

## Recycling waste rubber particles for the maintenance of different states of railway tracks through a two-step stoneblowing process

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### Abstract

Injecting recycled rubber particles under the sleeper through a two-step stoneblowing technique (partially replacing the small stones with rubber) could improve the performance of ballasted railway tracks. In addition, this results in fewer environmental impacts associated with maintenance whilst recycling an abundant waste material (End-of-Life-Tyres, or ELTs). Nonetheless, to continue the development of this solution before its widespread application, this paper assesses the volumes and dosages of rubber to be used during the correction of various levels of irregularities and track states. The aim is to extend the service life of the track whilst optimizing performance by the inclusion of the elastic particles (particularly in transition sections where gradual variation of track behavior is required). For this purpose, innovative laboratory tests were used to study the effect of applying various quantities of rubber (recycled from ELTs) over small stones to correct three different levels of settlement. This paper presents the resulting guide values for the volumes of small stones and rubber particles to be added. These values depend on the level of track settlement to be corrected and the need for resilience according to the section and characteristics of traffic to be supported. Further, it appears that it is preferable to add the rubber after the compaction of the layer of small stones, which results in a lower tendency towards settlement and irregularities. Therefore, the current findings indicate that a two-step stoneblowing process (adding appropriate quantities of rubber) could be a cleaner technique for improving track behavior and reducing environmental impacts associated with maintenance.

**Keywords:** Railway, Rubber particles, End-of-life tyres, Stoneblowing, Two-step process, Laboratory tests

### Introduction

Railway transportation is continuously evolving to adapt to the requirements of society, where sustainability, travel time, efficiency, safety and comfort are currently the most important factors. With these criteria in mind, the railway industry is continuously searching for more powerful and modern trains with higher loading capacity, faster speeds, and the incorporation of cutting-edge technology (UIC, 2008 and 2015). However, the potential of such modern trains could partially be limited by various factors related to track characteristics and state. Such factors include the influence of geometrical quality indicators (Chudzikiewicz et al., 2018) the deterioration of which requires maintenance operations, which involve the

consumption of energy and raw materials whilst generating other environmental, economic, and social costs.

The degradation of geometrical track quality is commonly monitored by different parameters (vertical and lateral alignment, gauge, and twist), measuring the maximum values of the irregularities and their deviation along a determined distance. This allows for defining different states of the track, which, for example in the UIC Code 518, are categorized as the three levels (depending on traffic speed), QN1, QN2 and QN3. These defects can appear at any point along the railway line due to various causes, although abrupt changes in track stiffness are considered to play a significant role in the acceleration of track degradation (Dahlberg, 2010; Sañudo et al., 2016; Stark et al., 2016). Therefore, regular maintenance interventions are required to recover the track profile whilst achieving optimal and constant values of track stiffness (or at least with gradual variations), all of which could help to reduce degradation.

Traditionally, ballast tamping has been the most widely used technique for correcting the profile of ballasted track, reducing the settlement of the layer and restoring its damping capacity. However, this procedure presents some technical and associated with the breakage of particles and consumption of materials and energy due to the need for frequent interventions (Selig and Waters, 1994). In light of these limitations, a technique known as Stoneblowing was developed for the injection of small stones (around 14–20 mm) into the gap between sleepers (in their theoretical position) and the ballast surface to recover track geometry. However, there are also some concerns regarding this procedure (Anderson and Key, 2000), such as the resulting track stiffness and reduced capacity to damp loads.

With the aim of improving the effectiveness of the stoneblowing process, previous studies (Sol-Sánchez et al., 2017, 2019) proposed the use of rubber particles (from end-of-life tyres) in combination with the small stones commonly applied during the stoneblowing technique. This requires a two-step process: the first for the injection of conventional stones and a second for including the waste rubber. Recycled rubber particles are then used as flexible aggregates to produce an elastic and flexible layer between the sleeper and ballast. Preliminary results indicate that this allows for optimizing track stiffness while reducing stress on the ballast and settlement, among other benefits (Sol-Sánchez et al., 2017).

This solution therefore improves the performance and durability of railway tracks whilst providing an innovative way of recycling an abundant waste material. So far, multiple ways of recycling waste rubber are being developed where it is highlighted its application as material (or modifier) in transportation infrastructures, such as in asphalt mixtures modifying the bitumen (Asgharzadeh et al., 2018; Chen et al., 2019; Pais et al., 2019; Wang et al., 2019a,b); in soils as cementitious component or material to increase the resistance of soils to frost, sulfates, bearing capacity, etc. (Wang et al., 2019a; Onuaguluchi and Banthia, 2019; Saberian and Li, 2019); in mortars and concrete to rise their resistance and durability under diverse in-service conditions (Richardson et al., 2016; Jalal et al., 2019; Zhong et al., 2019); or as flexible aggregates in seals for roads or into granular layers (Gheni et al., 2018; Saberian et al., 2019). However, the high generation of this waste (which is estimated around 800 million tons in Europe alone) (Sienkiewicz, 2012; ETRMA, 2017) demands for more applications like the proposed in this paper which is

estimated to allow for a reuse of more than 200–300 tires per railway kilometer, and then, providing a significant environmental benefits whilst further reducing the need for track corrections, all of which contributes towards reducing the life cycle costs of railway tracks (Bressi et al., 2018; Shinde et al., 2018; Guo et al., 2019).

Nonetheless, before the application of this innovative cleaner maintenance technique in railway tracks, it is necessary to design the proper composition of the mix stones-rubber for the two-step process to be applied in railway lines with diverse levels of defects and different mechanical performance requirements of the section. The current paper therefore focuses on evaluating the impact of using rubber in the two-step stoneblowing process when used to recover three characteristic levels of track deformation. Similarly, the effectiveness of various dosages of elastic particles was assessed for each height of settlement; this was aimed at providing maintenance solutions for transition sections that require the optimization of changes in stiffness and the correction of gradual track deformations. Thus, the goals of the present work were: to develop a range of solutions suited to different track requirements and characteristics; recycle an abundant waste material that would otherwise go to landfill; and further reduce the costs associated with maintenance along with its negative environmental impacts. For this purpose, innovative laboratory tests were conducted to reproduce traffic conditions in a full-scale railway section, and to simulate maintenance operations.

## **Methodology**

To achieve the main objectives of this paper, innovative laboratory tests were conducted to reproduce traffic conditions in a full-scale railway section to obtain different states of settlement in a standard ballasted section. Later, the laboratory tests also allowed for applying various maintenance solutions for correcting the different heights of settlement, injecting various combinations of small stones and rubber particles (forming a two-layer system from the two-step stoneblowing process). Materials, laboratory devices, and study stages are described in the following sections.

## **Materials**

The rubber particles to be used as flexible aggregates under the sleeper were obtained by grinding up end-of-life tyres from passenger cars, with a metal and textile content less than 0.5% by weight, resulting in irregular particles with moisture content lower than 0.75%. The density of the particles was close to  $1.15 \text{ Mg/m}^3$  (EN 1097-6) and the size range selected for this study was 14–20 mm, which is considered appropriate for avoiding percolation through ballast voids (Fair, 2003). This size range is also routinely used for the small stones included during the stoneblowing process (the technique by which rubber is applied under the sleeper) to fill the gap between the sleeper bottom and ballast surface after settlement. The flexibility of this solution is comparable to very soft and medium Under Sleeper Pads (USPs) when applying a ratio of 1 and 0.33 of rubber/small stones, respectively (Sol-Sánchez et al., 2019). Fig1. shows the granulometric curve of waste rubber in comparison with the standard small stones. This figure also displays the visual appearance of the elastic particles both independently and when used over a layer of small stones on the ballast surface to correct the position of the sleepers after settlement.

Fig. 1. Granulometric curve of rubber particles and small stones. Visual appearance of both rubber and two-layer system of rubber over small stones.

The small stones employed in this study (to be combined with different quantities of rubber to fill different levels of settlement) were also of a size that fell within this range. These stones were obtained from ophitic rocks and presented appropriate resistance to fragmentation (Los Angeles coefficient lower than 7% EN 1097-2), which limits breakage and thus helps to avoid the potential problems of particle migration or percolation and ballast packing (Fair, 2003). The size of these particles was fixed at between 14 and 20 mm Fig.1 with a density (EN 1097-6) of  $3.29 \text{ Mg/m}^3$ . To explore in detail the effect of rubber for different levels of settlement, a laboratory-testing box was employed to construct a conventional railway section at full-scale. This allowed for reproducing ballast settlement due to traffic action, after which, during maintenance operations rubber was then included by being joined to small stones to recover track geometry. The testing box was  $1 \text{ m} \times 1 \text{ m}$  (horizontal dimensions), with 0.5 m height, allowing for reproducing a railway track section from sub-grade to the top of the rail, considering half section (from the central axis of the track, as axial symmetry) under the rail seat zone of the sleeper Fig.2, where the highest concentration of stress occurs.

Fig. 2. Scheme and visual appearance of the track section area reproduced in laboratory.

For the construction of the track sections, granular sub-ballast (composed of ophitic aggregates) was first compacted by using a conventional vibratory compactor through 5–6 cm thick layers up to a total height of around 18 cm (Fig. 3a). This material had suitable characteristics for its use in railway tracks according to the Spanish specifications PF-7, most notably in terms of the size of the particles, which were smaller than 31.5 mm, with a Los Angeles coefficient below 8%. Following compaction, the sub-ballast layer presented a final elastic modulus higher than 120 MPa (according to the EN 103808 procedure), which is appropriate for high-speed lines (López-Pita and Teixeira, 2001; Berggren, 2009). Following this, a pressure cell was placed over the sub-ballast layer to measure the stress transmitted by the ballast layer (Fig.3b), which was 30 cm thick. The ballast aggregates had appropriate physical (a density of  $3.24 \text{ Mg/m}^3$  EN 1097-6) and mechanical properties (Los Angeles coefficient below 7%, EN 1097-2) for application in railway tracks while the gradation met the requirements of the European Standard EN 13450. Deeper details of ballast properties are collected in Sol-Sánchez et al. (2019).

Fig. 3. Construction stages of the laboratory section: (a) sub-ballast compaction, (b) pressure cell placement, (c) superstructure section; (d) crib ballast and final appearance.

Subsequently, the remaining components of the superstructure were placed over the ballast layer (Fig. 3c). These included a 90 cm long concrete sleeper with a

fastener system type VM (commonly used in Spanish railways, with a rail pad of static stiffness around 105 kN/mm), and a rail section type UIC-54 of 50 cm in length. The dimension of the sleeper was selected due to the fact that the stoneblowing process entails filling the gap sleeper/ballast under the rail seat zone, in a concentrated area of stress whose length usually varies between 80 and 100 cm. Finally, a ballast crib was included around the sleeper (Fig. 3d) while four LVDTs were placed (2 on the sleeper and 2 on the rail) to monitor track section movements and settlement. This process was repeated at least twice for each variable under study (different volumes of rubber and small stones for various levels of settlement).

Further, an injector tube was employed to incorporate the particles (small stones and rubber) under the sleeper during maintenance, simulating the stoneblowing process. The injector was specifically designed for this study, simulating those used for an automatic stoneblower. This consisted of a square section of metallic tubing (50 mm × 50 mm and 1 m of length) with a squared orifice (45 mm × 45 mm) on one side of the tube, near the extreme lower part of the structure. The bottom of the tube was closed with a metallic piece at 45° to the horizontal, to facilitate the projection of particles for their entry under the sleeper. In addition, a plastic tube (5 mm in diameter) was connected to the injector to apply pressure through compressed air while the particles were dropped from the extreme upper part of the metallic tube.

### ***Testing plan***

To evaluate the impact of various volumes of particles (combination of stones and rubber) for recovering different heights of section settlement, three levels of deformation were analyzed: around 5 mm; close to 9 mm; and 14 mm. These values correspond approximately to the maximum values of vertical alignment defects that trigger the vigilance of settlement evolution for tracks with train traffic at high, medium, and low speed (respectively), according to UIC Code 518. Similarly, these values are broadly related to the following three distinct periods of a high-speed track: the onset of vigilance, the need for maintenance, and emergency state, respectively.

For each level of settlement, four different solutions were applied (Fig.4) with the aim of defining the effect of rubber depending on track state, volume of particles added, and the technique used for the inclusion of rubber (with or without compaction of the layer of previously injected small stones):

- (i) Addition of the volume of small stones (referred to as SS) required to recover the level of settlement studied. For this solution, the bulk density of the layer of small stones was around 1.6 Mg/m<sup>3</sup>, while the stones were blown from two points under the section of the sleeper used in the tests (one to each side of the rail, in two corners of the same diagonal of the sleeper), as usually occurs with automatic stoneblowers.
- (ii) and (iii) Inclusion of 35% rubber (calculated by volume of stones) over the layer of stones previously mentioned in (i), obtaining a two-layer system through a two-step stoneblowing process, which has been shown to be effective (Abrashitov and Semark, 2017). The rubber dosage was selected since previous studies (Sol-Sánchez et al., 2017), have shown that this quantity is appropriate for modifying track performance.

Fig. 4. Scheme of the different solutions analyzed for each settlement level.

Within this solution, two alternatives were studied: (ii) one involving injection of the rubber just after the application of the stones (SS+35R); and (iii) another consisting of applying a compaction process (50 loading cycles) to the stones after injection, and thereafter continuing with the addition of rubber (SSc+35R).

- (iv) Inclusion of a constant quantity of rubber particles over the layer of stones (previously compacted following injection), regardless of the volume of aggregates added to recover track section settlement (SSc + R).

These configurations allowed for analyzing the effect of using different volumes of rubber (when calculated as a percentage over the volume of stones, the quantity increases as a function of the level of settlement) as well as a constant amount of rubber for each settlement level. Further, it should be noted that the volume of stones (SS) was constant for each level of settlement regardless of the solution studied (the quantity of aggregates used always corresponded to that necessary to recover track settlement with stones only). The rubber was then applied as an elastic layer over the natural stones commonly injected through the stoneblowing process.

Following other studies (Ho et al., 2013; Tutumluer et al., 2015; Horton et al., 2017), the test procedure for each configuration consisted of applying a series of dynamic loads (at 5 Hz and with a stress level of around 250 kPa at the bottom of the sleeper) over the head of the rail into the track section reproduced in laboratory. Each test began by constructing each configuration of the section (Fig.4) in the testing box described in the materials section. The first test stage then followed, in which 50 loads were applied (with the cited frequency and amplitude) to simulate the initial ballast compaction that can occur during the construction of railway tracks. Later, a series of loads were applied, measuring the evolution of settlement until achieving the required level of settlement to be studied (i.e. 5 mm; 9 mm; and 14 mm). At that point, the test was stopped and various maintenance interventions were conducted according to the following sequence:

- Lifting of the system rail-fastener-sleeper around 30 mm over the ballast surface (height selected to avoid the entry of ballast particles from crib into the gap between sleeper and ballast surface). For this step, an innovative device was used in laboratory to lift the rail-sleeper system (as occurs in real tracks, applying a similar lift height) to allow for simulating maintenance operations.
- Insertion of the injector up to the bottom of the orifice achieved the level of ballast surface.
- Injection of the total volume of stones from two points (at each side of the rail), half volume from each point, filling the gap between sleeper and ballast surface. The air pressure for the injection was fixed at around 300–350 kPa.
- Compaction of stones (when applicable, in configurations iii and iv – SSc+35R and SSc + R respectively) by applying 50 cycles at 5 Hz under stress of around 200 kPa at the bottom of the sleeper.

- Lifting again (when applicable – SS+35R, SSc+35R, SSc + R) the rail-fastener-sleeper to the position of the first step, and injecting the rubber at a pressure of around 200–250 kPa.

After the maintenance operations, the dynamic test was continued for 150,000 cycles, measuring the change in track performance in reference to conventional track behavior, just prior to the maintenance intervention. The main parameters evaluated were the stiffness of the track section, effect on irregular movement of sleeper (defined as variations in rail deflections at each side of the actuator), settlement, and stress under ballast layer.

Additionally to this testing plan, the influence of temperature and level of stress transmitted by traffic on the behavior of the track section was evaluated in order to have a deeper characterization of its performance after including the rubber aggregates. For this purpose, it was evaluated the changes in section stiffness when varying the testing temperature within 20°C–30°C–40 °C for two different levels of stress (around 125 kPa and 250 kPa under the sleeper). These tests were carried out for two different dosages of rubber (15% and 35% over the volume of compacted small stones, referred as SSc+15R and SSc+35R) as well as for the reference section with only stones (SS), and then, analysing the influence of the external conditions (temperature and stress) on sections with different quantity of rubber aggregates applied to correct in all cases 9 mm of track settlement.

## **Analysis of Results**

### ***Volume of rubber for different settlement levels***

Fig. 5 shows the mean values of the recovered height of the track section after filling 3 different levels of settlement (around 5 mm, 9 mm, and 14 mm) caused by traffic simulation (oscillation loads). This analysis was conducted for various volumes of small stones and rubber particles under the sleeper through the maintenance process of stoneblowing: SS – only stones; SS+35R and SSc+35R–35% of rubber over the volume of stones previously injected (without and with compaction, respectively); and SSc + R – a constant rubber quantity (750 cm<sup>3</sup>) over compacted stones. Fig.5a compares the volume of particles injected in each solution and the gap filled under the sleeper for each settlement level, while Fig.5b displays guide values for the volume of particles required for each solution depending on the height of settlement to be corrected. Note that these graphs show the influence of rubber on the final height of the two-layer system injected through the stoneblowing process, but not the effect of rubber on the tendency towards track settlement.

Fig. 5. Impact of volume of particles blown on recovered settlement. a) combination of aggregate and rubber volumes to fill different gaps; b) relationship between total volume of particles and gap filled.

The results revealed that, regardless of the settlement level to be corrected, the addition of rubber particles over the layer of stones had little effect on the height of the gap filled with particles, obtaining similar values to SS only. In fact, it appears that the quantity of rubber added under the sleeper had a limited impact. In particular, similar values of recovered settlement were recorded with 35% of rubber

by stones (solutions SS+35R and SSc+35R used volumes of flexible particles within the range of approximately 550 cm<sup>3</sup> and 1000 cm<sup>3</sup> depending on settlement level) and with a constant 750 cm<sup>3</sup> of rubber (SSc + R). Similarly, the effect of compacting the stones before the application had little impact on the height of settlement recovered for the different levels analyzed (when comparing SS+35R and SSc+35R). These findings could be due to the distribution of the flexible particles over the layer of stones and the deformability of rubber (even under low levels of load); thus the own weight of sleeper-fastener-rail leads to a reduction in height of the elastic particles. The results thus indicate that, to correct a given level of settlement, injection of the traditional volume of commonly used stones is required. This facilitates the widespread use of this solution, since the rubber particles can be added as an elastic component over ballast to modify section behavior (depending on track requirements) as in the case of standard flexible elements such as under sleeper pads.

Fig.5b also shows the possibility of graduating the height of the gap filled by using different volumes of stones and rubber. This could be useful when faced with, for instance, differential settlement in transition sections where various levels of settlement are to be corrected (from hanging sleeper to those properly supported on the ballast layer). In particular, the results reported for the traditional solution (stones only) reveal that around 200 cm<sup>3</sup> of stones is required for each 1 mm to be lifted. These results are in agreement with those of other studies (Tutumluer et al., 2015). In the cases in which rubber is used, for a given level of settlement, the final volumes of particles (stones + rubber) were higher. This is because the volume includes both the specified quantity of aggregates needed to correct the section geometry and the volume of rubber demanded by the characteristics of the track, calculated according to a number of criteria such as the need for modifying track stiffness (as will be seen in the following graphs).

Nonetheless, these results generally indicate that around 500–1000 cm<sup>3</sup> of rubber particles can be recycled for each half of sleeper corrected by maintenance operations, which translates to almost 300 tread layers of recycled ELTs per km of railway track, and 1.3 tons of recycled tyres per km of geometrical maintenance in ballasted tracks.

### ***Impact of rubber on section performance after correcting different settlement levels***

To analyze the impact of the rubber layer on track performance, Fig. 6 displays the change in the track deflections through the modulus stiffness parameter (measured as the stiffness per area under the sleeper) depending on the level of settlement to be corrected (Fig. 6a) as well as on the volume of rubber applied (Fig. 6b). Further, the results show the influence of the way in which the rubber is incorporated, by assessing the effect of compacting the layer of stones before injection of the rubber. The figures represent the percentage of change in reference to the values measured for the traditional section before maintenance, with negative values indicating a decrease in the parameter when including the particles, while positive values indicate the opposite.

Fig. 6. Change in track stiffness for different recovered settlement levels (a), depending on rubber volume (b).

In agreement with previous studies (Sol-Sánchez et al., 2016), the results show that including only stones led to a slight stiffening of the track section, with relatively little variation according to the height of the settlement to be corrected (Fig. 6a). In contrast, the addition of rubber led to negative values of changes in stiffness, which indicates an increase in section resilience, as occurs when using USPs (Dahlberg, 2010; Sañudo et al., 2016; Insa, 2011). In the current cases with rubber, it is possible to distinguish between the solutions where the volume of rubber was calculated as a percentage over the volume of stones (SS+35R and SSc+35R) and the solution including a constant volume of rubber (SSc + R).

In the first case, higher volumes of rubber are used when increasing the height to be corrected, leading to reductions in stiffness of up to 20% for rubber volumes around 550 cm<sup>3</sup> and values close to 50% for volumes higher than 1000 cm<sup>3</sup>, as observed in other studies analysing the influence of rubber quantity for the same level of settlement (Sol-Sánchez et al., 2017). In contrast, the change in track stiffness is practically invariable when applying a constant quantity of rubber (solutions SSc + R), regardless of the settlement values to be corrected (and thus, regardless of the volume of stones previously injected to recover section geometry). This indicates the important role played by the rubber in the optimization of track performance, since it is possible to uniformly modify track behavior or apply different dosages of rubber to gradually change the deflections of the section (particularly in transitions).

On the other hand, the results show that the effectiveness of rubber in modifying track stiffness is greater when the layer of stones is compacted prior to the injection of rubber (SSc+35R versus SS+35R). Higher changes in track stiffness are obtained, particularly when increasing the level of settlement, obtaining a reduction in stiffness of up to 30%. This could be linked to a more homogeneous distribution of rubber in the case of compacted stones (SSc+35R), this effect being more notable with higher volumes due to the difficulty of injecting such quantities of particles. These findings therefore indicate that the two-step process, including compaction of the stones, could be appropriate for track maintenance, with track performance being optimized with the use of rubber (see also Abrashitov and Semak, 2017).

On account of the possible increase in irregularities in sleeper-rail movements due to the heterogeneous distribution of particles under the sleeper, Fig. 7 shows the change in rail oscillations when applying different quantities of rubber, depending on the settlement level to be corrected. This was measured as the difference in rail deflection at each side of the sleeper, which was recorded with one LVDT on the rail surface at each side of the loading actuator. The results indicate that, in general, the addition of rubber reduces the irregular movement of the sleeper in comparison with the use of only stones. This could be associated with the deformability of rubber, which provides more stable support for the sleeper following maintenance.

Fig. 7. Results of change in rail oscillations at each side of the sleeper, depending on recovered settlement and volume of rubber.

Nonetheless, it is important to note that in the case of SS+35R (without compaction of the layer of stones prior to rubber injection), the irregularities considerably increased with an increase in the height of the gap to be filled, particularly in the 3rd level of settlement (from 9 to 10 mm). Despite including the same quantity of rubber as that used in the case of SSc+35R, the first solution (SS+35R) led to a considerably higher number of irregularities (an effect that was enhanced in the 3rd level). This is most likely a consequence of the smaller free gap for SS+35R due to the non-compaction of stones, thereby making it difficult to include a relatively high volume of rubber (greater than 800 cm<sup>3</sup>) over a thick layer of stones (required to recover the section settlement). It thus appears that the process used for the inclusion of particles during stoneblowing may be critical whilst the quantity of rubber has a lower impact. However, the performance of the section is generally improved in comparison with the conventional case in which only stones are used. These results thus confirm that injecting recycled rubber under the sleeper has the capacity to produce an elastic layer that contributes towards improving the conservation of the track.

Fig. 8 shows the influence of the rubber on the tendency towards deformation of the section following maintenance. The results show the total settlement after 150,000 cycles once the various levels of settlement have been corrected using different quantities of rubber over stones (with and without compaction). The results show that, in general, the tendency towards settlement increases when the operations are carried out on higher levels of section deformation, which could be related to higher recompaction due to thicker layers under the sleeper. Nonetheless, after 150,000 cycles the settlement values are lower than those corrected in a conventional section before applying the two-step stoneblowing process (which was fixed at around 10 mm after the application of only 50,000 cycles). This indicates the effectiveness of the stoneblowing technique for improving track durability in comparison with other alternatives such as tamping, which is in agreement with the findings of other studies (Nutbrown and Nicholas, 1999; Sol-Sánchez et al., 2016). This could help to limit the maintenance operations needed for geometrical corrections throughout the service life of the infrastructure, leading to environmental benefits such as the reduced consumption of energy and raw materials. This is in accord with the conclusions of other studies concerning the search for cleaner transportation (Zhang et al., 2019).

Fig. 8. Effect of each solution on section settlement after maintenance interventions, depending on the level of gap filled.

With respect to the impact of rubber, it appears that regardless of the settlement level and the quantity of flexible particles, the tendency towards settlement is reduced when applying rubber as an additional elastic layer over the stones, obtaining reductions of up to 25% in comparison with the use of only stones. Therefore, the higher the settlement level, the higher the benefit of using rubber. This could be due to the elastic behavior of this material and the possible improvement in sleeper support (greater and more homogeneous contact area due to the deformability of rubber), as seen in other studies that have applied elastic elements under the sleeper (Dahlberg, 2010; Wilk, 2016; Sol-Sánchez et al., 2014).

This positive effect of adding the flexible particles could significantly reduce the need for further maintenance operations (thus improving track conservation and the demand for raw resources). However, it should again be noted that the non-compaction of stones when recovering high levels of settlement could reduce the positive effect of rubber, as seen in the results reported here.

For a deeper analysis of the effect of rubber on improving track durability, Fig. 9 shows the impact of using different quantities of flexible particles on the stress values under the ballast layer. The results indicate that the inclusion of rubber under the sleeper has the positive effect of reducing stress on the sub-structure (by more than 30% in general), regardless of the volume of flexible particles added and the level of settlement recovered, which was shown to have little influence on this parameter (for the solutions with a constant quantity of rubber, SS – 0 cm<sup>3</sup> and SSc + R – 750 cm<sup>3</sup>) (Fig. 9a). In terms of the quantity of rubber (Fig. 9b), it appears that an increase in rubber volume increases the capacity to reduce stress on the ballast when this elastic component is applied over compacted stones (SSc+35R). This is shown by the fact that in the non-compacted case (SS+35R) there was relatively little influence of the volume of rubber, possibly as a result of a less homogeneous distribution of this material.

Fig. 9. Stress under ballast depending on the recovered settlement (a) and the quantity of rubber injected (b).

### ***Effect of external conditions on rubberized track performance***

Fig. 10 displays the influence of varying the testing temperature for two different levels of stress applied over track sections with diverse quantities of rubber (0%, 15% and 35% over volume of compacted stones), analysing the effect on the stiffness modulus of the section (measured as the stiffness per unit of the area of the sleeper bottom surface). Again, results clearly show that the increase in the dosage of rubber leads to the reduction in global section stiffness, regardless of temperature and level of stress, obtaining decreases even higher than 50% when applying the solution of SSc+35R.

Fig. 10. Influence of stress level and temperature on the stiffness of sections with different quantity of rubber.

Regarding the influence of the testing conditions, it is seen that while in the section of reference (SS, without rubber) the increase in temperature led to lower stiffness values while in the cases with rubber this parameter increased. This fact could be related to a slight softening of the rail pad in the case of the reference section, and then, reducing the track stiffness, while in the solutions with rubber under the sleeper, the softening of these elastic particles (due to higher temperatures) led to reduce their effect to provide with flexibility to the section. This phenomenon took place for both levels of stress. Thus, this must be considered in areas with high temperatures, but also it must be taken into account that the rubber particles are protected with the sleeper and ballast shoulders, and then, their variation in temperature is expected to be minimized. On the other hand, results reflect that the

increase in stress level led to the stiffening of the track sections, regardless of the solution tested and the temperature applied.

## **Conclusions**

This paper focused on recycling rubber from end-of-life-tires for use in a two-step stoneblowing process. The aim was to improve the geometrical conservation of ballasted railway tracks by providing an elastic layer under the sleeper (as in the case of standardized Under Sleeper Pads), which could limit environmental impacts associated with track maintenance. This solution also represents an innovative use of ELTs by significantly consuming an abundant source of waste material. The full-scale laboratory tests carried out in this work aimed to evaluate the effect of applying different volumes of rubber (over small stones) for correcting various levels of track settlement while optimizing track performance. On the basis of the findings obtained from these tests, the following conclusions can be drawn:

- The different levels of settlement in railway tracks can be corrected with standard volumes of small stones commonly used in the stoneblowing process. Recycled rubber particles are then added as an extra layer over the stones after their compaction, providing an elastic component under the sleeper, which has the capacity to modify general track performance.
- The inclusion of recycled rubber allows for increasing the resilience of the section, graduating the global stiffness of the section depending on the volume of rubber applied. The results also show that once a specific volume of rubber has been selected, its effect on track stiffness is practically independent of the level of settlement to be corrected.
- The addition of recycled rubber generally led to fewer fluctuations in the sleeper-rail oscillation after the maintenance process in comparison with the case in which only stones were used. This could be due to the more stable support offered to the sleeper on account of the resilience of rubber particles, which modify the contact between sleeper and ballast.
- Similarly, the injection of recycled rubber particles can modify the global performance of railway tracks, reducing the settlement of the track in reference to the traditional (stones only) solution, this benefit being more notable when there is a greater level of settlement to be corrected. This is due to the fact that the addition of recycled rubber led to lower stress values on the ballast layer, obtaining a greater reduction in pressure when increasing the quantity of rubber.
- These results confirm that this solution could represent a cleaner maintenance technique that reduces the need for further track interventions, and therefore, the consumption of resources (including the energy needed by machines, and raw materials such as extra aggregates). The dosage of rubber will depend on track requirements, but generally speaking, it appears that this solution could lead to the recycling of around 300 tread layers per kilometer of track.
- Nonetheless, it must be considered that the laboratory results reflect that the temperature can play an essential role on the performance of the rubberized track sections, decreasing increasing their stiffness when rising

the temperature as a possible consequence of the softening of the particles, and then, reducing their capacity to provide flexibility to the section. On the other hand, the variation of stress level seemed to lead to comparable variations in track performance to those obtained for the reference section without rubber particles.

Based on the results reported here, it appears that injecting rubber particles from ELTs over the conventional layer of stones (applied by stoneblowing) presents the opportunity to recycle waste rubber. In addition, track durability is improved, optimizing its mechanical behavior by using different volumes of rubber, which could be particularly advantageous in transition sections. Nonetheless, in-situ studies are needed to confirm and extend these findings before the widespread implementation of this technique. In particular, further research is required regarding the different parameters that could influence the behavior of rubber in real tracks.

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