Recycled Aggregates with Enhanced Performance for Railways Track Bed and Form Layers

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Abstract The use of aggregates with high abrasion resistance is key to guaranteeing a good track performance over time; however, obtaining these high-quality aggregates is not always feasible at a reasonable cost. Because of this, the creation of new alternatives with lower life cycle costs and lower environmental impacts, such as steel furnace slag-rail (SFS-Rail), is fundamental for the economic and environmental sustainability of the railway infrastructure. SFS-Rail is made of recycled aggregates from electric arc furnace slag aimed to be used in subgrade and subballast layers as it offers excellent physical and mechanical properties. In this paper, a worldwide review of the state-of-the-art experiences and legislation in using ferrous slag in railway applications is carried out. Next, an introduction of SFS-Rail and their main benefits in terms of track performance and environmental sustainability is presented, based on both laboratory tests and a life cycle assessment. Results from laboratory tests are compared to those of the existing European norms regulating the use of aggregates in track bed layers to prove their suitability. Finally, the field tests in the Spanish infrastructure manager (Administrador de Infraestructuras Ferroviarias, ADIF) network and the monitoring equipment and techniques used to assess the track performance are described, while the main results obtained are discussed.

Keywords Slag · Aggregate · Railway · Foundation

Introduction

Track bed layers (which usually refers to ballast and blanket layers) and form layers (meaning the upper part of the subgrade aimed at providing the required characteristics to the platform) play a key role in track behavior with respect to track support stiffness, maintenance of track geometry and drainage, among others. It is well known that many problems related to track geometry come from a deficient condition of track bed layers. Therefore, if resilience and stability of railway infrastructure are sought, high-quality aggregates for track bed and form layers should be employed.

Traditionally, materials employed in track bed and form layers are natural aggregates that derive from quarries. New challenges have arisen in view of the fact that high-quality aggregates are a natural resource and they have started to be scarce and not always available. As a result, in some specific locations and projects, long transport routes are needed in order to get the right material, which results in an increase of not only cost, but of the environmental burdens associated to track construction.

This occurs in a context where European Commission (EC) policies are increasingly stringent in environmental issues, whereas they encourage the adoption of more sustainable, durable, and cost-efficient solutions. For these reasons, the appearance of a new recycled material with enhanced mechanical properties seems to align perfectly with the future development of track infrastructure, where materials with best life cycle cost (LCC) and best life cycle assessment (LCA) will prevail.

Within the framework of the GAIN project (funded by EC LIFE+ programme), a new recycled aggregate is being developed not only to fulfill all the technical requirements of the national and European norms regulating their
utilization in track bed and form layers, but aspiring to go beyond them and offer excellent mechanical properties. These aggregates are obtained through the valorization of (black) electric arc furnace slag (EAFS), which are produced during carbon steel production. Black EAFS is the major subtype of steel slag (75%), while the remaining is white slag.

**State-of-the-Art: Experience and Legislation Regarding Furnace Slag as Aggregate in Railways**

The steel furnace slag (SFS) generated in Europe is mainly applied for road construction (43%) while 19% is for interim storage, according to the “European Association representing metallurgical slag producers and processors” (EUROSLAG) statistics from 2012 [1]. Recent investigations have been carried out with regard to the use of EAFS as coarse aggregate for concrete, finding that it can be a reasonable use and that it can even increase its mechanical properties [2]. The use of ferrous slag in railway applications is not as common as in road construction and the only experiences found were in USA, Brazil, Canada and India.

According to Van Oss [3], in the USA in 1975 railroad ballast was the second most important application of blast furnace slag (BFS), with 3.66 million tons (18%), and the third most important of SFS, with 0.56 million tons (8.4%). Despite these low percentages, road base was by far the most common application for both types of slag. According to the data of the Mineral Yearbook by the U.S. Geological Survey [4], in 2011 less than 6.6% of BFS was used for railroad ballast application. No SFS was intended for this application. Road base and surfaces continued to be the primary application of both BFS (with 38.7% of the production) and SFS (with 46.8% of the production).

In Canada, specific norms regulate the use of slag in railway applications, namely the Canadian national railways (CNR) Specification 12–22, Slag ballast. On the other hand, in Brazil there is a process of standardization of the steel slag underway at the Brazilian association for technical standards (ABNT) for its use as railway ballast. With regards to India, some tests have been undertaken to prove that steel slag fulfills the specifications required by the Indian railways (IR) for railway ballast [5].

In contrast, no evidence has been found regarding railroad application of SFS in Europe or relevant research on this topic. Hence, according to Ref. [1], in 2012 the uses of SFS were road construction (43%), interim storage (19%), final disposal (13%), metallurgical purposes (11%), cement production (5%), hydraulic engineering (3%), fertilizer (3%) and other uses (3%). As a result, the GAIN project aims at developing a new type of aggregates coming from EAFS that complies with the European norms so that they can be used similarly as in other industrialized countries.

Slag aggregates must comply with the existing norms regulating the use of aggregates in subgrade and subballast layers. At this moment, only a specific railway standard at a European level for ballast aggregates (i.e., EN 13450:2013) exists but that does not cover the subballast or subgrade aggregates. There is a more general standard regulating the aggregates for civil applications (EN 13242:2013), which includes some specifications regarding the use of steel slag as aggregate for foundation layers. The standard states that slag aggregates can be considered stable if the expansion (according to EN 1744-1) does not exceed the maximum values, depending on the application or its final use.

Although there is not a common norm for Europe, in each country, the railway administration has developed its own regulations establishing the specifications that aggregates must comply to, in order to be used in track bed layers. In Table 1, the different criteria among countries can be seen.

On the other hand, slag aggregates should comply with additional norms compared with natural aggregates obtained from quarries, given that in many countries they are still treated as wastes, and specific tests must be carried out in order to allow them to be recycled and used as a product.

Classification of slag by European legislation has evolved during the last years as a result of 25 years of discussion on this issue. How slag aggregates are classified according to EU legislation—waste, product or byproduct—has a direct effect on the strictness of the requirements they have to fulfill. According to the revised Waste Framework Directive 2008/98/EC [8], some types of slag can be considered as byproduct or even as a product. At a national level, some of the slag types are recognized as nonwastes, products or byproducts (e.g., in Belgium, Finland, Germany, Austria and the United Kingdom) but still have a waste status in some other countries. Steel slags, in particular, are often considered as a waste, especially in the liquid state and before treatment [9].

There are several countries in Europe such as Germany that have developed specific standards for regulating the use of steel slag as subballast and other civil applications. Nevertheless, there is a lack of these norms in some other European countries (e.g., Spain, Portugal, among others) and, therefore, much work is still needed to address the development of these regulations. The development of new solutions based on ferrous slag such as SFS-Rail contributes to a high extent towards the standardization and regulation on this matter.
SFS-Rail: EAFS Aggregates for Subballast and Subgrade Layers

SFS-Rail refers to the commercial brand of the new aggregates made of EAFS to be used in railway applications, namely for subballast and subgrade foundation layers. It can be produced with different granulometries (see Fig. 1). Its physical, mechanical, chemical, and environmental features have been assessed by an extensive campaign of laboratory tests, with fresh samples, and a LCA, whose main considerations and results are described below.

Physical and Mechanical Characterization of SFS-Rail

Tests to determine the physical properties of SFS-Rail have reported a bulk density of 3.56 kg/m$^3$, a water absorption of 1.6 %, a fines content of 4.20 %, and a high percentage of voids space. The tests have been carried out according to the Spanish standards UNE-EN 1097-6 for density, water absorption, and voids space; and UNE-EN 933-1 for the determination of the fine content. Other physical properties assessed are the fracture faces and the expansiveness index. SFS-Rail offers 100 % of fracture faces, which guarantees a good interlocking between particles, while the accelerated expansiveness according to UNE-EN 1744-1 has proved to be 0.3 % after 168 h.

Regarding the mechanical characterization of SFS-Rail, the Los Angeles (LA) test has been carried out, provided that it measures the abrasion resistance of aggregates, which is one of the most relevant parameters for aggregates in railway applications. The tests give a LA value of 15–20, favorably comparing with good hard rocks and most standards, which require a maximum LA of 30 (e.g., the maximum value established by the Spanish norm is 28 [10]). Note that the LA value for aggregates to be used in concrete applications is considerably higher (i.e., less demanding) and goes up to 50, as stated by the Spanish norm UNE-EN 12620.

The high performance of SFS-Rail against abrasion is confirmed by the results of the Micro-Deval (MD) test and the polished stone value (PSV). SFS-Rail showed a MD below 20, in compliance with the Spanish norm [8], while it offers a PSV between 57 and 65, which is within the aggregates “High Performance” category, where it is difficult and expensive to obtain a rock with such characteristics. Finally, to assess the California bearing ratio (CBR) index were carried out according to UNE 103502.

Table 1 National specifications for earthworks and track bed layers

<table>
<thead>
<tr>
<th>Organization</th>
<th>Country</th>
<th>Dmax (mm)</th>
<th>Fines (%)</th>
<th>Fracture faces</th>
<th>Los Angeles</th>
<th>Micro deval</th>
<th>Permeability K (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deutsche Bahn</td>
<td>Germany</td>
<td>56</td>
<td>&lt;5–7</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&lt;10$^{-6}$</td>
</tr>
<tr>
<td>Infrabel</td>
<td>Belgium</td>
<td>63</td>
<td>&lt;5–7</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&gt;5–10 × 10$^{-8}$</td>
</tr>
<tr>
<td>ZSR</td>
<td>Slovakia</td>
<td>40</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>SCNF</td>
<td>France</td>
<td>31.5</td>
<td>4–8</td>
<td>100</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Network Rail</td>
<td>Great Britain</td>
<td>2.36</td>
<td>&lt;10</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>RFI</td>
<td>Italy</td>
<td>25.4</td>
<td>6–10</td>
<td>&gt;67</td>
<td>&lt;30</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>CD</td>
<td>Czech Republic</td>
<td>32</td>
<td>&lt;5</td>
<td>&lt;50</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Banverket</td>
<td>Sweden</td>
<td>150</td>
<td>0–6</td>
<td>100</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>ADIF</td>
<td>Spain</td>
<td>40</td>
<td>3–9</td>
<td>100</td>
<td>&lt;28</td>
<td>&lt;22</td>
<td>&lt;10$^{-6}$</td>
</tr>
</tbody>
</table>

Adapted from Refs. [6, 7]
In all cases, CBR results were above 100, which is considerably higher than that of conventional aggregates.

It has to be stressed out that all the above values are in line with the results reported by scientific literature regarding steel slag characterization, such as [11], which reports a bulk density of 3.5 kg/m$^3$ and a PSV of 61, among other parameters; and [12], which reports a LA value of 17% and a water absorption of 0.8%. Indeed, EUROSLAG states that the chemical, mineralogical, and physical properties of steel slag are similar to those of natural rocks, with enhanced performance due to their high density (3.6 kg/m$^3$), low impact value (17%), high compressive strength (200 N/mm$^2$), good polishing performance (PSV of 57) and high freeze/thaw resistance [13].

Besides these good performance indicators, as a result of a large experimentation on the field, such as [14], an increased lateral stability is expected due to: (a) a better interlocking of particles as a consequence of the sharp corners and rough, pitted surfaces, as can be seen in Fig. 1; and (b) to the heavier weight of aggregates.

As a result, tracks using SFS-Rail are not only more durable but also more resistant to lateral track movements in tight curves, consequently track geometry will last longer, and thus, maintenance costs will diminish. Moreover, the higher percentage of voids space provides SFS-Rail with a higher drainage capacity than conventional aggregates.

The above statements are supported by other relevant research on slag material applications in the railway field, such as Ref. [15], which highlights the advantages of steel slag when used as ballast.

Note that SFS-Rail has a lack of fine material and, in order to comply with the granulometry curve for the sub-ballast layer, as defined in [10], it must be mixed with natural aggregates in a proportion of 75% SFS-Rail and 25% natural aggregates. The LCA and the field tests, which are detailed in the following sections, have been carried out with this proportion.

### Chemical/Environmental Characterization of SFS-Rail

Laboratory tests have been also carried out to determine the chemical composition of SFS-Rail. They have proved to be highly resistant to wetting and drying, to freezing and thawing, as well as, to extreme changes in temperature and to chemical attacks. Besides, the absence of organic matter prevents the growth of unwanted vegetation.

Sulfate and sulfur tests have been done according to EN-1774-1:2010. To obtain the total chloride content, the potentiometer technique has been used. Results, expressed in weight percentage, are shown in Table 2.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water soluble sulfates (% SO$_3$)</td>
<td>0.0070</td>
</tr>
<tr>
<td>Acid soluble sulfates (% SO$_3$)</td>
<td>0.0814</td>
</tr>
<tr>
<td>Total sulfur (% S)</td>
<td>0.0955</td>
</tr>
<tr>
<td>Chloride content (% Cl$^-$)</td>
<td>0.0200</td>
</tr>
</tbody>
</table>

Table 2 Soluble sulfates, sulfur, and chloride content of the valorized slag

A special focus has been put on the leaching tests, whose main objective has been to quantify the mobility of the chemical species (pollutant or not) contained in the SFS-Rail aggregates. The leaching tests have been undertaken according to EN 12457-4, where SFS-Rail is submerged into water, and its release of constituents is monitored.

The analysis criteria to classify SFS-Rail as inert or hazardous consist of a list of maximum concentration values for each chemical substance, which may vary depending on the standard applied. In Table 3, the thresholds for the Decree 32/2009 [16] of Catalonia are shown together with the results of the leaching tests performed on SFS-Rail, showing that none of the thresholds were surpassed.

The presence of conductive elements (e.g., metals) in the black slag may cause potential hazard of eddy currents leading to interferences with the railroad signaling systems. Although the presence of conductive elements in SFS-Rail has not been studied in the context of this project, there are two factors worth mentioning: (i) during the valorization...
process, iron removal is carried out up to three times (see Fig. 2) to reduce the presence of iron particles as much as possible, and (ii) SFS-Rail is not employed in the ballast layer, but in the subgrade and subballast layers, which have a 20 cm thick ballast layer above made of siliceous aggregates and a high percentage of voids, both contributing towards the isolation of the rail superstructure from its infrastructure. At the present time, no trouble due to eddy currents has been detected in the field tests.

LCA of SFS-Rail

In recent years, life cycle thinking (LCT) has taken a more prominent role in environmental policy making. Renowned institutions, have adopted life cycle thinking and an increasing number of different stakeholders are feeling the pressure to reduce the environmental impact associated with global consumptions.

Among the tools available to evaluate environmental impacts, the life cycle analysis (LCA) provides a holistic approach to evaluate environmental performance by considering the potential impacts from all stages of manufacture, product use, and end-of-life stages. The LCA is a tool for quantifying the environmental performance of products taking into account the complete life cycle, starting from the production of raw materials to the final disposal of the products, including the material recycling if needed [17, 18].
The LCA undertaken for the GAIN project comprises four major components, which are summarized in the following subsections:

- **Goal and scope definition**
- **Life cycle inventory (LCI)**—data collection and calculation of an inventory of materials, energy and emissions related to the system being studied
- **Life cycle impact assessment (LCIA)**—analysis of data to evaluate contributions to various environmental impact categories
- **Interpretation**—where data are analyzed in the context of the methodology, scope, and study goals and where the quality of any study conclusions is assessed.

**Goal and Scope Definition**

The primary goal of the LCA carried out is the comparison of SFS-Rail with the conventional aggregates and soil employed in the subballast and subgrade layers in accordance with ISO 14040:2006 and ISO 14044:2006 standards [19, 20]. LCA results will be of a high value to assess Railway Infrastructure Managers and Public Administration to use SFS-Rail in their rail networks due to its lower maintenance and renewal actions would not take place so often. With no consideration of exploitation and maintenance of the track line on the LCA, it leaves us again on the conservative side.

The realization of these assumptions may substantially reduce the quality of data provided due to its uncertainty, and taking into account the relevance of data quality in an LCA study, this may reduce the reliability of the study. For this reason a cradle-to-gate approach plus transport to site has been considered, covering all the production steps from raw materials in the earth (i.e., the cradle) to finished product on site (although not yet placed and compacted), so that a proper comparison between SFS-Rail and natural aggregates can be performed.

The construction stage does not imply any differences between SFS-Rail and natural aggregates, since the same amount of material, equipment and construction processes are expected. However, the thickness of the subballast and subgrade layers (amount of material needed) could be reduced if employing SFS-Rail, leading to a reduction of the resources allocated for the construction and, therefore, their environmental impact. This way, one can state that there no consideration of the potential materials savings in the LCA keeps the results on the conservative side.

The same happens with the exploitation and maintenance stage, provided that the enhanced durability of the SFS-Rail would lead to a longer lifespan of the subballast and subgrade layers and, hence, the impact associated to maintenance and renewal actions would not take place so often. With no consideration of exploitation and maintenance of the track line on the LCA, it leaves us again on the conservative side.

Finally, it has to be said that the impact that the landfilling of the steel slag would imply, in case it were not valorized (i.e., if natural aggregates were used), has been taken into account to perform a fair comparison of the cradle-to-gate LCA of both SFS-Rail and natural aggregates options.

The models for the subballast and subgrade layers with SFS-Rail and natural aggregates have been made using the GaBi 6 software system for life cycle engineering, developed by PE International GmbH. The considered flows in the LCA are shown in Figs. 3 and 4. The system boundaries involve all the processes from raw material provision to the product delivered on site, ready to be placed on the track bed. All raw materials and resources are included in the system boundaries.

The database used for this LCA has been the GaBi Professional database 2014. In accordance with the LCA purpose and taking into account GaBi manual explanations, the methodology adopted has been the so-called CML 2001 method [21]. The CML method includes classification, characterization, and normalization.
The data that have been used for this study can be classified into three groups:

- Primary data provided by the steel slag valorization plant of ADECGLOBAL
- Primary data from similar studies or analyses [22–24]
- Primary data from GaBi 6 Professional database

For the aggregate extraction, the following processes have been considered: overburden removal, excavation, loading and conveying, preprocessing storage, scalping screening, crushing, sizing screening, washing–scrubbing, wet classification, de-watering, product storage, pit preparation, and re-vegetation.
The steel slag is a waste created in the steel manufacturing process and its procurement has been assumed as a collateral effect of the steel production, not evaluated here. The usage of steel slag as a raw material for construction purposes avoids its landfilling and spilling, with the consequent environmental impact. However, its preparation to be ready as a construction material introduces additional crushing, sieving and iron separation processes in the valorization plant.

The transport considered in the study is that from the steel slag valorization plant to the construction site, from the quarry to the valorization plant (for the mixture of natural aggregate with EAFS) and from the quarry directly to the construction site (for the natural aggregate conventional solution). An average distance of 50 km has been deemed between the quarry and the valorization plant, while an average distance of 100 km has been considered between the quarry and the construction site, and between the valorization plant and the construction site. The study has been done with dump trucks with a payload of 24 tons.

Finally, the steel slag landfilling, in the case natural aggregates are used, takes into account the pit-preparation and re-vegetation.

**LCIA**

Results of the LCIA are given for a cradle-to-gate approach for the subballast layer of a 1 km long single railway line. In particular, the subballast layer considered has a width of 8.5 m and a thickness of 25 cm, for both SFS-Rail and natural ballast, although a reduction of the thickness could be achieved with the employment of SFS-Rail. Results of the subgrade layer are qualitatively similar and hence have not been included in this paper.
Up to eight LCIA categories have been analyzed, highlighting two of the most concerning nowadays:

- Global warming potential (GWP) is a warming of the atmosphere, which causes climate changes, which may include increased global average temperatures in the lower atmosphere and sudden regional climatic changes.

- Human toxicity potential (HTP) covers a number of different effects (acute toxicity, irritation effects, allergic effects, etc.) and exposure via different media (air, water, and soil) related with human health. It does not include indoor consumer exposure or workplace.

The GWP is dominated by carbon dioxide (CO$_2$) emissions and methane (CH$_4$) emissions, which represent almost all the emissions of all Green House Gases (GHG) emissions for the aggregate industry. Processes with more GWP are the ones that most contribute to carbon dioxide and methane emissions. The combination of SFS-Rail with natural aggregate reduces the overall GWP by a 45 %, as shown in Fig. 5.

HTP is based on both the inherent toxicity of a compound and its potential dose. The SFS-Rail scenario reduces HTP by 193 % with respect to the natural aggregates scenario, as shown in Fig. 6.

The remaining categories of the study are: acidification potential (AP), eutrophication potential (EP), marine aquatic ecotoxicity (MAE), freshwater aquatic ecotoxicity (FWE), ozone layer depletion (OLD), and terrestrial ecotoxicity (TE).

AP is dominated by air emissions, which contribute to nearly the totality of this impact. The combination of SFS-Rail with natural aggregate reduces the overall AP by a 44 %, as shown in Fig. 7a. EP potential is predominated by emissions to air; being the nitrogen oxide the main contributor. The SFS-Rail scenario reduces the EP by 9 %, as shown in Fig. 7b.
TE and FAE are increased due to the amount of energy necessary for the SFS-Rail valorization process, as shown in Fig. 8. However, MAE and OLD are significantly reduced because of the lower and null impact of the production process and the diminishment of the aggregate extraction, as shown in Fig. 9.

**Interpretation of Results**

The most determining factor in GWP, EP and AP is the transport from the valorization plant to the construction site. This is comprehensible, since the steel slag raw material production is done in a sustainable way, including only magnetic separation, sieving and crushing processes. Moreover, acquisition is considered to be free of impact. However, there is a recent study which attributes carbon to slag [25], so attention will be required for further investigations. The transport from quarry to the valorization plant has a minor impact, provided that only 25% of the volume is made of natural aggregate, and distances from quarry to the valorization plant have been deemed of 50 km.

In the HTP, instead, the major contributor is the aggregate extraction and production, especially due to the overburden removal and the aggregate crushing. It is remarkable to note that with only a 25% of the total volume, the natural aggregate extraction and production imply almost a 70% of the overall impact of this category.

As a conclusion of this analysis one can state that, beyond its technical improvements, SFS-Rail is a better product for the environment than the conventional solution employing natural aggregates/soil in the subballast and...
subgrade layers of railway lines. The use of SFS-Rail is even better if the location of the valorization plant is close to the construction site, since the environmental impact associated to road transport diminishes, which is the major contributor to GWP, EP and AP. Indeed, SFS-Rail allows a reduction of the thickness of the subballast and subgrade layers of railway tracks, hence reducing the demand of natural aggregates and transport needs, and, consequently, decreasing even further their associated environmental impacts.
Field Tests for Validation

Although the laboratory results have shown that SFS-Rail has excellent mechanical properties, two field tests have been performed in order to demonstrate and validate its performance in real conditions. The first field test has been set up in a freight line in El Musel harbor in Gijón, Spain, in a line owned by the harbor authority. The second one has been constructed in a mixed line (i.e., passengers and freight) owned by ADIF in Castellbisbal, near Barcelona, Spain. The description that follows refers to the latter, provided that ADIF is the main Spanish infrastructure manager and the field tests carried out in their network have a major demonstration and replicability potential.

Thus, in the field tests of Castellbisbal, three sections of 50 m each have been constructed:

- A 50-m-long section with the subballast layer made of SFS-Rail and the subgrade layer with the existing conventional aggregates
- A 50-m-long section with both the subballast and subgrade layers made of SFS-Rail
- A 50-m-long section with the existing conventional aggregates (control section). The control section has been divided into two zones: one at each end of the field tests.

The field tests have been designed to assess the performance of the different track sections in terms of the following three parameters:

- Track settlement and geometry, as a measure of the track alignment, thickness of the compacted layers, strength, density (compaction) and moisture.
- Subballast and subgrade stress under traffic, as a measure of the capability of distributing the stress towards the platform, which relates to the track strength (bearing capacity)
- Rail deflection under traffic, as a measure of the track stiffness (soil modulus) and its elastic deformation.

Track settlement and geometry are monitored by periodical topographic surveys (every 2 months). To monitor the settlement of each layer, 12 tubes have been designed ad hoc and positioned on the subballast and subgrade layers (see Fig. 10a) so that their head can be read from a topographic station placed outside the track. The subballast and subgrade stress under traffic is monitored through vibrating wire pressure cells, which have been installed under the subballast and subgrade layers made of SFS-Rail (see Fig. 10b). After the extension and compaction of the upper layers, the track assembly (see Fig. 11) and ballast profiling and tamping, the field tests have been opened to traffic (see Fig. 12). Rail deflection can then be measured by instantaneous topographic surveys of rail web references during passage of trains (see Fig. 13).

At the moment, three readings have taken place in the field tests besides the initial survey, according to the monitoring plan.

The stress measured on the subballast and subgrade layers made of SFS-Rail is presented in Table 4, showing
admissible values (under 0.15 MPa) while evincing a reduction on the stress of the subgrade compared to the subballast layer, hence proving SFS-Rail bearing capacity and its capability to distribute stress. Stresses are scaled up in the second reading due to a higher axle load of the commuter unit circulating at the time of the measurements.

Rail deflection under the passage of a commuter unit is presented in Table 5, indicating a compaction of the infrastructure with time while manifesting acceptable values (under 3 mm in the second and third readings) and a reduction in deflection when SFS-Rail is used, which demonstrates the increase in soil modulus (track stiffness) with respect to conventional aggregates.

Finally, results on track settlement are presented in Fig. 14, showing an overall progressive but restrained settlement during time. Track settlement is more pronounced where SFS-Rail is used in both layers (i.e., subballast and subgrade layers), as the existing aggregates have been removed and their previous compaction has been lost. In contrast, in the control section, the existing aggregates have not been replaced, and, hence, they keep the compaction gained due to the passage of trains since the last track renewal, which results in lower settlements.

**Conclusions**

In this paper, the main results of the SFS-Rail characterization by laboratory tests, the LCA, and the field test implementation and monitoring have been presented.

It has been proven that SFS-Rail emerges as a high-quality aggregate offering an abrasion resistance and hardness considerably higher than most of the natural aggregates commonly employed in railway foundations. Its suitability in track bed layers has been validated through the field tests demonstration, which has evinced its contribution toward improved track stiffness, track stability, bearing capacity (strength) and durability, hence enabling a reduction of maintenance needs and the frequency of track renewal operations.

### Table 4 Stresses measured on the subballast and subgrade layers made of SFS-Rail under the passage of a commuter unit

<table>
<thead>
<tr>
<th></th>
<th>1st reading</th>
<th>2nd reading</th>
<th>3rd reading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress (MPa) on SFS-Rail subballast layer</td>
<td>0.077</td>
<td>0.104</td>
<td>0.097</td>
</tr>
<tr>
<td>Stress (MPa) on SFS-Rail subgrade layer</td>
<td>0.032</td>
<td>0.042</td>
<td>0.056</td>
</tr>
</tbody>
</table>

### Table 5 Rail deflection (in mm) measured under the passage of a commuter unit

<table>
<thead>
<tr>
<th></th>
<th>1st reading</th>
<th>2nd reading</th>
<th>3rd reading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subballast and subgrade layers with SFS-Rail</td>
<td>1.2</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Subballast layer made of SFS-Rail and subgrade layer with conventional aggregates</td>
<td>2.7</td>
<td>1.3</td>
<td>1.1</td>
</tr>
<tr>
<td>Control section (conventional aggregates)</td>
<td>4.5</td>
<td>3.0</td>
<td>2.4</td>
</tr>
</tbody>
</table>

![Fig. 14 Overall track settlement with respect to the initial survey](image)
The enhanced performance of SFS-Rail in track bed layers jointly with a reduction of acquisition and maintenance costs and a reduced environmental impact (it avoids the environmental impact of quarries while reusing an abundant industrial waste) makes it a very attractive alternative to natural aggregates.

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