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Case study

Electric arc furnace slag as aggregates in semi-dense asphalt

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ABSTRACT

Electric Arc Furnace Slag (EAFS) is one of the primary by-products of the steel recycling industry, which comes out initially as large pieces, that can be further crushed and be used as aggregates in infrastructure materials. While being a waste product, the relatively high strength of the aggregates means that EAFS can provide favorable properties when used correctly. One possible destination for EAFS of higher value is semi-dense asphalt (SDA), a surface course used as low-noise pavement. Due to the relatively high percentage of air voids in SDA (10–18%), the mixture mechanical properties depend on strong interlocking of the aggregates. This study looks at the incorporation of EAFS fractions (2/4 and 0.125/2 mm) into SDA 4 mixtures at replacement of 13% by volume of the aggregates. These mixtures are compared to the control mixture with sandstone aggregates in terms of volumetrics, water sensitivity, stiffness modulus and fatigue by cyclic indirect tensile loading, along with permanent deformation by the cyclic compression test. The water sensitivity, rheological properties and fatigue resistance of the EAFS mixtures did not vary significantly from the control. The life cycles assessment (LCA) shows that compared to the reference SDA, the EAFS-modified SDA reduces the greenhouse gas emissions and ecological scarcity eco-points by 40% and 90%, respectively due to the avoidance of EAFS landfilling. However, the non-renewable cumulative energy demand is not improved by using EAFS in SDA, due to the additional consumption of bitumen.

1. Introduction

Slag as a by-product from steel fabrication, has been long employed in construction materials and continues to be, even as the locations of steel fabrication are shifting elsewhere [4]. In places where the fabrication of new steel is being reduced, steel recycling remains a significant part of the industry and source of steel slag production [50]. The two most common types of steel slag are blast furnace slag (BFS) and electric arc furnace slag (EAFS), which are named after the different furnaces that they are sourced from [48]. Among these, BFS is more common, while EAFS, the subject of the current study, remains prevalent and a significant source of industrial waste.

Abbreviations: SDA, Semi-dense asphalt; EAFS, Electric arc furnace slag; PmB, Polymer modified bitumen; VMA, Voids in mineral aggregate; VFB, Voids filled with bitumen; B_{eff}, Effective bitumen content; IT, Indirect tensile; ITS, Indirect tensile strength; ITSR%, Indirect tensile strength ratio; N_f, Number of cycles to failure; LCA, Life cycle assessment; LCI, Life cycle inventory; GHG, Greenhouse gases; CED, Cumulative energy demand.

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EAFS has been found to be a viable aggregate substitute given that its strength is typically at the level of high quality virgin aggregates such as granite [39]. Besides concrete and railroad ballasts, asphalt roads are another potential destination for EAFS being the sixth most produced material in the world by mass [46]. Research conducted on the use of steel slags as aggregates in asphalt mixtures has been more prevalent in the past decade, including with EAFS [53].

EAFS aggregates have high contents of iron, calcium and silica, with smaller amounts of alumina or magnesium [25]. They have shown improved physical properties in terms of higher angularity [43,51], shear strength [53] and fracture resistance relative to virgin aggregates such as limestone [63] and even granite [39]. This makes them more viable relative to other types of waste aggregate replacement such as with recycled concrete. On the other hand, the surface voids formed on these aggregates leads to higher bitumen absorption [29], requiring higher bitumen contents to ensure adequate bitumen coverage of aggregates. However, the bitumen-EAFS interface strength may be enhanced from additional absorbed bitumen [26].

The improved mechanical properties of the aggregates have been show to transfer well in their use in asphalt mixtures. In terms of asphalt durability, studies have found lower stripping [62]. Improved mechanical properties have been found with higher Marshall stability [29,51], resistance to permanent deformation (rutting) [38,43], indirect tensile strength [41,42] (ITS), resilient modulus [63] and skid resistance [24].

Mixed results have been found with fatigue resistance with some authors finding improvement [23,40,51], while other studies finding a decrease in fatigue life [53]. Water sensitivity has also been found to improve in some studies [42] and decreased in others, where a lack of bitumen coverage of the aggregates allowed water to enter, although the resulting water sensitivity ratio was still within minimum specifications [38]. Resistance to low-temperature cracking has been higher when the higher absorbed bitumen by EAFS has been accounted for and [37,59], and lower when it has not been [27].

There have been some issues with post-compaction expansion [23], but on a much smaller level than with BFS. Larger fractions of EAFS have sometimes shown improved properties relative to smaller sizes, such as when asphalt sand is replaced, due to water sensitivity issues with the latter [53], although the finer EAFS was shown to perform better in a different study [1].

To demonstrate the environmental performance with EAFS replacement, several studies conducted life cycle assessment (LCA) to compare the EAFS-modified asphalt pavements with conventional ones. Their results presented significant [12,13,36,58] or negligible [12,18] improvements with various environmental impact factors for using EAFS. This difference can be explained by the mix design, hauling distance, the categories of impact factors, and the considerations of avoided process (such as landfilling). In addition, leaching from the aggregates to the environment has not been found to be a significant issue [61], with the bitumen immobilizing the metals from EAFS [35]. A potential added value for EAFS is the microwave healing potential, from the improved response to microwave energy [17,19,27].

SDA is a low-noise mixture used in several European countries with its porosity limited to 12–18% (SN 640 436 [56]). It is designed to be more durable compared to porous asphalt (voids >20%), while retaining the benefits of low-noise and reduction of aquaplaning [33]. The finely graded SDA 4 (nominal maximum aggregate size of 4 mm) has been shown to have improved acoustic performance compared to the coarser SDA 8 [2]. Due to the elevated amount of air voids compared to conventional mixture, the aggregates are generally high quality and expensive, making the use of steel slag a promising alternative to reduce the cost and improve the environmental footprint [44] of SDA.

Based on the evidence of improved mechanical performance of asphalt mixtures with EAFS slag replacement, especially with regards to porous mixtures [42,43] which have higher aggregate performance requirements, along with the potential benefits of reducing landfill waste, the current study examines EAFS replacement in semi-dense asphalt (SDA). EAFS fractions (0.125/2, 2/4 mm) were utilized as replacement for virgin aggregates in SDA 4 at 13% replacement by volume of the total aggregates. The durability and mechanical properties of these mixtures were evaluated according to water sensitivity, indirect tensile (IT) stiffness modulus and IT fatigue resistance [57]. Additionally, the environmental impact of employing the EAFS in SDA is evaluated through life cycle assessment (LCA).

2. Experimental

2.1. Materials

2.1.1. Aggregates

The control aggregates were sandstone from Massongex, Switzerland (FAMSA), complying with the performance requirements for SDA by Swiss standards (SN 640 436 [56]). The EAFS were provided by the Gerlafingen AG steel recycling plant in Gerlafingen, Switzerland. The initial 0/10 mm batch was sieved into 2/4 mm and 0.125/2 mm fractions and their volumetric properties were determined according to EN 1097–6 [5] (Table 1), where the slag is expectedly much more dense than the control sandstone.

Table 1
Properties of aggregates (%WA_{24} =24 h water absorption using EN 1097–6 [5]).

Aggregate fraction	Apparent Density (kg/m^3)	Bulk Density (kg/m^3)	WA_{24} (%)
Control 0.1/4 mm	2699	2657	0.57
Control 2/4 mm	2711	2647	0.89
EAFS 0.125/2 mm	3414	3012	3.91
EAFS 2/4 mm	3432	3050	3.64

Furthermore, the water absorption (%WA_{24}) is significantly higher than the control aggregates due to higher porosity.Fig. 1.

2.1.2. Bitumen

SBS (styrene–butadiene–styrene) polymer modified bitumen (PmB) graded at 45/80 – 65 according to EN 1426 [65] was used for the bitumen as required for the SDA mixtures (SN 640 436 [56]).

2.1.3. Semi-dense asphalt mixtures

The SDA mixture was a 4–12 according to the gradation prescribed in SN 640 436 [56], having a 4 mm nominal maximum aggregate size and 12 ± 2% air void content. In addition to the control mixture, two mixtures we produced with 13% replacement by volume (14.4% by mass) of aggregates of 2/4 mm and 0.125/2 mm EAFS fractions. This content was chosen from previous experience with waste aggregate replacement in SDA [34], in replacing enough to observe the effects of the EAFS, but not so much as to require much additional bitumen. As showin in Fig. 2, the gradations were very similar with the replacement. The bitumen was added based on the comparative water absorption of the aggregates in Table 1, with additional bitumen added (0.79% for both) with the goal of getting the same effective bitumen content as for the control mixture. This was based on a relationship established between the aggregate % WA_{24} and the absorbed bitumen for a similar mixture [32]. The filler content of the EAFS mixtures was lower due to a higher content of fines in their respective control aggregate fractions.

The mixtures were prepared at 170 °C as specified for the bitumen and the maximum density (ρ_m) of the resulting mixtures was determined according to EN 12697–5 [6]. The asphalt samples were compacted using gyratory compaction at 155 °C. The samples were compacted to a diameter of 99.5 ± 0.5 mm and a height of 62 ± 2 mm (stiffness modulus/fatigue tests) or 64 ± 2 mm (water sensitivity test). For the stiffness modulus and fatigue tests, about 10 mm were cut from the top and bottom of the samples, bringing their height to 42 ± 2 mm. The bulk density (ρ_b) and air voids (V_m) of the compacted samples were then determined geometrically according to EN 12697–29 [11] and EN 12697–8 [7] as in Eq. 1:

$$V_m = \frac{\rho_m - \rho_b}{\rho_m} \tag{1}$$

Further volumetrics were calculated according to EN 12697–8 [7] and Superpave volumetrics [30], including the voids in mineral aggregate (VMA), the voids filled with bitumen (VFB) along with an estimation of the volume of absorbed (B_{abs}) and effective (B_{eff}) bitumen content. The *VMA* was calculated based on Eq. 2:

$$VMA = V_m + B\frac{\rho_b}{\rho_B} \tag{2}$$

Where B is the bitumen content for the mixture and ρ_B is the bitumen density. The *VFB* was calculated according to Eq. 3:

$$VFB = \frac{B\frac{\rho_b}{\rho_B}}{VMA} \times 100\% \tag{3}$$

The B_{abs} and B_{eff} are calculated as follows in Eqs. 4 and 5:

$$B_{abs} = \rho_B\frac{\rho_{eff} - \rho_b}{\rho_{eff} \times \rho_b} \times 100\% \tag{4}$$

$$B_{eff} = B - \frac{B_{abs} \times A}{100} \tag{5}$$

Fig. 1. EAFS from 2/4 mm fraction (left) and 0.1/2 mm fraction (right).

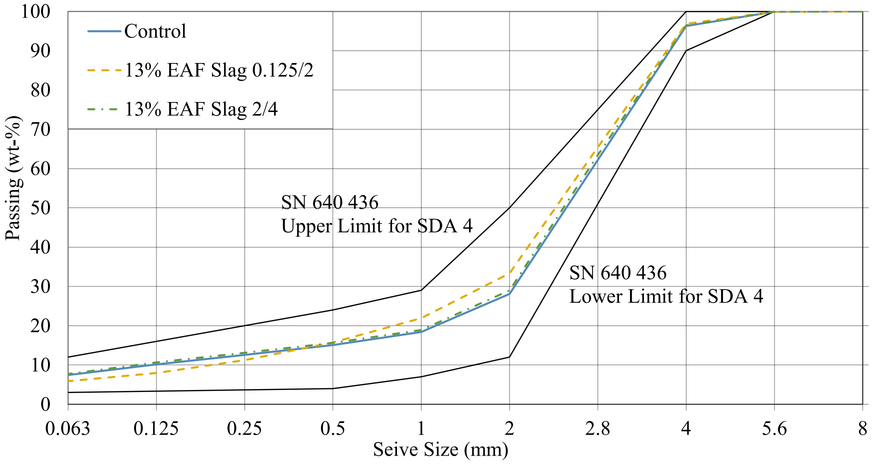

Fig. 2. Gradation curves for SDA 4 mixtures according to SN 640 436 [56].

Where ρ_{eff} is the effective density of the mixture [30] and A is the aggregate content of the mixture.

2.2. Testing

2.2.1. Water sensitivity and indirect tensile strength

The IT strength and water sensitivity were determined according to EN 12697–12 [8] (Fig. 3). Three samples were tested after dry (at 25 °C.) and wet (70 ± 2 h at 40 °C in water) conditioning. After loading, the IT strength (ITS_{max}) was calculated based on Eq. 6:

$$ITS_{\max} = \frac{2P_{\max}}{\pi dt} \tag{6}$$

Where P is the maximum force to failure, t is the thickness of the sample, and d is the diameter. The indirect tensile strength ratio ($ITSR$ %) was calculated as in Eq. 7, where ITS_{wet} and ITS_{dry} are average ITS values for three samples after the respective conditioning.

$$ITSR\% = 100\%x\frac{ITS_{wet}}{ITS_{dry}} \tag{7}$$

2.2.2. Indirect tensile (IT) stiffness modulus

The IT stiffness modulus was tested according to the TP Asphalt-StB Part 25 B 1 [57] the guidelines established by the German Road and Transportation Research Association, using the setup with sinusoidal cyclic loading [14]. This test (Fig. 4) is very similar to IT-CY defined in EN 12697–26 [10]. The horizontal deformation was measured by linear variable differential transducer sensors (LVDTs) on either side of the sample. The sinusoidal loading frequencies were 0.1, 1 and 10 Hz conducted at temperatures of 5, 10 and 15 °C (conditioned for 4 h). First, the load amplitude required for 75 με deformation for each mixture at each temperature and frequency was determined. Subsequently, the testing was conducted on four specimens per mixture. The horizontal stress (σ) is calculated from Eq. 8:

Fig. 3. Water sensitivity testing (EN 12697–12) including the water bath (left) and IT loading frame (right).

Fig. 4. IT setup for stiffness modulus and fatigue testing (TP Asphalt-StB Part 25 B 1 [57]), including sample and loading frame in climate-control chamber.

$$\sigma = \frac{2F}{\pi \times d \times h} \tag{8}$$

Where F is the peak load, h is the sample height and d is the sample diameter. From the stress, the stiffness modulus ($|E|$) of the samples could be calculated according to Eq. 9:

$$|E| = \frac{\Delta F \times (0.274 + \mu)}{h \times \Delta u} \tag{9}$$

Where ΔF is the difference between maximal and minimal force from the sinusoidal loading, μ is the Poisson ratio of the material at the temperature (0.239 for 10.0 °C from [14], h is the sample height and Δu the difference between the maximal and minimal displacement.

After attaining the stiffness modulus at each temperature/ frequency, the Master curves were built along a reduced frequency axis with the Christensen- Anderson-Marasteanu (CAM) model [28]. The William-Landel-Ferry equation [60] was employed for the shift factor around a reference temperature of 10 °C. Additionally, the phase angle was plotted for the different frequencies and temperatures.

2.2.3. *Fatigue resistance*

The fatigue resistance of the samples was tested according to TP Asphalt-StB Part 25 B 1 [57], using the IT setup (Fig. 4) as for the stiffness modulus, with cyclic, sinusoidal, stress-controlled loading. The mixtures were tested at three stresses between 20,000–1000,

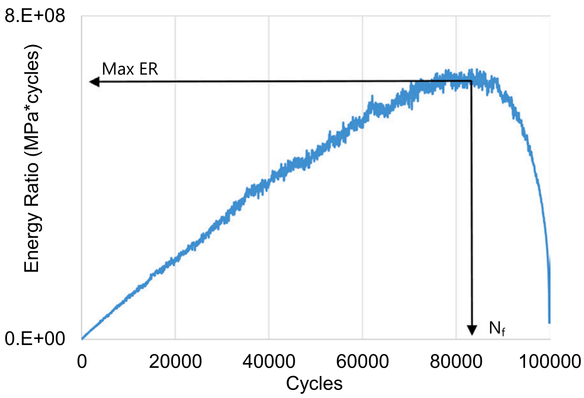

Fig. 5. Energy ratio (ER) and finding Nf for typical fatigue test [31].

000 cycles of fatigue life, with 3 samples for each stress level per mixture.

The failure criteria was based on the "Energy Ratio" (ER), taken as the stiffness modulus (see previous section) multiplied by the number of cycles ($|E|*N$). The failure (N_f) is taken at the number of cycles where the *ER* has reached its maximum (Fig. 5). The initial strain level (average from 98th to 102nd cycle) corresponding to 1 000 000 cycles (ε_6) was determined by plotting log N_f versus the log of the initial strain level ($log\ \varepsilon_{ini}$). This test is very similar to the EN 12697–24 [9] IT-CY. The main difference is the failure criteria; *ER* results in similar number of cycles to failure as the $N_{f50\%}$, the number of cycles to reach modulus values equivalent to 50% of initial modulus, defined in EN 12697–24 [9].

3. Environmental analysis

Life cycle assessment (LCA) is a frequently applied method to demonstrate the environmental feasibility of asphalt pavements, which quantifies the environmental impacts along the whole value chain [20,45]. Previous research by the authors [47] has conducted LCA to evaluate the greenhouse gases (GHG) emissions and non-renewable cumulative energy demand (CED) of SDA with waste polyethylene (PE) and EAFS modifications. Since Piao et al. [47] includes the treatment of waste PE in LCA, the results cannot be used directly in the current study, which only compares the use of natural aggregates and EAFS in SDA. Therefore, this paper considers the life cycle inventory (LCI) data of Piao et al. [47] but excludes waste PE. Furthermore, in addition to GHG and CED, this study also calculates ecological scarcity eco-point, which weighs and integrates different impact categories into one indicator using a "distance-to-political target" approach [16].

According to the standards (ISO 14040 [21]; ISO 14044 [22]), this LCA follows the four steps which are (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. In the first step, a reference SDA scenario that includes no waste materials and a test scenario that includes EAFS were considered. The functional unit (FU) was defined as an SDA surface with a length of 1 km, width of 7.5 m, and thickness of 30 mm, for a daily traffic load of 300–1000 equivalent single axle loads (ESAL) under the average climate conditions in Switzerland. The thickness was determined according to the Swiss standard SN 640 430c [55], considering the defined traffic load and climate condition for SDA. Based on the results of mechanical testing (Section 4.1.1), we assume that both the reference and EAFS-modified SDAs can satisfy the requirements of SNR 640 436 [56] and have the same service life of 10 years. Thus, the thickness of the reference SDA (30 mm) can be applied to the EAFS-modified SDA. According to the volumetric results in Table 3, and considering the fact that the replacement was volumetric, we also assume the same bulk density (2.1 metric ton/m^3) for all the SDA scenarios. The analyzed processes include raw materials production (natural aggregates, polymer-modified PmB, asphalt mixing, road construction, demolition, and landfilling of EAFS. For the test scenario, 95% of EAFS is processed to replace the natural aggregates for SDA, 5% of EAFS is landfilled due to high levels of impurities. At the end of its service life, after demolition the reclaimed asphalt pavement (RAP) from all scenarios is assumed to be fully recyclable, thus RAP is considered burden free in this analysis.

In the second step of LCA, the LCI data is based on Piao et al. (2022). Specifically, the amounts of asphalt mixtures are calculated from the bulk density (2.1 metric ton/m^3) and road dimensions (1 km x 7.5 m x 30 mm). The quantities of natural aggregates, PmB, and EAFS are determined by the mix design in Table 2. To process 1 t of EAFS for SDA, it requires 0.25 m^3 of water, 1 L of diesel, 0.5 kWh of electricity, and a processing machine with weighing 150 t (25 service years with an annual processing capacity of 100’000 t). The asphalt mixing consumes 216 MJ of natural gas and 8.6 kWh of electricity for 1 t of mixtures. The construction and demolition processes consume 34.1 and 16.3 MJ of diesel per metric ton of mixtures respectively, including the use of generators, material transfer vehicles, paving and milling machines. The transportation distances from the suppliers of natural aggregates, PmB, and EAFS to the mixing plant are assumed as 50, 100, and 50 km, respectively. The distance between the mixing plant and paving site, and the distance between the EAFS supplier and landfilling site, are estimated for the Swiss conditions and are both assumed as 50 km. The lorry for transportation has a loading capacity of 25 t and total weight of 40 t. The LCI data for producing natural aggregates, electricity, natural gas, diesel, processing machine, along with lorry transportation and EAFS landfilling, are obtained from the ecoinvent database (version 3.8, cut-off). More details of the inventory data are explained in Piao et al. [47].

In the third step, the life cycle impact assessment (LCIA) considers the mid-point indicators of GHG emissions and non-renewable CED, and the end-point indicator of ecological scarcity eco-point. The software Simapro (version 9.1) is used to perform all the modeling.

Table 2
Asphalt mixture designs by % mass.

Mixture	Control Fraction %			EAFS %		Bitumen %
	2/4	0.1/4	Filler	2/4	0.1/2	PmB
Control	62.8	23.8	7.2	—	—	6.10
EAFS 2/4	49.5	26.9	2.4	14.4	—	6.89
EAFS 0.125/2	63.8	12.5	2.4	—	14.4	6.89

Table 3
Volumetric properties of mixtures.

Sample	ρ_b (kg/m^3)	Voids %	VMA %	VFB %	B_{abs} %	B_{eff} %
Control	2142.2	12.8	24.3	47.4	0.6	5.5
13% EAF Slag 0.125/2	2117.2	13.8	27.0	45.1	1.0	5.9
13% EAF Slag 2/4	2095.9	13.6	28.1	43.5	0.9	6.0

4. Results and discussion

4.1. Volumetrics

The volumetrics (EN 12697–8 [7]) of the samples are shown in Table 3 based on the average of ten samples per mixture. The VMA is a measure of the intergranular void space in the compacted mixture and was higher for the EAFS mixtures. This is likely related to the somewhat higher effective bitumen content/bitumen film [52] of the EAFS mixtures, as the absorbed bitumen content was less than expected base on the relative water absorption. The absorbed bitumen of the EAFS mixtures was only 0.3–0.4% higher than for the control, and higher than what was estimated based on the difference in water absorption between the EAFS and control aggregates.

4.2. Water sensitivity and indirect tensile strength

The IT strength and water sensitivity results are shown in Fig. 6. The water sensitivity % is very similar for all of the mixtures and well above the 70% minimum prescribed by Swiss standards for SDA (SN 640 431–1c-NA [54]). In terms of the absolute ITS values, they were higher for the EAFS mixtures, which corresponds to the higher strength and angularity of the EAFS reported in the literature [53].

4.3. Stiffness modulus

The results of the IT stiffness results are presented though Master curves (Fig. 7) and the phase angle (Figs. 8–8). The Master curves were constructed around a reference temperature of 10 °C. The control mixture appears to be somewhat stiffer than the EAFS mixtures. Although EAFS has been found to increase the stiffness [63], the discrepancy here could be due to the influence of the additional effective bitumen content or from the 1% higher air voids (Table 3). The predicted curve for the coarser EAFS samples seems to trend to a higher modulus at higher temperature/ lower frequency compared to the control.

The phase angle is an indicator of the viscoelastic behavior of the bitumen, with a higher phase angle indicating more viscous properties, increasing with higher temperatures as is typical for asphalt mixtures (Figs. 8–10). Here, the rankings of the phase angle for the three mixtures rearrange with different temperatures. As the differences are within the standard deviation values, we can suggest that 13% EAFS replacement does not significantly change the viscoelastic behavior of the given mixture. In absolute terms the obtained modulus values for the three materials tested at 10 °C and 10 Hz which is the type testing parameters was 9952, 7960, 7479 MPa. These values are somewhat below the Modulus values obtained for a similar mixture in a previous study of 10,231 MPa [49].

4.4. Fatigue resistance

The IT fatigue resistance was evaluated based on the initial strain between for 98th and 102nd cycle (ε_{ini}) versus the number of load cycles to failure. The results shown in Fig. 11 show similar fatigue resistance for the EAFS samples compared to the control. The EAFS

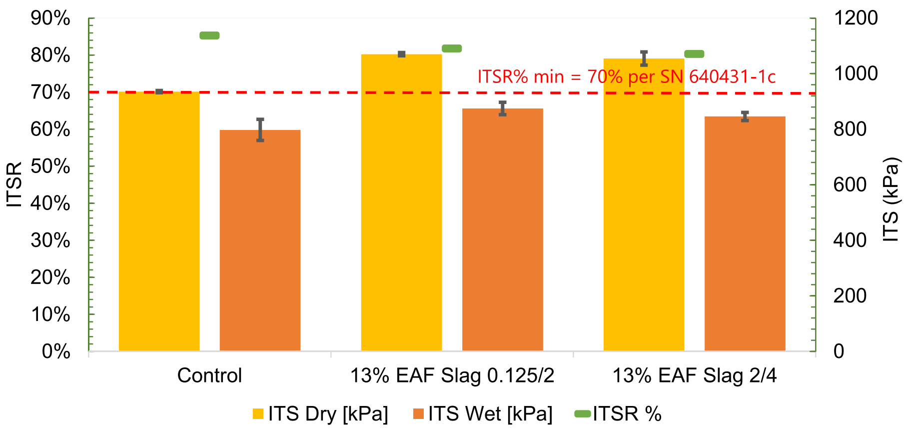

Fig. 6. Dry (ITS_{dry}) and wet (ITS_{wet}) strength and water sensitivity (ITSR) results error bars indicate standard deviation.

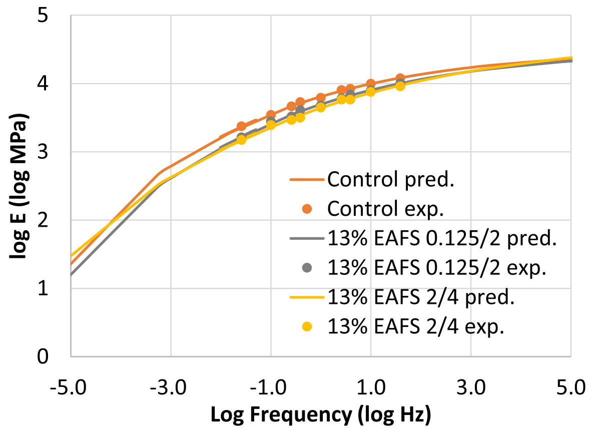

Fig. 7. Stiffness modulus master curves at reference temperature of 10 °C.

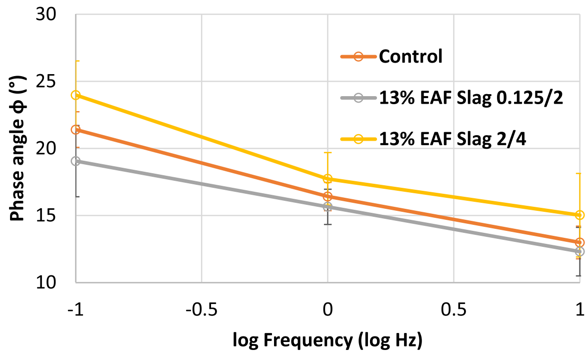

Fig. 8. Phase angle (°) from stiffness modulus tests at 5 °C.

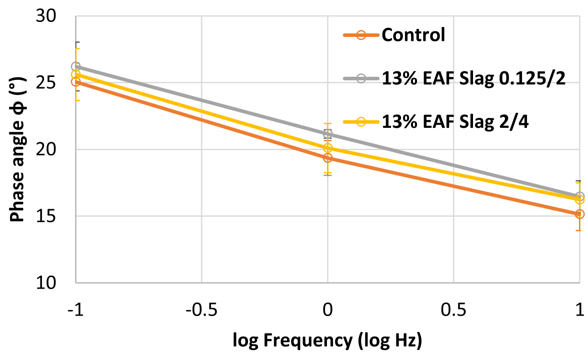

Fig. 9. Phase angle (°) from stiffness modulus tests at 10 °C.

tended toward longer fatigue lives at higher strain levels, with the opposite relationship at lower strain levels. As shown in Table 4, strain for a millions cycles (ε_6) for the sample with the coarser EAFS was similar to the control and somewhat higher than for the sample with finer EAFS replacement. The literature shows varied results with EAFS in terms of fatigue life, but there have been results showing reduced performance of finer fraction EAFS replacement compared to in coarser fractions [3,64]. The slightly higher effective bitumen content of the EAFS mixtures be effecting these results.

4.5. Environmental impacts

As shown in Fig. 12, the GHG emissions of EAFS-modified SDA are lower than that of the reference scenario by 40%. The main difference comes from the landfilling of EAFS. According to the ecoinvent database, cement is used to solidify the landfilling waste, where the production of cement leads to large amounts of GHG emissions. This is much higher than that of the EAFS processing to

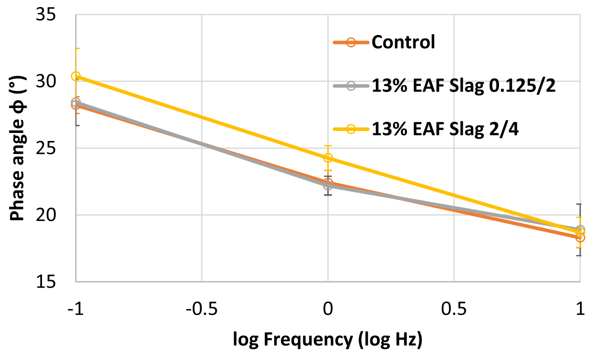

Fig. 10. Phase angle (°) from stiffness modulus tests at 15 °C.

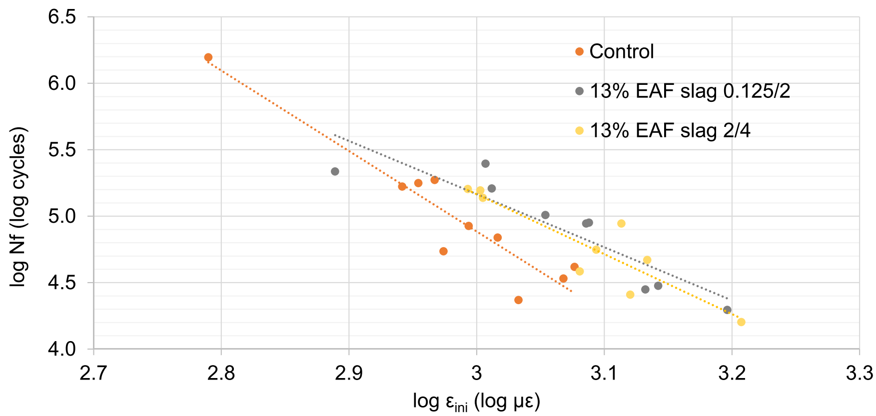

Fig. 11. Indirect tensile fatigue initial strain level versus cycles to failure.

Table 4
Initial strain level vs cycles to failure equations and initial strain (ε_6) levels to 1 million fatigue cycles.

Sample	ε_6 equations	ε_6 (με)	R^2
Control	$N_f = 1.14E23\varepsilon_{ini}^{-6.06}$	653	0.89
13% EAF slag 0.125/2	$N_f = 1.46E17\varepsilon_{ini}^{-4.00}$	618	0.81
13% EAF slag 2/4	$N_f = 5.02E18\varepsilon_{ini}^{-4.51}$	655	0.81

replace natural aggregates in SDA. Therefore, the incorporation of EAFS into SDA avoids the landfilling of EAFS and the corresponding GHG emissions. For the EAFS scenario, the major contributors of GHG are bitumen production and asphalt mixing. This follows the results of previous publications [13,36]. The non-renewable CED is however, not improved by EAFS-modified SDA. It can be seen that bibitumen production is the major contributor of CED, accounting for nearly 80% of the total. Since the EAFS-modified SDA has higher bitumen content to achieve comparable performance to the reference SDA, it presents more non-renewable CED. Similar results can also be found in [36]. For the ecological scarcity eco-point, the EAFS-modified SDA shows significant reduction by 90%, where the main reason is the avoidance of EAFS landfilling. This implies that landfilling is an option with quite low priority in Switzerland, and the alternative option without landfilling could gain great advantage in the eco-points.

Based on the results of Fig. 9, some uncertainties should be emphasized. Firstly, the transportation distance of materials from domestic suppliers (e.g. natural aggregates, steel slag, and asphalt mixtures) in Switzerland is similar to 50 km. This may not be realistic for other countries where the mixing plant is closer to the mining quarry or steel factory with transportation distance more than 100 km. Furthermore, according to the regulations of landfilling in Switzerland (FOEN, 2022 [15]), it is required to use sanitary landfilling for disposing of steel slag. As a result, certain amounts of cement are used for solidification. Since the production of cement generates huge quantities of GHG, the avoidance of landfilling in this case study presents considerable benefits. However, for the countries allowing other types of landfilling (e.g. open dump), the results could be different compared to this paper.

4.6. Summary of results using radar chart

The data obtained in the previous sections allow to perform a multi variate analysis comparing the slag mixtures with control using

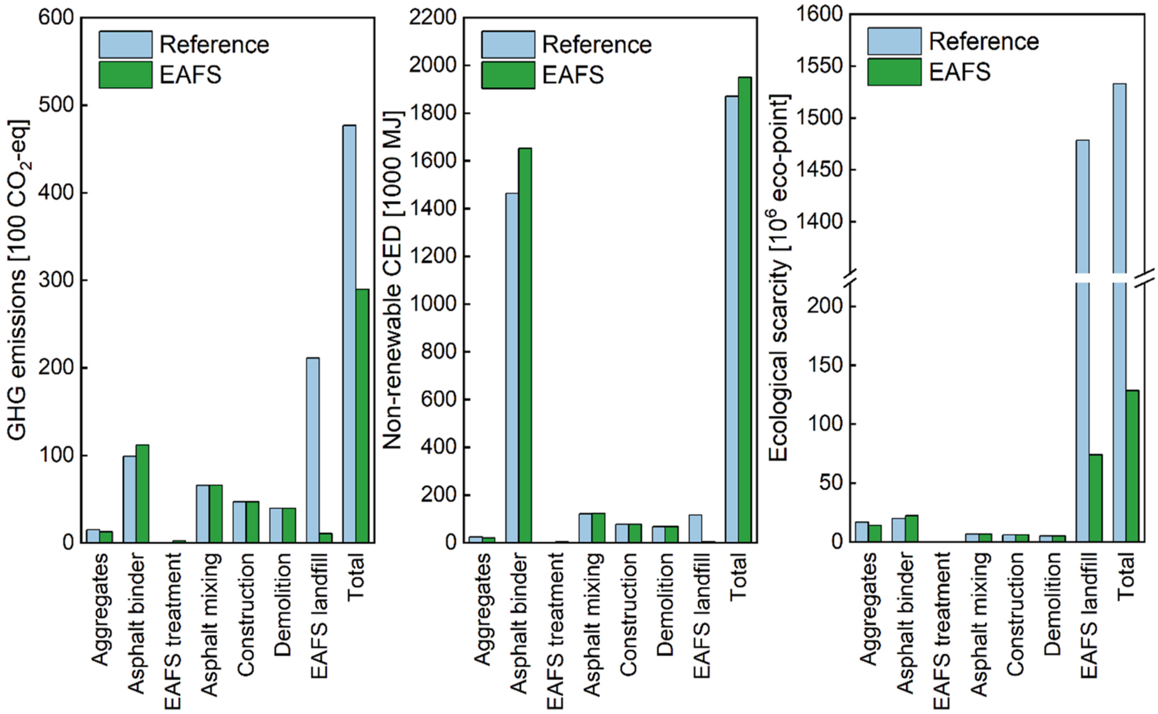

Fig. 12. Various environmental impacts in terms of greenhouse gas emissions, non-renewable energy demand and eco points from reference SDA and SDA with EAFS.

a radar chart shown in Fig. 13. In this chart some of the discussed parameters are shown simultaneously namely, ITS_{dry}, ITS_{wet}, ITSR%, phase angle (φ) and modulus (G^*) at 10 Hz and 5 and 15 °C, fatigue parameter ε_6 as well as LCA analysis in terms of GHG, CED and Eco points. It is clear from this chart that the slag mixtures deviate from the control sometimes showing sometimes better performance and sometimes worst. The deviation is primarily in the modulus values with the deviation higher at higher temperature. The phase angle at 5 °C is higher than control and therefore showing a more viscous response that could be beneficial in cold temperatures in resisting cracks. The strength (ITS) in wet and dry state was somewhat lower than control but all mixtures fulfilled the water sensitivity requirement (ITSR%). The fatigue behavior indicated by the σ_6 parameter of the coarser EAFS mixture also shows a reduction in comparison to the control. The slag mixtures showed beneficial in terms of GHG and Eco points and slightly worst in terms of CED.

5. Conclusions

The current study employed electric arc furnace slag (EAFS) aggregate replacement in low-noise semi-dense asphalt (SDA). The

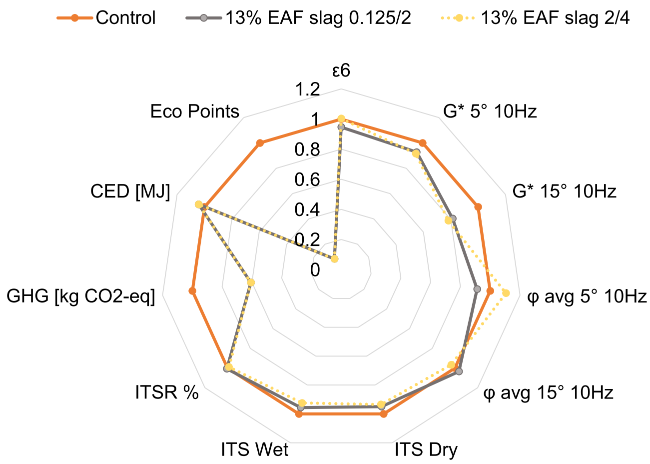

Fig. 13. Summary of the normalized results between mixtures.

goals were to improve the mechanical performance of the SDA, find a destination for EAFS waste and find a low cost alternative for costly SDA aggregates. The steel slag was separated into coarser and finer fractions to isolate the effects of both and the mixtures were evaluated considering water sensitivity, stiffness modulus and fatigue testing as well as environmental impacts through a life cycle analysis. The main findings are as follows:

- EAFS have higher densities and water absorption compared to virgin sandstone aggregates. However, the relationship with the water absorption and the absorbed bitumen may be different, and should be taken into account when calculating the amount of additional bitumen.
- The water sensitivity, rheology and fatigue resistance of the SDA mixtures were not significantly changed significantly with 13% EAFS replacement for both fractions investigated, indicating suitable replacement performance wise.
- The fatigue life of the finer EAFS mixture was slightly lower than with the coarser one and the control.
- Compared to the reference SDA, the EAFS-modified SDA reduces the GHG emissions and ecological scarcity eco-points by 40% and 90%, respectively. The main reason is the avoidance of EAFS landfilling. However, the non-renewable CED is not improved by using EAFS in SDA, due to the additional consumption of bitumen. In order to optimize the energy demand focus should be put on optimizing and reducing bitumen content.

Overall, EAFS aggregates are promising as an alternative for using waste aggregates in asphalt mixtures. The mechanical properties of SDA with a moderate amount of EAFS replacement were shown to be similar to those made entirely with conventional SDA aggregates. The substantial benefits under the conditions investigated are on the environmental side, in reducing the EAFS that goes to the landfill. The decision on EAFS aggregate replacement should be accompanied by a life cycle assessment for the fabrication, construction and waste management conditions where it would be employed.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Peter Mikhailenko reports supplies (EAFS) provided by Stahl Gerlanfingen AG.

Data Availability

Data available upon request to authors.

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