be the most significant factors influencing the low-temperature cracking performance of bituminous mixtures (ductility, stiffness, penetration, etc.) [210–212]. However, some correlations between the aggregate characteristics and low-temperature cracking can also be found since the lithic part affects the internal friction and adhesive bond. Low-temperature performance assessments in asphalt mixes can be performed according to the EN 12697-46 [213] standard. However, tests of indirect tensile strength at low temperatures (e.g., 0°C) are often conducted to study resistance to cracking and analyze stress-strain curves [138,214]. Based on the few existing studies, mixtures prepared with steel slags seem to show increased critical values with respect to reference mixtures, demonstrating better resistance to low-temperature cracking and good failure behavior (e.g., comparable values substituting gabbro aggregates with ladle furnace slags, in representative mixtures of base course and surface asphalt layers, or enhanced benefits with electric arc furnace slags included in stone mastic asphalt mixtures) [138,208,215]. Similarly, the low-temperature cracking resistance of steel slag asphalt mixtures was found to be greater than that of conventional asphalt mixes (containing basalt aggregates) through three-point bending tests (the edge angle of basalt was greater with respect to steel slag, and this caused serious stress concentrations, making the specimens easy to crack) [25].

On the other hand, Pasetto and Baldo (2015) [214] obtained a lower thermal cracking resistance while investigating asphalt mixtures for road base courses made with reclaimed asphalt pavement and steel slags, depending on the RA and steel slag contents (up to 70% in weight as limestone substitution), as well as the aging conditions of samples. Suitable bituminous mixtures can be produced using both EAF steel slags and RA (up to 50%), in combination with the warm technology (by synthetic wax additive), without compromising the fracture characteristics of the asphalt concrete [216].

A related literature summary is reported in Table 5. Here, the limited number of studies addressing this specific aspect, along with the variability of findings, are highlighted. Thus, further research is needed to depict a more consistent picture of the low-temperature properties of asphalt mixtures containing steel slags.

6.1.7. Durability

The assessment of asphalt mixture durability is generally referred to with multiple aspects. The most analyzed issue concerns moisture susceptibility, even if other relevant studies about the effects of aging and raveling resistance can be mentioned. As far as moisture resistance is concerned, the threatening water presence in asphalt mixtures is believed to represent one of the main reasons for flexible pavement failures, leading to structural and functional degradations [217,218]: these phenomena, caused by adhesive (aggregate–mastic bonding) and cohesive (bitumen film bonding) failure [219], are widely influenced by the properties of aggregates, binders, aggregate–binder interfaces, and mixing temperatures [220]. The moisture susceptibility of asphalt mixtures is generally evaluated through the determination of the typical parameters (that may not be representative of the fundamental material characteristics) of unconditioned and water-conditioned samples prepared with the same method: a common procedure is Indirect Tensile Strength Ratio
(ITSR) analysis, i.e., the ratio of the indirect tensile strength of water-conditioned specimens to the indirect tensile strength of unconditioned samples [221,222]. Furthermore, ITSR can be substituted or integrated by the analysis of other parameters, such as the retained stability (Marshall Stability Ratio, MSR), the Resilient Modulus Ratio (RMR), and Fracture Energy Ratio (FER), or by energy-based parameters, such as the Dissipated Creep Strain Energy limits (DCSEf) [223,224]. In order to determine water damage, rut depth can also be used: EN 12697-22 [193] reports the procedure to perform wheel tracking tests in a saturated environment, and AASHTO T324-14 [225] designates the development of wet rutting and stripping tests with a Hamburg Wheel Tracking Device—HWTD. Obviously, the conditioning procedures are crucial for moisture damage responses. The widespread ASTM D4867M-09 [226] method considers moisture conditioning through partially saturated specimens soaked in distilled water (60.0 ± 1.0 °C) or with samples subjected to a single freeze–thaw cycle. In terms of ITSR results, steel slag mixtures are generally reported to be characterized by higher water resistance than the corresponding traditional mixes [32,149,227], usually presenting satisfactory ITSR values (higher than 0.7) in the case of EAFS [145], BOFS [190,228], and ACBFS [171]. Sometimes, appreciable moisture resistance improvements were recorded when slags were combined with warm modified bitumen [137,220] or warm asphalt containing RA [229]. Consistent conclusions can be obtained from other analyzed parameters, mainly MSR, RMR, and FER [220], as well as DCSEf [142] and rut depth [190]. These findings can surely be attributed to the rougher slag surface that improves the adhesion ability of the asphalt binder [230]; indeed, it is worth noting that the integration of slags in the lithic skeleton involves the need for a proper mix design [64]. This could often require a higher binder content [75] to obtain a proper thickness of the bitumen film covering the aggregate grains that can prevent moisture damage due to possible water penetration into the porous structure of steel slags [145]. In this sense, stripping could be significantly mitigated [75,228].

In general, the inclusion of coarse slag fractions is suggested to improve the water resistance of asphalt mixtures thanks to enhanced aggregate surface characteristics, above all, in the presence of polymer-modified bitumen [65]. As far as open-graded asphalt mixtures are concerned, the complete replacement of natural aggregates with BOFS has been demonstrated to be a very effective technique to optimize water resistance; this is mainly due to the significant role of the adhesion mechanisms developed, which are a direct consequence of an excellent bitumen–aggregate affinity, within both alkaline and non-alkaline environments [231].

Concerning aging resistance, durability must be correlated with the adhesion properties linked to the aging processes affecting the bitumen; in this sense, Bell and Sosnovske (1994) [232] found that the higher the adhesion, the lower the effects of aging. On the other hand, Oluwasola et al. (2015) [145] verified that aged EAFS mixes exhibited higher properties if compared to aged granite-based mixes in terms of resilient modulus.

A related literature summary is reported in Table 5.

Table 5. Summary of the main findings about asphalt mixture performance.

<table>
<thead>
<tr>
<th>Performance</th>
<th>Ref.</th>
<th>Slag Type</th>
<th>Control 1</th>
<th>Trend 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITS</td>
<td>[67,149,150]</td>
<td>n.a.</td>
<td>[L],[L],[L]</td>
<td>▲</td>
</tr>
<tr>
<td></td>
<td>[35]</td>
<td>EAFS</td>
<td>[L]</td>
<td>▲</td>
</tr>
<tr>
<td></td>
<td>[151]</td>
<td>BOFS</td>
<td>[L]</td>
<td>▲</td>
</tr>
<tr>
<td></td>
<td>[137]</td>
<td>EAFS</td>
<td>[L]</td>
<td>▼</td>
</tr>
<tr>
<td>Stiffness</td>
<td>[77,106,143,149,167,170,172,173]</td>
<td>n.a.</td>
<td>[n.a.],[G],[D],[L],[G],[R],[L],[L],[L]</td>
<td>▲</td>
</tr>
<tr>
<td></td>
<td>[44,137,165,166,175]</td>
<td>EAFS</td>
<td>[L],[L],[L],[L],[L]</td>
<td>▲</td>
</tr>
<tr>
<td></td>
<td>[72,151]</td>
<td>BOFS</td>
<td>[n.a.],[L]</td>
<td>▲</td>
</tr>
<tr>
<td></td>
<td>[171]</td>
<td>BFS</td>
<td>[n.a.]</td>
<td>▲</td>
</tr>
</tbody>
</table>
Table 5. Cont.

<table>
<thead>
<tr>
<th>Performance</th>
<th>Ref.</th>
<th>Slag Type</th>
<th>Control ¹</th>
<th>Trend ²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rutting resistance</td>
<td>[138,150,186,189,191]</td>
<td>n.a.</td>
<td>{B}[L][L][L][L]</td>
<td>▲</td>
</tr>
<tr>
<td></td>
<td>[42,75,76,175,197]</td>
<td>EAFS</td>
<td>[L][L][L][L][GR]</td>
<td>▲</td>
</tr>
<tr>
<td></td>
<td>[190,195]</td>
<td>BOFS</td>
<td>n.a.</td>
<td>▲</td>
</tr>
<tr>
<td></td>
<td>[171]</td>
<td>BFS</td>
<td>[L]</td>
<td>▲</td>
</tr>
<tr>
<td></td>
<td>[137]</td>
<td>EAFS</td>
<td>[L]</td>
<td>▼</td>
</tr>
<tr>
<td>Fatigue resistance</td>
<td>[143,208]</td>
<td>n.a.</td>
<td>[D][L]</td>
<td>▲</td>
</tr>
<tr>
<td></td>
<td>[24,37,75,76,80,207]</td>
<td>EAFS</td>
<td>[L][n.a.][L][L][L][L]</td>
<td>▲</td>
</tr>
<tr>
<td></td>
<td>[105]</td>
<td>n.a.</td>
<td>[L]</td>
<td>▼</td>
</tr>
<tr>
<td></td>
<td>[166,175]</td>
<td>EAFS</td>
<td>[L][GA]</td>
<td>▼</td>
</tr>
<tr>
<td></td>
<td>[207]</td>
<td>BOFS</td>
<td>[L]</td>
<td>▼</td>
</tr>
<tr>
<td>Low-temperature</td>
<td>[25,138,208]</td>
<td>n.a.</td>
<td>{B}[B][L]</td>
<td>▲</td>
</tr>
<tr>
<td>resistance</td>
<td>[215]</td>
<td>BOFS</td>
<td>[L]</td>
<td>▲</td>
</tr>
<tr>
<td></td>
<td>[214]</td>
<td>EAFS</td>
<td>[L]</td>
<td>▼</td>
</tr>
<tr>
<td>Moisture resistance</td>
<td>[149,220,227]</td>
<td>n.a.</td>
<td>[L][L][n.a.]</td>
<td>▲</td>
</tr>
<tr>
<td></td>
<td>[35,137,145]</td>
<td>EAFS</td>
<td>[L][L][GR]</td>
<td>▲</td>
</tr>
<tr>
<td></td>
<td>[151,190,228]</td>
<td>BOFS</td>
<td>[L][n.a.][B]</td>
<td>▲</td>
</tr>
<tr>
<td></td>
<td>[171]</td>
<td>BFS</td>
<td>[L]</td>
<td>▲</td>
</tr>
</tbody>
</table>

¹ types of aggregate of the control mixture (L = limestone; GR = granite; D = dacite; GA = gabbro; B = basalt); ² of slag mixture, with respect to control one: ▲: higher, ▼: lower; n.a.: non available data.

6.1.8. Thermal Properties

A further factor addressed in the literature is related to the thermal state of the in-service road pavement containing slags [233] since it is known that the surface and inner temperatures can strongly affect the mixtures’ mechanical properties, long-term serviceability [234], as well as specific sustainability aspects connected to the heating of the environment [235]. In this sense, recent studies tried to assess the thermal responses of various bituminous mixtures manufactured with different steel slags. As an example, Luo et al. (2022) [236] modeled the behavior of asphalt mixes containing steel slags, coupling electromagnetic and heat transfer processes; they found that microwave heating performance was enhanced with the increase in slag content up to a certain limit (excessive slag contents led to overheating in most areas of the asphalt mixture). Jiao et al. (2020) [237] proposed an experimental study to investigate the thermal conductivity of open-graded polymer-modified asphalt mixes prepared with steel slags (up to the complete replacement of the natural aggregate). Through laboratory infrared tests and 3D image modeling, they were able to optimize the overall conductivity of the mixture using a threshold value of steel slag content equal to 60%. Analogously, some researchers proposed a laboratory investigation to study several asphalt mixtures with different steel slag contents and found that, compared with traditional aggregates, slags had a higher thermal conductivity thanks to their higher density, composition (Fe₂O₃), and particle size (the most effective particle sizes were 9.5–13.2 and 1.18–2.36 mm) [237]. On the other hand, some authors reported slightly lower thermal conductivity values in the case of the EAF slag-based asphalt mix [238]; other literature findings seem to confirm this trend (typical conductivity values for standard paving materials range from 1.2 to 2.2 W/m·°C and 1.3 to 1.7 W/m·°C for steel slag-based mixes) [239–241]. However, such concerns should not compromise the overall conductivity of a pavement [238]. For instance, a coupled analysis of the microscopic and thermal properties of an open-grade asphalt mixture containing BOF slag demonstrated that the optimum amount of steel slag should not exceed 60% of the aggregate volume of 3–5 mm (6.6% of the total mixture) in order to have a beneficial effect on the thermal conductivity (linked to a reduced iron oxide content). At 60% content, the highest thermal coefficient (equal to 1.746 W/m·°C) was recorded for the mixture [242].
6.2. Field Applications

Despite the significant costs and time, field applications are crucial for assessing the effective pavement behavior and verifying the consistency with laboratory studies. However, given that the inclusion of slags in road constructions is a relatively recent practice, little literature exists about long-term field monitoring. In this sense, field pendulum tests (EN 13036-4 [243]) show that coarse steel slag aggregates definitely improve the surface skid resistance [43,138,228,244,245]. In particular, Xue et al. (2006) [190] performed skid and abrasion tests on a 2-km-long field trial, subjected to a traffic volume of approximately $3 \times 10^7$ standard axels, a design vehicle speed of 110 km/h, with annual rainfall near to 2000 mm, and average temperatures from $-10$ to 40 °C. They found excellent performance in terms of roughness, without cracking, rutting, or stripping phenomena in the first 2 years of service-life for steel slag pavements. Similar findings were reported by Emery (1984) [36], who performed skid resistance tests on 17 road sections constructed with limestone, steel slag, and ACBFS aggregates. These flexible pavements were subjected to high-traffic volumes and seemed to show adequate friction values; however, the real-scale observations also demonstrated relevant weather influence on slag pavements’ behaviors. Stock et al. (1996) [246] conducted summer skidding surveys on 69 sites, providing relationships between skid values and traffic densities, as well as recording better skid resistance for slag pavements. They also observed that the steel slag surfaces were able to retain their skid resistance over the service periods, exhibiting more durable characteristics, at least, with respect to those of corresponding sections made with natural aggregates.

Furthermore, in order to compare steel slag and basalt stone mastic asphalt, Wu et al. (2007) [138] analyzed 2 test sections in China, 400 and 2000 m long, subjected to an annual traffic volume up to $1 \cdot 10^7$ standard axels, under severe rainfall (more than 2000 mm) and temperature (from 0 to 70 °C) conditions. Through visual inspections over 2 years of service, they found no significant distresses (rutting, bleeding, cracking, or stripping) on steel slag paved surfaces; they also recorded excellent performances for steel slag SMA pavements in terms of surface texture depth, abrasion, and friction coefficient BPN (British Pendulum Number) measured through field tests planned every 6 months (55 BPN and 0.8 mm mean texture depth after 2 years of service life). Sofilić et al. (2010) [247] detected negligible issues in the paving operations constructing field trials with EAFS aggregates. They also observed surface course mixtures exhibiting excellent rutting and skid resistances in the case of EAFS asphalt mixes. On the other hand, the field suitability of asphalt mixtures including BOFS was assessed by Lin et al. (2015) [151]: they investigated the service quality of test roads, after 2 years with open traffic, through evenness and skid resistance measurements. BOFS asphalt concrete showed higher capabilities in maintaining the pavement evenness with respect to conventional mixtures (after 2 years of service life, BOFS pavement exhibited 50% higher performance than the conventional one subjected to the same traffic and environmental conditions). In addition, BPN reduction after 2 years was sensibly lower on BOFS asphalt concrete, with respect to the traditional one, thanks to the hardness and roughness characteristics of BOFS aggregates (after 2 years, the initial BPN of 77, registered after the construction phases for both pavements, decreased to 63 for the BOFS asphalt surface and to 49 for the conventional one). Finally, field analysis, in terms of rutting, showed shallower rut depths with BOFS (after 15 months of service, a rapid increase was observed in rut depth for the conventional pavement—close to 10 mm after 24 months, instead of 4 mm in the case of BOFS). The BOFS ability to enhance skid resistance has also recently been demonstrated by Li et al. (2020) [47], who related such findings, mainly, to the physical and mechanical properties of the slag (high density, angular shape, irregular texture), reporting a certain relationship between the skid durability over time and the final grading of the mixture. A further field experience was reported by Wang and Zhang (2021) [230], who dealt with high-grade highway surface layers made with asphalt concretes including steel slags (10 cm of thickness). They stated that, after 2 years of service of the tested highway, the road surface was still smooth, without visible cracks or ruts, and characterized by a good skid resistance and excellent overall performance.
7. Conclusions

Steel-making manufacturing processes involve the separation of molten steel from impurities and provide different types of metallurgical wastes. A million tons of steel slags are produced worldwide every year, especially in European countries. Such large amounts of steel by-products represent a significant motivation for effective recycling applications to meet the current awareness of the circular use of resources. This is in order to promote environmental saving, pollution reduction, and costs control, which are basically achievable by saving natural mineral resources while recycling waste products. The use of steel slag in road pavements is a promising recycling option that is progressively gaining the attention of researchers and practitioners. In this sense, wide literature reports research studies about steel slag-based bituminous mixtures for road pavements. Based on an extensive literature review, this state-of-the-art study about steel slag recycling in asphalt pavements proposed a wide picture, reporting various experiences at laboratory and field scales. Commonly, bituminous mixtures containing steel slags of various types demonstrated equal, or even enhanced, performance with respect to asphalt concretes prepared with conventional natural aggregate. As main findings regarding slags’ properties:

- the main slag types (blast furnace slag, basic oxygen furnace slag, electric arc furnace slag, and ladle furnace slag), the characteristics of which depend on the original scraps, production furnace type, and cooling method applied to the molten mass, differ in properties and, consequently, in the performance conferred to asphalt mixtures;
- the rough texture, high angularity, and superior mechanical properties commonly owned by steel slag aggregates generally contribute to improving the performance of bituminous mixes;
- steel slags can result in good interlocking properties of the asphalt mixtures thanks to improved adhesion forces at binder–particle contacts (improvement of bituminous film thickness around the aggregate);
- a proper stabilization (stockpiling for some months in an outdoor environment) is a crucial aspect of yielding slags suitable for recycling in asphalt pavements, in order to avoid expansion problems caused by the hydration of the calcium and magnesium oxide components;
- leaching of heavy metals and pollutants included in steel slags are typically experienced in low percentages, within the prescribed legal limit of various local environmental regulations.

Therefore, the main influence of steel slags on the asphalt mixture can be summarized as follows:

- a correct mix design, with adequate granulometric distributions and bitumen contents, in accordance with the volumetric proportions and physical characteristics of the constituent materials, is mandatory since slag aggregates are heavier than natural ones;
- the high particle density of steel slag could restrict its use in road pavement construction, mainly due to the consequently higher transportation costs, above all, in the finer fractions;
- influenced by the aggregate surface texture, the indirect tensile strength is often reported to be higher with respect to conventional mixes;
- a wide collection of literature found that the progressive steel slag introduction, as a replacement for natural aggregate, leads to stiffer asphalt concrete;
- improved rutting and fatigue resistance of steel slag-based asphalt mixtures is often measured, ascribing this to steel slag high angularity, rough texture, and polyhedral shapes;
- steel slag mixtures are generally reported to be characterized by lower moisture susceptibility than the corresponding traditional mixes;
- steel slag asphalt pavements exhibit excellent skid resistance, surface texture depth, abrasion, and friction coefficients.
8. Research Gaps and Future Efforts

The state-of-the-art study showed existing research gaps with respect to several technical aspects of steel slag asphalt mixtures (bitumen–aggregate affinity, low-temperature behavior, brittleness, etc.). In this sense, future efforts could be addressed to thoroughly evaluate pavement performance with respect to slag morphology and properties, while also trying to clarify some controversial outcomes reported in the literature. In turn, standardized mix designs could be promoted to include slags in asphalt mixtures considering the slag type also. This should encourage the diffusion of slag-based asphalt mixtures in the paving industry, moving research concepts to prompt guidelines suitable for practitioners, agencies, and organizations. In particular, further efforts could be addressed towards concerns related to a reported lower affinity with bitumen, as well as to establish standard procedures to tackle potential expansion behavior. Finally, the realization and long-term monitoring of more real-field applications (not yet widely diffused) could further promote the promising current findings.

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References


32. Yildirim, I.Z.; Prezzi, M. Subgrade stabilisation mixtures with EAF steel slag: An experimental study followed by field implementation. *Int. J. Pavement Eng.* 2020, 23, 1754–1767. [CrossRef]


44. Rodríguez-Fernández, I.; Lastra-González, P.; Indacochea-Vega, I.; Castro-Fresno, D. Technical feasibility for the replacement of high rates of natural aggregates in asphalt mixtures. *Int. J. Pavement Eng.* 2019, 22, 940–949. [CrossRef]
56. Energy Manager Training. EN 1744-1


118. EN 13242; Aggregates for Unbound and Hydraulically Bound Materials for Use in Civil Engineering Work and Road Construction. European Committee for Standardization: Bruxelles, Belgium, 2002.


122. Khasreen, M.; Banfill, P.F.; Menzies, G. Life-cycle assessment and the environmental impact of buildings: A review. Sustainability 2009, 1, 674–701. [CrossRef]


133. EN 12457-2; Characterization of Waste—Leaching—Compliance Test for Leaching of Granular Waste Materials and Sludges—Part 2: One Stage Batch Test at a Liquid to Solid Ratio of 10 L/kg for Materials with Particle Size below 4 mm (without or with Size Reduction). European Committee for Standardization: Bruxelles, Belgium, 2002.


156. Wang, R.; Xiong, Y.; Ma, X.; Guo, Y.; Yue, M.; Yue, J. Investigating the differences between steel slag and natural limestone in asphalt mixes in terms of microscopic mechanism, fatigue behavior and microwave-induced healing performance. Constr. Build. Mater. 2022, 328, 127107. [CrossRef]
163. Anagnos, J.N.; Kennedy, T.W. Practical Method of Conducting the Indirect Tensile Test; Report 98-10; Center of Highway Research, University of Texas at Austin: Austin, TX, USA, 1972; pp. 1214–1219.


219. Kennedy, T.W.; Anangos, J.N. *Wet-Dry Indirect Tensile Test for Evaluating Moisture Susceptibility of Asphalt Mixtures*; Research Report 253-8; Center for Transportation Research, University of Texas: Austin, TX, USA, 1984; pp. 1–3.
229. Goli, H.; Latifi, M.; Sadeghian, M. Moisture characteristics of warm mix asphalt containing reclaimed asphalt pavement (RAP) or steel slag. Mater. Struct. 2022, 55, 53. [CrossRef]
240. Liu, Q.; Li, B.; Schlangen, E.; Sun, Y.; Wu, S. Research on the mechanical, thermal, induction heating and healing properties of steel slag/steel fibers composite asphalt mixture. Appl. Sci. 2017, 7, 1008. [CrossRef]
242. Cao, Y.; Sha, A.; Liu, Z.; Zhang, F.; Li, J.; Liu, H. Thermal conductivity evaluation and road performance test of steel slag asphalt mixture. Sustainability 2022, 14, 7288. [CrossRef]
244. Akbari, A.; Babagoli, R. Laboratory evaluation of the effect of temperature on skid resistance of different asphalt mixtures. Mater. Res. Innov. 2020, 25, 83–89. [CrossRef]