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Quality Assurance of Steel Slag Asphalt Mixtures for Sustainable Pavement Surface Courses

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Abstract: The present study investigates the use of electric arc furnace (EAF) steel slag, a by-product of the steel industry, in asphalt pavement surface courses instead of virgin aggregates (VAs). Therefore, a general performance evaluation of such mixtures compared to conventional mixtures is carried out through laboratory and in situ tests, while both mixtures are environmentally assessed using the life cycle assessment (LCA) tool. The results of the laboratory and in situ tests show that asphalt mixtures containing granulated EAF slag aggregates perform as well as mixtures containing only VA. In addition, the LCA results show that the use of EAF slag aggregates in the asphalt surface course has a lower environmental impact than the exclusive use of VA when it comes to the impact categories of acidification, climate change, marine and terrestrial eutrophication, energy consumption and photochemical pollution. In summary, these results show that replacing virgin aggregates with a proportion of EAF slag aggregate is a viable and sustainable method for road pavement construction.

Keywords: electric arc furnace (EAF) slag; asphalt mixture; surface course; mechanical performance; life cycle assessment; pavement construction

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1. Introduction

The main task of road infrastructure is to make the transportation of people and goods efficient while ensuring the quality and safety of traffic. A central role is played by the road surface, which in the case of flexible pavements is referred to as the asphalt surface course. Plati et al. [1] report that safe driving depends on the surface condition for maneuvering, turning and braking vehicles. Asphalt surface courses not only provide a suitable and safe surface for road users but also protect the structure and substructure of the pavement from environmental influences such as moisture. In other words, by constructing durable asphalt overlays, high crack resistance can be ensured, limiting water penetration into the sublayers of unbound material or soil and thereby preventing serious failure of the pavement structure [2]. In addition, surface layers reduce the stresses acting on the pavement due to traffic loads, thus protecting it from possible deformation or destruction [3]. Therefore, the road surface plays an important three-part role in the structure of the road pavement.

Environmental protection is also an important aspect of human activity today. As set out in the Sustainable Development Goals of the United Nations Agenda, environmental problems such as the dumping of waste and the depletion of resources, including energy and raw materials, are to be solved by 2030 [4]. In this context, construction and maintenance works, including road infrastructure projects, should apply new sustainable practices. According to UEPG [5], a single kilometer of newly constructed road pavement requires a large amount of aggregates—up to 30,000 tons—further depleting already limited natural resources, while the waste generated during road pavement rehabilitation is part of construction waste, which accounts for more than 30% of global waste generation [6]. An

alternative technique for sustainable roads is therefore the replacement of natural aggregates with so-called waste materials, which can be incorporated into all pavement layers, including asphalt surface courses.

To this end, the use of steel slags as aggregates for asphalt surface courses was investigated in detail. Slags from electric arc furnaces (EAFs) account for almost 30% of the by-products of global steel production and are reported to impart satisfactory physical and mechanical properties to the mixture [7]. Paseto and Baldo [8] demonstrated that EAF slags have physical and mechanical properties very similar to those of virgin aggregates. Studies such as those of Asi et al. [9] and Arabani et al. [10] reported that asphalt mixtures containing granulated EAF slag have better mechanical properties in terms of rutting, fatigue life and resilient modulus compared to conventional asphalt mixtures as they have higher angularity, shear strength and polish resistance. In addition, granulated EAF slag aggregates have been reported to provide high crack resistance in asphalt mixtures [11,12], while they improve pavement skid resistance and reduce the risk of aquaplaning due to their higher permeability [13]. Pattanaik et al. [14] also demonstrated that asphalt mixtures containing up to 75% EAF slag performed better than mixtures containing only VA. In addition, Autelitano and Giuliani [15] suggested a slag content of 54% in asphalt mixtures and emphasized that an optimal degree of compaction, high stiffness in the viscoelastic range, Marshall stability and longer fatigue life are ensured. Similarly, Gowda and Naveen [16] concluded that the optimum percentage for replacement with granulated EAF slag is 30% VA, as these mixtures have higher performance in terms of moisture sensitivity, rutting resistance, fatigue behavior and resilient modulus of elasticity compared to conventional mixtures. In addition, the results of de Pascale et al. [17] underline the contribution of EAF slag in strengthening the weak structure of porous asphalt mixtures used in surface courses.

Regarding environmental assessment, only a few authors have investigated EAF slags as aggregates in asphalt surface courses. Mladenovic et al. [18] conducted an analysis to compare the environmental impacts of the construction of two asphalt overlays containing conventional aggregates and granulated EAF slag aggregates, respectively. The results showed that impacts such as acidification, eutrophication, photochemical ozone formation and human toxicity are reduced by almost 80% when EAF slag is used in asphalt overlays. Ferreira et al. [19] conducted a similar analysis and emphasized the variability of results depending on the chemical and physical properties of EAF slags, while the authors concluded that the use of EAF slags in road construction could bring significant environmental benefits. Finally, Esther et al. [20] investigated the environmental impact of replacing virgin aggregates with EAF slag by considering different methods of EAF slag distribution, aggregate moisture content and transportation distance. The results showed that both aggregate absorption rate and moisture content are of great importance and that EAF slag can replace natural aggregates even when transported up to 144 km from the asphalt plant.

Overall, several studies have demonstrated the suitability of granulated EAF slag aggregates for use in asphalt surface courses and have shown that asphalt mixtures containing granulated EAF slag aggregates perform as well or even better than conventional asphalt mixtures, while also highlighting the environmental benefits of using EAF slag for surface course construction. Research seems to be mainly focused on investigating the rutting and cracking resistance, fatigue life and stiffness modulus of asphalt mixtures with EAF aggregates through laboratory tests [10,11,15,16], which indicates the gap in knowledge regarding the performance of these mixtures under real conditions. Therefore, this paper presents an overall evaluation of asphalt mixtures with granulated EAF slag aggregates compared to those with virgin aggregates to show their feasibility in terms of mechanical, functional and environmental properties. The study consists of three parts: (1) laboratory procedures for the comparative description of the mechanical properties of asphalt mixtures containing granulated EAF slag aggregates and conventional asphalt mixtures, (2) field tests on asphalt pavements of two different flexible pavements differing by the asphalt mixture of the surface course, i.e., with or without granulated EAF slag aggregates, and (3) a comparative environmental analysis using the life cycle assessment

(LCA) tool to justify the environmental footprint of using granulated EAF slag as aggregate instead of VA in asphalt surface courses. The materials used and the individual parts of the research methodology are described in detail in the following sections.

2. Materials and Methods

2.1. Materials

Two types of asphalt mixtures are considered for this study: Mixture A and mixture B. Mixture A is a conventional asphalt mixture containing VA and modified bitumen, and mixture B is an asphalt mixture containing VA and EAF aggregates in the ratio of 30:70 of the total aggregate mixture and modified bitumen. Both mixtures are semi-open graded asphalt mixtures for surface courses, in order to meet the skid resistance and drainage capacity requirements of the road. Table 1 shows the volumetric properties of the individual mixtures.

Table 1. Volumetric properties of mixtures A and B.

Properties	Standard	Mixture A	Mixture B
Bulk density (kg/m^3)	EN 12697-6 [21]	2395	2605
Maximum density (kg/m^3)	EN 12697-5 [22]	2670	2924
Void content (%)	EN 12697-8 [23]	10.3	10.9

As far as the asphalt binder is concerned, mixes A and B contain 4.30% and 4.40% bitumen, respectively, by weight of the asphalt mix. The binder used for both mixtures is a polymer-modified bitumen (PMB), the properties of which are listed in Table 2. The aggregates used for VA are 11–16 mm and 4–11 mm gabbro aggregates from a quarry and for EAF 11–16 mm and 4–11 mm electrical steel slag from a metal recycling plant. In addition, both aggregate mixtures contain limestone sand 0–4 mm. Table 3 shows the composition of the aggregates contained in mixes A and B and their respective properties, including bulk density and water absorption according to the EN 1097-6 standard [24]. Table 4 also shows the gradation for each aggregate mix, while Figure 1 shows the respective grain size distributions.

Table 2. Properties of PMB.

Properties	Standard	PMB
Penetration at 25 °C (pen)	EN 1426 [25]	25/55
Softening point (°C)	EN 1427 [26]	70

Table 3. Aggregate mixture properties per material type.

Materials	Aggregate Mixture A	Aggregate Mixture B	Bulk Density (kg/m^3)	Water Absorption (%)
Gabbro 11–16 mm	10%	-	2957	0.790
Gabbro 4–11 mm	60%	-	2955	1.039
EAF 11–16 mm	-	10%	3442	1.644
EAF 4–11 mm	-	60%	3418	1.990
Sand 0–4 mm	30%	30%	2710	1.150
Aggregate mixture A			2877	1.036
Aggregate mixture B			3172	1.605

Table 4. Sieve analysis for aggregate mixtures A and B.

No Sieve	Passing Percentage	
	Aggregate Mixture A	Aggregate Mixture B
40	100	100
31.5	100	100
20	100	100
12.5	92.6	91
10	70.5	69.5
4	30.4	30.4
2	22.7	23.2
1	15.1	15.5
0.25	5.9	6.2
0.063	3.1	3.1

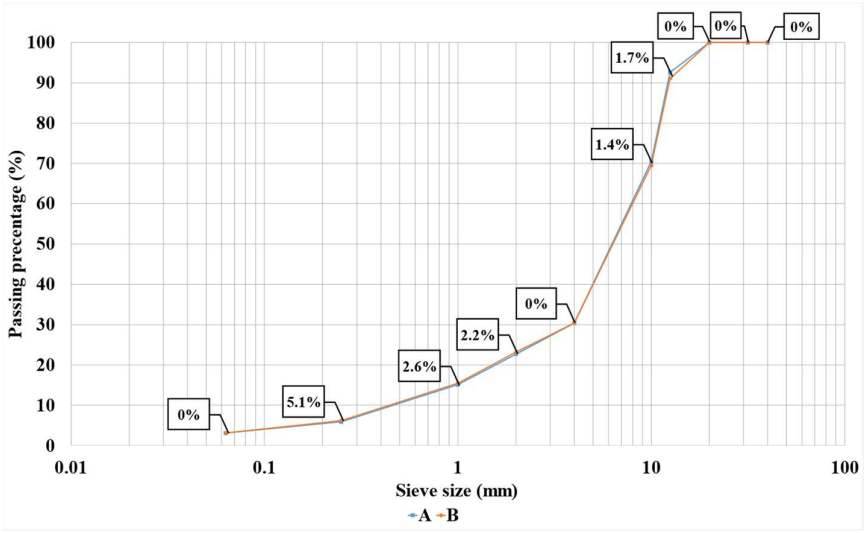


Figure 1. Grain size distribution of aggregate mixture contained in asphalt mixtures A and B.

Figure 1 also shows the percentage difference in the gradation of aggregate mix B compared to aggregate mix A for each sieve size. The two grain size distributions are almost identical, with the largest deviation of 5.1% for the 0.25 mm sieve.

2.2. Methods

2.2.1. Laboratory Testing

The first part of the current research is the laboratory tests to investigate the mechanical properties of the asphalt mixtures under investigation. The laboratory program includes the determination of the indirect tensile stiffness modulus (ITSM) at 15, 20 and 25 °C based on the EN 12697-26—Annex C [27] standard for cylindrical specimens and the determination of the susceptibility to deformation of asphalt mixtures under wheel track load based on the EN 12697-22 [28] standard.

In particular, eighteen (18) specimens were prepared from each mix, A and B, and tested at each of the mentioned temperatures. During the ITSM test, a load was applied along the vertical diameter of the specimen, creating an indirect tension along the horizontal diameter. By measuring the horizontal deformation during the loading cycle and knowing the respective initial load, the stiffness modulus of each specimen was measured. The characteristic stiffness modulus for each mixture, i.e., A and B, at each temperature was calculated as the average of all eighteen measured values.

For the second laboratory test, two (2) test specimens were made from each asphalt mixture and compacted in quadrangular molds. During the test, a loaded wheel was repeatedly driven over the surface of each specimen at a constant temperature of approximately

60 °C and the tester continuously recorded the rut formed. The test procedure ends after 20,000 wheel passes or when the rut depth is 20 mm. The result of the test is the average of the rut depth formed on each two-piece sample.

2.2.2. In Situ Testing

The second part of this study deals with the evaluation of the mechanical and functional performance of the investigated mixtures used for the construction of asphalt surface courses on two different highway sections in southern Europe. The first section is 5 km long and is part of an urban highway with three lanes in each direction that has been rehabilitated. The second section is 2 km long and is part of a rural highway with two lanes in each direction that was built about 10 years ago. The specific highway sections were selected on the condition that the surface course for both was constructed with mix A on the first half and mix B on the second half. In both sections, the thickness of the asphalt layers and base layer ranges from 17 to 19 cm and from 26 to 30 cm, respectively, based on ground-penetrating radar (GPR) measurements.

Deflection data were used to assess the structural condition of the two highway sections. These data were collected using a falling weight deflectometer (FWD). The in situ functional properties of mixes A and B were evaluated using skid resistance data collected with a Grip Tester system. This procedure was only carried out on the rural highway, as the urban highway had only recently been rehabilitated and the field tests concentrated on evaluating the pavement properties. In situ testing procedures were carried out as part of the planned pavement condition monitoring program. Thus, the data for the urban highway were collected shortly after its rehabilitation, while the data for the rural highway used in this study were collected during a 10-year monitoring period. Therefore, the period labeled "Year 0" refers to data collected shortly after construction, and the period labeled "Year 9" refers to data collected 10 years after construction.

In FWD, a dynamic load of 50 kN is applied to the pavement surface via a load plate, and the resulting deflections in the right wheel path of the heavy-duty lane are recorded by a nine-sensor system at various distances from the center of the load plate, as shown in Figure 2. The load was applied at 200 m intervals on both highways, while the temperature of the asphalt layers was measured by drilling holes during the test.

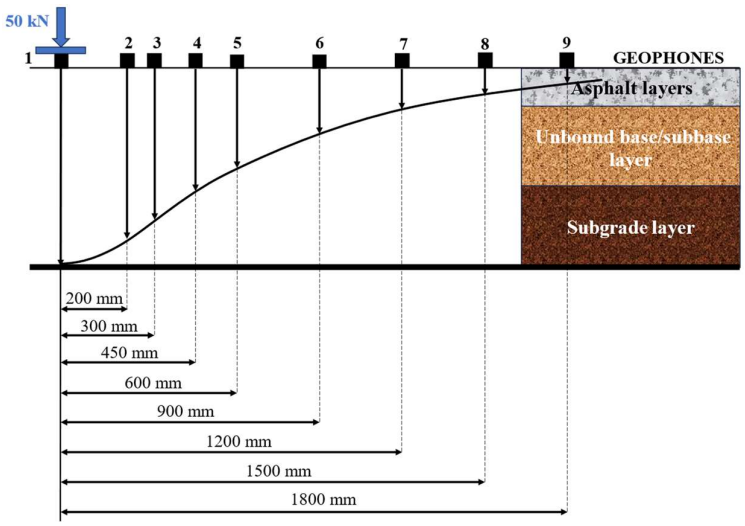


Figure 2. Schematic FWD configuration.

For the structural assessment of asphalt surface courses, the surface curvature index (SCI) is calculated at each interval point of investigated pavement sections using Equation (1):

$$SCI = D_0 - D_{300} \quad (1)$$

where

D_0 is the deflection measured under the loading plate (Geophone 1).

D_{300} is the deflection measured at the radial distance of 300 mm (Geophone 3).

Following Hakim and Brown [29], it is assumed that SCI values below 90 correspond to a good structural condition of asphalt layers.

The Grip Tester (GT) system used is a friction measurement trailer that uses a fixed slip wheel to simulate the anti-lock braking system on wet roads. It consists of a three-wheel system, including a test wheel with a smooth tread tire [30]. The slip of the test wheel is fixed at 14% while the GT is moving at a speed of about 50 km/h. To ensure wet road conditions, the GT's watering system creates a constant water film depth of 0.5 mm on the test wheel. While driving, the GT system reports an average index of skid resistance measurements, the grip number (GN), which for this study is measured at 10 m intervals and ranges from 0 to 1. Higher GN values correspond to increased friction of the pavement surface. The GN measurements were taken along the outer wheel path of the heavy-duty lane of the pavement sections studied.

2.2.3. Life Cycle Assessment

Life cycle assessment (LCA) is a commonly used tool that allows decision makers to thoroughly identify and evaluate the environmental impacts and their influence on social aspects of infrastructure pavement systems throughout their life cycle [31]. The LCA methodology is based on ISO requirements [32] and essentially consists of four steps: (1) goal and scope definition, which concern the reason for conducting the study and provides a description of the system under study in terms of its boundaries and functional unit, (2) life cycle inventory (LCI), which captures and quantifies the inputs and outputs of the system under study during the life cycle stages, including the boundary system, (3) life cycle impact assessment (LCIA), which is the quantification of the environmental impacts caused by the resource consumption and emissions identified in the LCI, including a prior compilation of impact categories and indicators and (4) interpretation, in which the results of the previous phases are analyzed and evaluated in terms of significance, variability and quality, while conclusions and recommendations for the improvement or modification of the system under study are included with respect to the objective of the study [33].

For the current research, the goal of the LCA study is the environmental assessment of two types of asphalt mixtures containing virgin and recycled aggregates—EAF slags—respectively, previously analyzed in terms of mechanical and functional performance through laboratory and in-situ testing. By comparing their environmental performance, this study aims to demonstrate potential environmental benefits of using recycled aggregates instead of conventional ones in pavement construction.

Considering that the main difference between the tested mixtures is the type of aggregate included, the following LCA is a cradle-to-gate approach, which includes the comparison of the environmental footprint of the production process of virgin and EAF aggregates. Specifically, this approach for the VA production process includes VA extraction, transportation of the extracted material to the crushing plant and VA processing in the crushing plant, including screening and crushing into finer fractions. EAF slag is produced in electric furnaces where the temperature is raised to 1640–1670 °C, melting the iron scrap (smelting process). During the melting process, the additives combine with the non-metallic components of the scrap iron and the elements that are incompatible with the selected steel grade to form the EAF slag. Due to its lower specific weight, the EAF slag floats and flows into a specially equipped area at the end of the casting process, where it cools down. The EAF slag is then transported to the crushing plant where it is screened and crushed into the desired fractions, with magnetic iron separation also taking place in each process. This approach therefore includes the generation of electricity and fuel for the production of slag aggregates in the EAF of the steel industry, the transportation of the steel slag to the crushing plant and the screening and crushing of the slag into finer fractions. The system boundaries of the two processes are shown in Figures 3 and 4. A

lorry of 16–32 tonnes, EURO 4, was used to transport the raw materials in both production processes and a distance of 1 km was considered, while the crushing plant is powered by electricity in both cases. Finally, 1 tonne of aggregates, VA or EAF was defined as a functional unit.

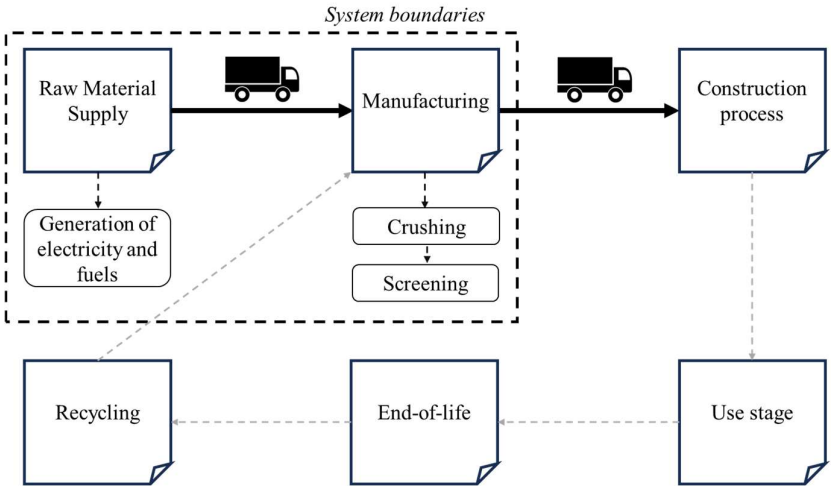


Figure 3. LCA system boundaries for EAF slag production process.

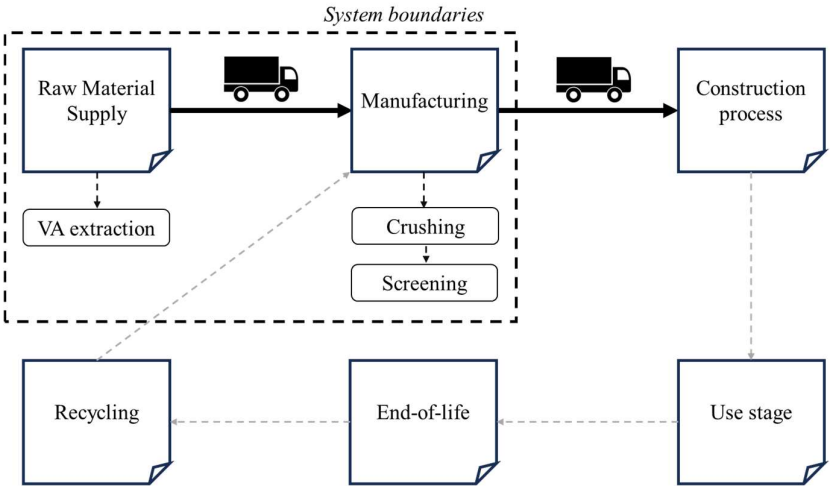


Figure 4. LCA system boundaries for VA production process.

The inventory data used for the environmental assessment of EAF slag production were supplied by the steel slag recycling company. Accordingly, the data connected to the VA production were based on the Environmental Footprint v.2.0 database [34]. All inputs and outputs were developed using the openLCA v.2.2 software [35], while the LCIA process was performed using the method of environmental footprint (mid-point). This method transforms the inputs and outputs of the LCIA phase into the following main impact indicators:

- Acidification (mol H+ eq);
- Climate change (kg CO_2 eq);
- Eutrophication, marine (kg N eq);
- Eutrophication, freshwater (kg P eq);
- Eutrophication, terrestrial (mol N eq);
- Ozone depletion (kg CFC11 eq);
- Photochemical ozone formation—human health (kg NMVOC eq);
- Resource use, fossils (MJ);
- Resource use, minerals and metals (kg Sb eq);

- Water use (m^3 depriv.).

During this step, the impact quantification value of each impact category is calculated using Equation (2):

$$\text{Impact category indicator}_i = \sum (E_j \text{ or } R_j) \times CF_{i,j} \quad (2)$$

where

The impact category indicator is the quantification value for each impact category (i) per 1 tn of aggregates (functional unit).

E_j or R_j is emission j, e.g., CO_2 (kg), CH_4 (kg), SO_2 (kg), NO_2 (kg), or resource consumption j, e.g., crude oil, metal, ground water, per 1 tn of aggregates (functional unit).

CF_{ij} is the characterization factor that represents the contribution of emission j or resource consumption j to impact category i. For example, the contribution of NO_2 to the impact category of acidification is expressed as 0.74 mol H+ eq/kg NO_2.

The values of E_j or R_j and CF_{ij} for each procedure included in the production of virgin and EAF aggregates are the inputs of the LCA process provided by the Environmental Footprint v2.0 database and the recycling plant, respectively. Accordingly, the values of each impact category indicator are the outputs of the LCA process.

The final step involves the LCA results based on LCI and LCIA phases, which are presented in the following section along with the comparative analysis of the environmental impact profile of each aggregate production process.

3. Results and Discussion

3.1. Laboratory Testing

3.1.1. ITSM Results

The ITSM for eighteen specimens produced from each examined asphalt mixture, A and B, was determined according to the standard EN 12697-26 [27]. Then, the stiffness modulus for mixtures A and B was estimated as an average of all 18 ITSM values at 15, 20 and 25 °C, respectively. In Figure 5, box plots illustrate the range of measured ITSM values for mixtures A and B at each temperature, while the center line of each box represents the average of ITSM values, namely the stiffness modulus of mixtures A and B.

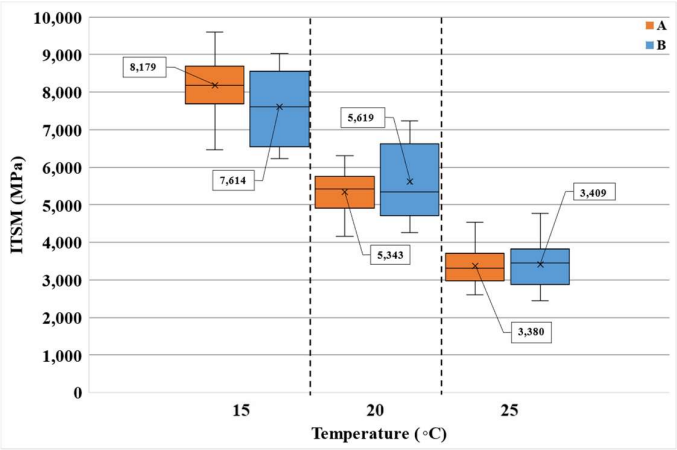


Figure 5. Measured ITSM values for mixtures A and B at 15, 20 and 25 °C.

Figure 5 shows that the stiffness modulus of asphalt mixtures containing EAF aggregates (mixture B) exhibits greater variation at each temperature, as each box plot has a greater height, indicating that mixture B is less homogeneous than mixture A, which contains only VA. It can also be observed that these fluctuations become smaller at higher temperatures. Although the mean values of the ITSM, i.e., the stiffness modulus of mixtures A and B, are similar at all temperatures, mixture B has a slightly higher stiffness modulus

than mixture A at 20 and 25 °C. These observations can also be confirmed by Figure 6, which shows the stiffness behavior of mixtures A and B with temperature changes.

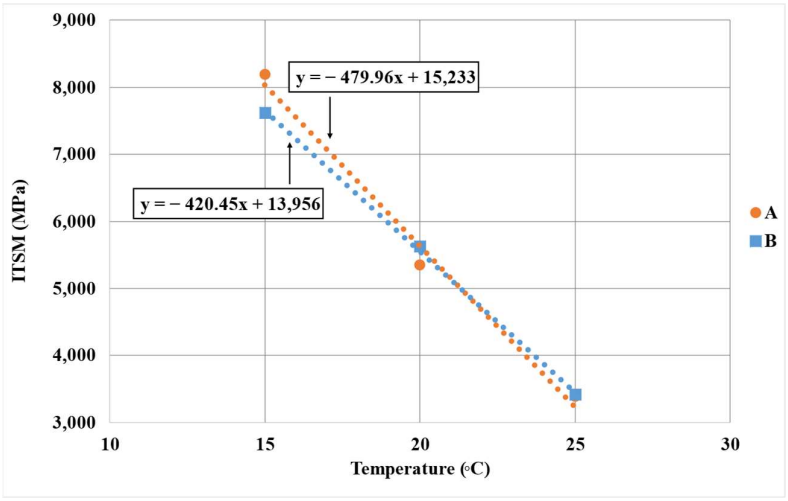


Figure 6. Stiffness behavior of mixtures A and B regarding temperature.

According to the slopes shown in Figure 6, mixtures A and B show similar mechanical behavior due to the temperature change. However, as mentioned above, at higher temperatures, mixture B seems to tend towards higher stiffness values than mixture A, although this is not a significant difference.

3.1.2. Rutting Performance Results

The rutting resistance of mixtures A and B was determined on the basis of standard EN 12697-22 [28]. For each mixture tested, the average of the rut depth of two samples after each wheel pass was considered as a representative value. It is also worth noting that the test procedure reached 20,000 passes for all test specimens. Figure 7 shows the rutting curve for each mixture.

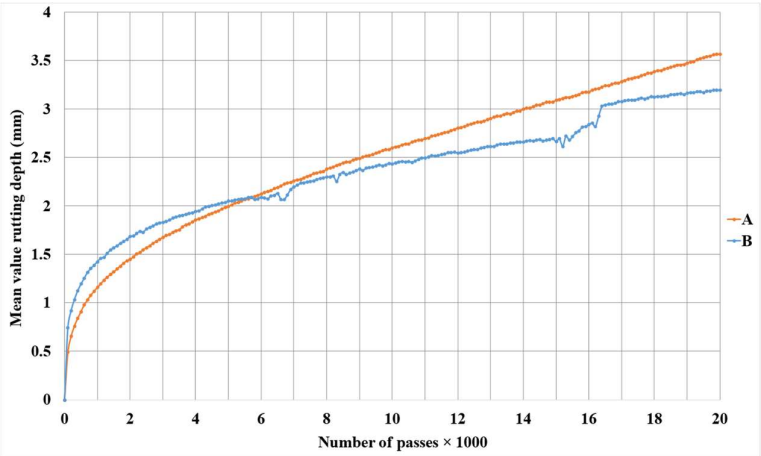


Figure 7. Rutting curve for mixtures A and B.

As can be seen in Figure 7, the asphalt mixture with EAF aggregates (mixture B) exhibits a higher deformation than mixture A in the initial phase of the test. This could be due to the fact that mixture B is less homogenous than mixture A as already mentioned. On the contrary, after almost 6000 wheel passes, the recorded rut depth of mixture B is lower compared to mixture A. It can be also noted that, after 20,000 passes, the rut depths of mixtures A and B are 3.57 and 3.20 mm, respectively. Overall, the rutting curves of both

mixtures have similar trend, showing comparable behavior. However, the rutting curve of mixture has some inconsistent points, which also proves that mixture B is less homogenous compared to mixture A.

3.2. In Situ Testing

3.2.1. FWD Results

FWD measurements were taken along the right lane of both highway pavements. Based on FWD data, SCI indicator was calculated for all intervals of each pavement according to Equation (1). Then, the calculated SCI values were normalized at 20 °C, so that the outputs can be comparable. For the urban highway, in Figure 8, the structural condition of asphalt layers in each pavement section is presented in the form of box plots. The center line of each box indicates the mean values of SCI, which are equal to 25.06 and 24.70 for pavement sections with mixtures A and B, respectively. Both are under the threshold value of 90, suggesting a good structural condition. As can be observed, the structural behavior of asphalt layers containing VA (mixture A) and EAF aggregates (mixture B) is comparable. It is also noted that the range of SCI values for mixture A indicates slightly higher deviation when compared to the respective values for mixture B. This observation is in contrast to the results of the laboratory tests of the mechanical properties of mixtures A and B, as the values of the stiffness modulus for asphalt mixtures with EAF aggregates (mix B) show greater deviations.

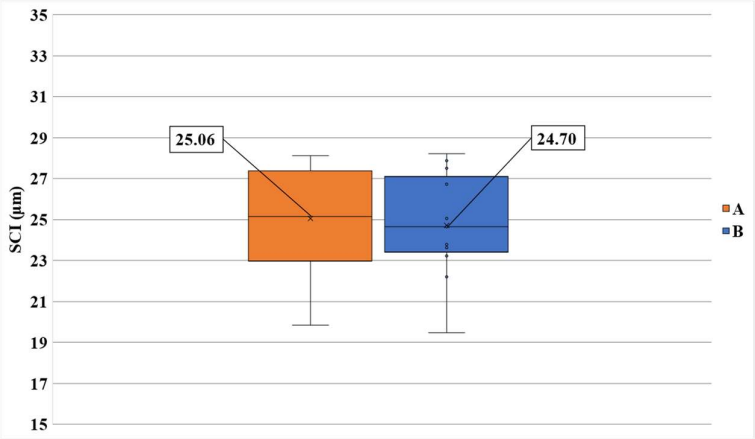


Figure 8. SCI values for asphalt surface courses consisted of mixtures A and B used in urban highway.

For the rural highway, FWD data were collected during a 10-year monitoring period. Figure 9 presents the structural condition of asphalt layers consisting of conventional materials (mixture A) and EAF aggregates (mixture B) for each monitoring year in the form of box plots. The SCI values for each pavement section are represented by the median value of respective data, as the coefficient of variation for all data samples is higher than 10%. Thus, it can be noted that all SCI values, illustrated by the center lines of each box, for both pavement sections are under 90 during the 10-year monitoring program, showing that the asphalt layers containing either conventional or recycled materials perform satisfactorily throughout the years. Comparing the SCI values of asphalt layers containing mixtures A and B in each monitoring year, it can be also stated that both pavement sections have an equal structural condition, as the center lines of the respective boxes are almost at the same level. Typical examples of this observation can be considered the SCI values of the 1st, 4th, 6th and 7th monitoring year. In addition, the data of SCI values for the asphalt layers with EAF aggregates seem to have a lower coefficient of variation than the corresponding data for the asphalt layers with VA in all monitoring periods, indicating that mix B is more homogeneous than mix A under field conditions.

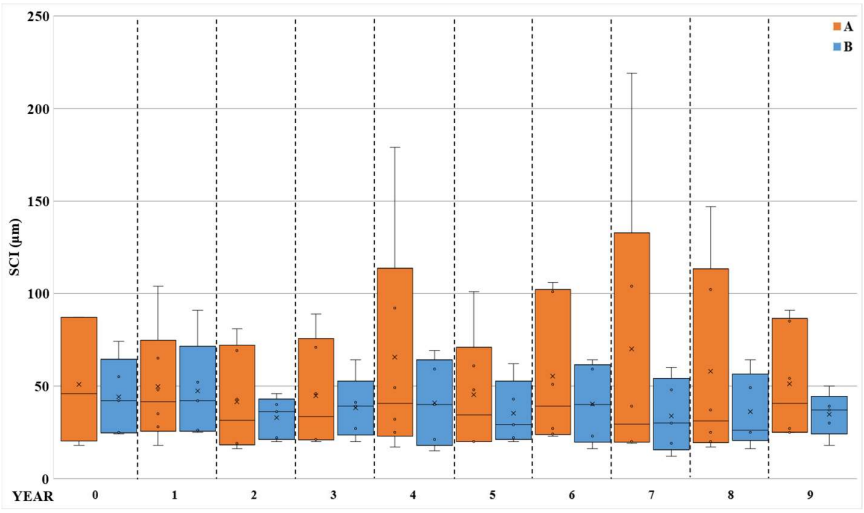


Figure 9. SCI values per year—rural highway.

An overview of the mechanical performance of mixtures A and B in field conditions is also presented in Figure 10 through trendlines for SCI values.

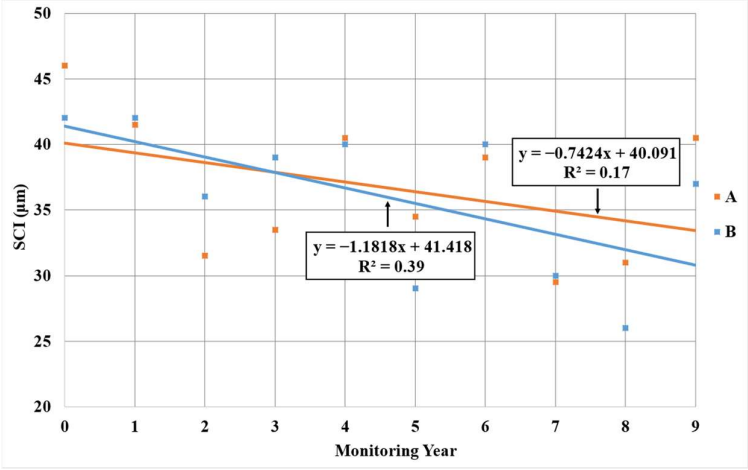


Figure 10. Mechanical performance over time—rural highway.

The trendline for the asphalt courses containing slag aggregates (mixture B) has a steeper slope compared to the trendline of mixture A, which means that asphalt mixtures containing slag aggregates (mixture B) deteriorate faster than conventional asphalt mixtures.

3.2.2. GT Results

Skid resistance data were collected only from the rural pavement sections, as the urban highway has been recently reconstructed and the traffic effect on pavement friction is not apparent yet. In Figure 11, the functional condition of the asphalt layers consisting of mixtures A and B is illustrated in the form of box plots for all monitoring periods. The characteristic value of the GN data sample in each case is considered to be the median value of the whole sample, as the coefficients of variation for GN data of pavement sections containing mixture B are higher than 10% in all monitoring periods except "Year 0", "Year 1" and "Year 3". Overall, according to GN values, it can be stated that pavement sections containing virgin and slag aggregates have the same level of friction in every monitoring period.

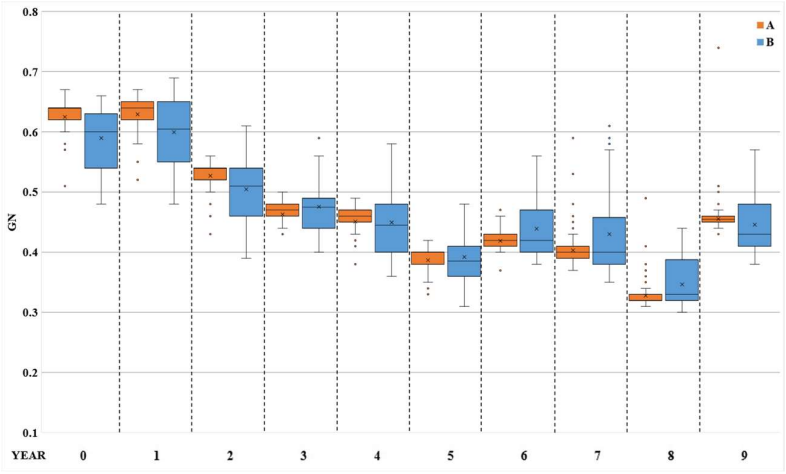


Figure 11. GN values per year—rural highway.

The last observation can be confirmed by Figure 12, in which an overview of the skid resistance of mixtures A and B in field conditions is presented through trendlines for the characteristic values of GN data throughout all monitoring years.

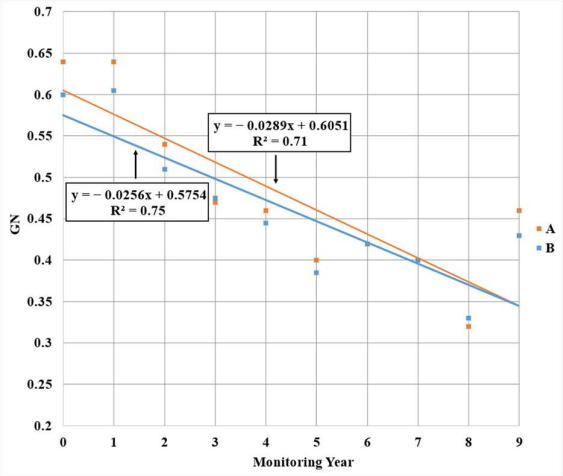


Figure 12. Functional performance over time—rural highway.

Looking at Figure 12, the trendlines for the skid resistance of both mixtures have a similar slope, which indicates comparable behavior in terms of friction over the years. The increase in GN values observed in "Year 9" is due to the heavy rainfall in the last monitoring year. Finally, it should be mentioned that although the Los Angeles (LA) values for virgin and EAF aggregates are not available for this study, they are not likely to provide any important insights into the differences between the asphalt mixtures in terms of skid resistance, as the aggregate requirements for the surface course mixture under consideration are LA < 25 anyway.

3.2.3. LCA Results

Following the LCA, Table 5 includes the LCIA results for the processes included in system boundaries, namely the environmental impact profile for each production process. The value differences for each impact category are also noted. Positive values refer to an increase in the respective impact category for VA production compared to EAF production, while negative values denote the opposite result.

Table 5. Values of each impact category for VA and EAF slag production process.

Impact Category	Unit	VA Production	EAF Production	Value Difference
Acidification	mol H^+ eq	0.03	0.018	+0.014
Climate change	kg CO_2 eq	5.93	4.38	+1.55
Eutrophication, marine	kg N eq	0.011	0.003	+0.008
Eutrophication, freshwater	kg P eq	0.037×10^{-3}	3.6×10^{-3}	−0.0036
Eutrophication, terrestrial	mol N eq	0.12	0.022	+0.1
Ozone depletion	kg CFC11 eq	0.0041×10^{-7}	6.2×10^{-7}	-6.2×10^{-7}
Photochemical ozone formation—human health	kg NMVOC eq	0.031	0.008	+0.02
Resource use, fossils	MJ	74.5	70.9	+3.6
Resource use, minerals and metals	kg Sb eq	0.99×10^{-6}	5.7×10^{-6}	-4.7×10^{-6}
Water use	m^3 depriv.	0.56	1.34	−0.78

Figure 13 illustrates the environmental results of Table 5, showing in which impact categories the EAF slag production process is environmentally superior to VA production. The orange color indicates that conventional materials have a lower value of the measured impact category compared to EAF slag aggregates, while the blue color corresponds to an increased value of the measured impact category for the EAF slag production process.

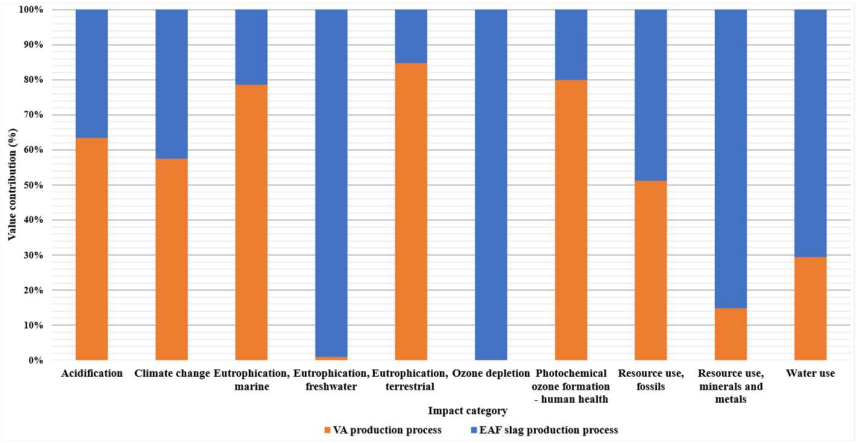


Figure 13. Comparison of the environmental impact profile of VA and EAF slag production process.

Table 5 and Figure 13 show that the values for six of the ten impact categories account for 15 to 50% of the total value for both productions. They are therefore lower for EAF slag production than for VA production. These impact categories are related to acidification, the greenhouse effect, in particular the generation of CO_2 emissions, eutrophication due to nitrogen emissions (marine and terrestrial), photochemical pollution in relation to human health and fossil fuel consumption. It is noteworthy that the value contribution for the impact categories of acidification, climate change and fossil fuel consumption is about 40–50%, indicating that the two processes are almost equivalent in terms of environmental valuation. This can be confirmed by the fact that the main difference between the two processes is the provision of the two materials, EAF slag and VA, prior to production. In addition, the value contribution for the impact categories marine and terrestrial eutrophication and photochemical pollution is significantly lower at up to 20%, which shows that the EAF slag production process mitigates the impact of these environmental phenomena compared to the VA production process. On the other hand, the values for the remaining four pollution categories are higher when comparing the two processes. As shown in Figure 13, the values for the generation of phosphorus emissions (eutrophication), depletion of the ozone layer, water consumption and consumption of minerals and metals are significantly higher in the case of the EAF slag production process. Overall, it appears that the environmental benefits of EAF slag aggregates outweigh those of virgin aggregates, although it should be noted

that EAF aggregates are waste materials that can end up in landfills if not used. Therefore, the production of granulated EAF slag is an environmentally friendly process compared to VA production. In other words, the use of granulated EAF slag instead of VA in asphalt surface courses could be considered a sustainable practice to reduce the environmental footprint of road pavements.

4. Conclusions

The focus of this study was to demonstrate the suitability of asphalt mixtures containing aggregates from EAF slag (mix B) for use in pavement surface courses, considering their mechanical and functional performance based on laboratory and field tests, as well as their environmental compatibility compared to conventional asphalt mixtures (mix A). Therefore, the stiffness modulus of mixes A and B and their rutting resistance were determined in laboratory tests. Both mixtures were also tested under field conditions using structural and functional pavement evaluation methods. In a final step, the environmental impact of each aggregate production process was calculated using an LCA tool. Based on this process, the following conclusions can be drawn:

- Laboratory and in situ tests have shown that asphalt mixtures containing only VA (mix A) and VA with EAF slag as an additive (mix B) exhibit comparable behavior in terms of mechanical and functional properties.
- In general, the mechanical properties of mixtures A and B are equivalent. However, at higher temperatures, mix B has a greater stiffness modulus than mix A.
- In terms of rut resistance, mix B is slightly more susceptible to deformation due to wheel tracking compared to conventional asphalt mix.
- FWD field measurements showed that the pavement sections with EAF aggregates are structurally equivalent to those with VA in both highway sections investigated.
- The skid resistance of sections with EAF aggregate and only A is equally high over a measurement period of ten years.
- The LCA study proves that the use of EAF aggregates instead of VA in asphalt surface courses could reduce the impact of environmental phenomena such as acidification, climate change, eutrophication and photochemical pollution.

All in all, asphalt surface courses with EAF slag aggregate have an equivalent or even better performance in terms of material quality than asphalt surface courses containing only VA. In terms of environmental impact, although there are impact categories such as freshwater eutrophication, water consumption and ozone depletion that are higher in the case of EAF aggregates, these are waste materials used in construction projects and support the Sustainable Development Goals of the United Nations Agenda. The overall evaluation of steel slag asphalt mixtures has therefore shown that the replacement of virgin aggregates with EAF slag aggregates is a viable and sustainable method that can be integrated into road construction. Future research should investigate the weather-related influence of water or increased humidity on the performance of asphalt mixtures with EAF aggregates and, in particular, the seasonal fluctuations in their functional state, as higher water absorption values have been found for EAF aggregates compared to VA. In addition, the crack resistance of asphalt mixtures with EAF aggregates should be considered as a key parameter in the evaluation of these mixtures. As electricity appears to be the main energy source for the provision and production of EAF slag, the potential for electricity generation should be included in the LCA, as well as an assessment of the financial prospects for the use of such materials in surface courses by conducting a life cycle cost analysis (LCCA). It is expected that this approach will be beneficial to the paving industry, especially if an energy crisis is imminent.

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