Case studies & non-highway applications; Success and failure from real practice

Bituminous materials for railway engineering

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Abstract

Railway is considered to be a fundamental transportation system by providing diverse environmental and economic advantages, particularly after the development of high speed railway. However, during the design of modern railway, it should be also considered that the continuous rise in train speed leads to important increases in the dynamic loads transmitted to the track, while these infrastructure requiring higher resistant and quality indexes. In this context, the application of bituminous mixtures at the top of the substructure could allow for improving the mechanical performance and durability of the global track section while reducing maintenance costs. However, to obtain such benefits, it is required a proper design and analysis of the bituminous materials to guarantee its long-term performance. Thus, the present paper focuses on developing high-performance asphalt materials designed according to their application in railway tracks. For this purpose, diverse studies were carried out for the design of resistant asphalt mixtures for railways through laboratory tests specifically developed to simulate real traffic and climate conditions expected during this application. Similarly, a laboratory test was designed to analyse the effect of the bituminous mixtures on the global railway section under different track states and conditions. Results showed that the application of the asphalt materials designed in this paper allows for improving the mechanical behaviour and durability of the railway track in reference to the conventional bituminous materials used in this field.

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1. INTRODUCTION

Railway transportation is regarded as an advanced means of communication due to a number of environmental and economic benefits in comparison with other transportation systems. It should be noted that the railway is considered to allow for reducing CO2 emissions (around 30% lower than a car or plane), requiring a lower energy per passenger-kilometer than bus, car, or plane (carrying 3 times more passengers whilst using a similar amount of energy), using 3 times less land than highways, and reducing external costs (caused by accidents, air pollution, urban effects, and climate change), among others [1].

However, in order for the railway to be fully accepted as the main transportation of the future and to guarantee its efficiency (indicated as a focus of the Horizon 2020 program), it will be necessary to continue with the development and evolution of the system. In this context, whilst special attention has been paid in vehicles and communication systems during last decades to provide a modern and attractive means of communication, infrastructure demands for improvement to support the traffic and requirement of modern trains. In this sense, it is highlighted the demand for enhancing the track substructure to support the higher dynamic loads transmitted by trains at high speed and with higher loading capacity while offering longer service life and higher quality indexes. For this purpose, last decades focused on adding stiffer granular layers (one of them being known as sub-ballast) between the subgrade and the ballast, or even the inclusion of bituminous layers as sub-ballast with the aim of limiting the deterioration of the substructure to a minimum while allowing for reducing the thickness of such bearing layer [2-3].

To date, the common bituminous sub-ballast has consisted of an asphalt layer with a thickness of around 12-15 cm, and is composed of a dense-graded bituminous mixture with a maximum aggregate size of 22-25 mm and a conventional bitumen [4]. However, it should be considered that this material has been commonly designed with the similar characteristic and procedure as that used in base layers of pavements in highways, despite the fact that the requirements on railway infrastructures will be different. Similarly, conventional bitumen has been considered for the manufacturing of the mixtures by using traditional production techniques. However, it must be taken into account that a great development of bituminous materials has taken place during last decades, mainly for the application of these products in pavement for roads. Then, it could result interesting the adaption of these technologies and materials for their application into railway infrastructure to provide tracks with higher quality, strength and durability, and therefore collaborating in the development and evolution of this means of transportation.

In this context, a research consortium, composed by the companies CEPSA and Ciesm-Intevia, and the Laboratory of Construction Engineering at the University of Granada, is carrying out a research project where one of their goals is focused on the development of high performance binders and bituminous materials for their application as structural layers in railway tracks, searching for improving their mechanical behavior and durability. Similarly, these bituminous layers will include smart functions to collaborate in the monitoring of railway track behavior (which results essential in modern infrastructures), being this functionality evaluated through innovative laboratory tests. Particularly, this paper presents some of the goals and steps to be followed along the project while providing initial results into the influence of using bituminous sub-ballast with high performance binders on its mechanical performance.

2. HIGH PERFORMANCE BINDERS AND BITUMINOUS MIXTURES FOR RAILWAY INFRASTRUCTURES

Previous studies have proved the key role of the substructure strength on the global performance and durability of the railway track. Particularly, full-scale laboratory tests [5], focused on analysing the influence of the design of the section on their performance, proved that the bearing capacity of the substructure has a direct and remarkable relationship with the stiffness modulus of the whole railway track. Also, it was seen that this parameter is also associated with the trend to settlement of the infrastructure, and therefore, this denotes the importance of using a strong substructure to reduce the geometrical degradation of the track. In fact, Figure 1 shows such relationships associated with varying the strength of the substructure to evaluate its influence on global track modulus, and later, with the settlement of the section reproduced in a laboratory testing box after applying 200,000 loading cycles simulating the continuous passage of trains. An image of the testing box used for this study can be seen in Figure 2.

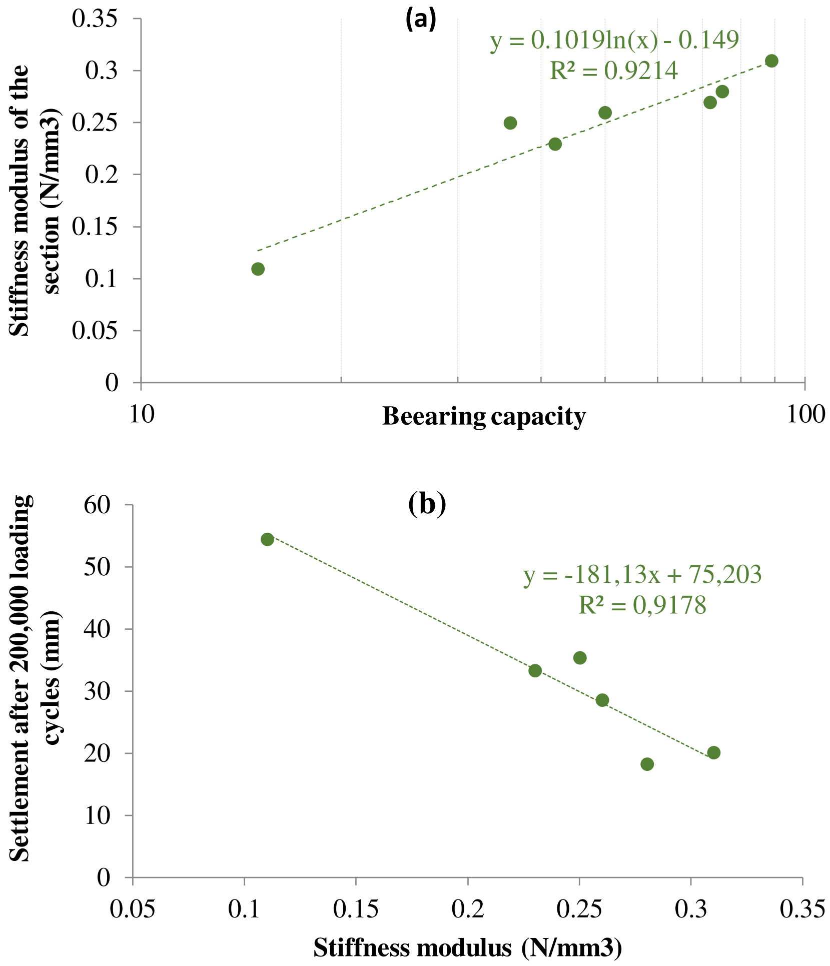

Figure 1: Results from full-scale laboratory tests: (a) influence of sub-structure strength on global section stiffness; (b) effect of track stiffness on section settlement. (Adapted from Sol-Sánchez et al., 2016).

Figure 2: Full-scale laboratory tests.

In this context, from the 80' it has been considered the possibility of using asphalt materials as structural layers in the railway infrastructure, searching for improving the performance of the track while reducing the consumption of aggregates, in comparison with tracks with only granular materials where thicker layers are required to provide the strength to support the current traffic conditions. Among the diverse applications carried out to date, it is possible to highlight some experiences in France, Italy, Japan, Spain or United States, among others. Although different designs and applications of the bituminous mixtures have been carried out, it is remarkable its use as sub-ballast to replace the conventional granular layer (with a thickness around 20-25 cm) with a bituminous layer with thickness around 12-15cm.

Most of the experiences using bituminous sub-ballast proved that this solution could allow for increasing the global track stiffness (despite the fact of using layers with lower thickness), while decreasing the track settlement and irregularities due to abrupt changes in track stiffness, which leads to lower need for maintenance. Also, previous laboratory tests [6] have demonstrated (Figure 3) the potential ability of bituminous sub-ballast (B.S. at 25ºC, which is a common temperature for this material in this application) to reduce the stress on subgrade (Figure 3a) more than 50% in reference to the conventional granular sub-ballast (G.S.), which could be associated with the higher stiffness modulus of the asphaltic solution (Figure 3b).

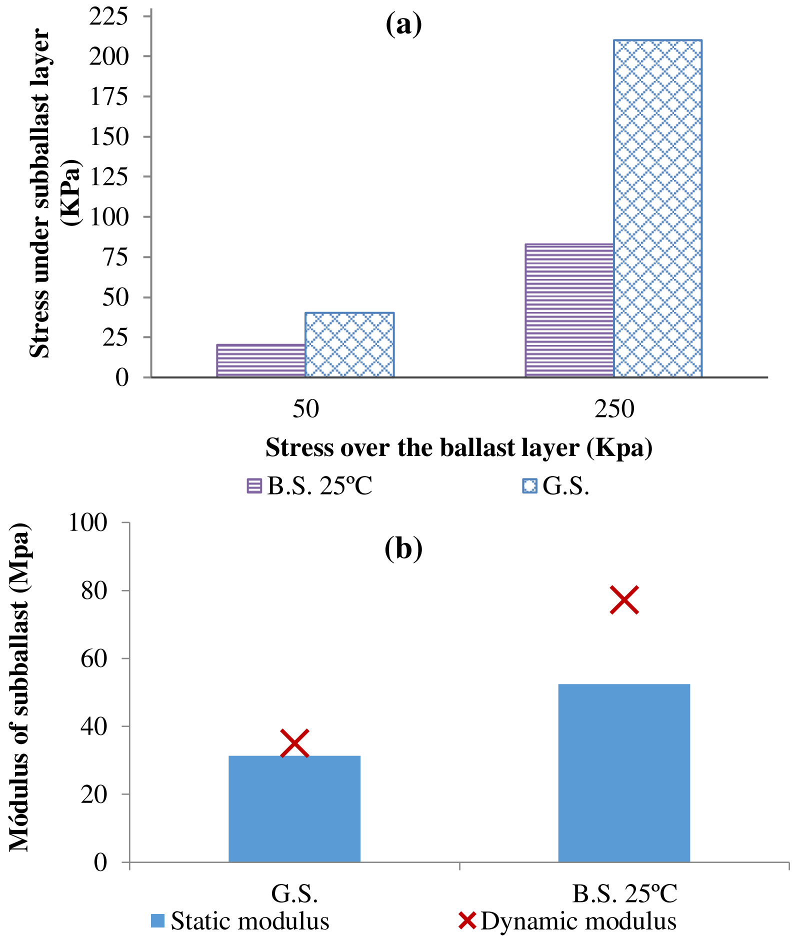

Figure 3: Influence of using bituminous sub-ballast (B.S.) instead of the usual granular one (G.S.) on: (a) capacity to reduce the stress transmitted to subgrade; (b) stiffness modulus of the layer. (Adapted from Sol-Sánchez et al., 2015).

Nonetheless, despite these benefits associated with bituminous sub-ballast, it must be considered that this material commonly has been designed following criteria and methods usually used for its application in pavement for roads [7] while the requirements and functions of the asphalt layer in railway tracks will be different from those in roads. Then, it could be interesting the establishment of a designing procedure for the bituminous sub-ballast for its application in railway, considering the main failure modes and in-service conditions expected in this type of infrastructure.

Commonly, it has been used a dense asphalt mixture (like a type AC 22 S), with a conventional bitumen like the type B50/70. However, it must be considered that other types of mixtures could also be appropriate (or even better) to reduce some failure modes like fatigue cracking (which is an essential issue when used as sub-ballast due to the difficulty for repairing this bituminous layer under the ballast) or the resistance to permanent deformations due to the punching of ballast particles. Similarly, it should be taken into account that the petroleum industry has demonstrated great advances during last decades providing high performance binders, with higher capacity to resist the stresses transmitted by traffic while contributing to enlarger the life of the asphalt mixture.

Therefore, in this context, the research project in which is focused this paper, aims to develop a range of bitumen with specific composition and characteristics for its application in railway tracks, considering environmental and economic criteria searching for a more competitive and sustainable infrastructure. Similarly, new types of asphalt mixtures will be developed by considering the function of the asphalt layer in railway tracks while applying the new high performance bitumen. In this sense, it will be analysed the rheological behaviour and resistance to fatigue of new binders (using a Direct Shear Rheometer and Dynamic Mechanical Analysis tests) while different mixtures will be designed, like:

-AC 22 S with B50/70 (the reference that has been used in railway infrastructures).

-AC 22 S with B15/25 as high modulus asphalt with the aim of reducing more the thickness of sub-ballast layer.

-AC 22 S with modified bitumen with the aim of optimizing the structural design of the track while increasing the service life.

-AC 16 S with B50/70 in order to analyse the influence of the granulometric curve on the bituminous sub-ballast performance.

-Anti-cracking mixture with the aim of considering one of the main concerns with bituminous mixtures as sub-ballast in railway tracks.

To analyse the performance of these mixtures, it will be used conventional tests commonly used to determine basic properties like air void content (EN 12697-8) [8]; Marshall test (EN 12697-34) [9], water sensitivity test (EN 12697-12) [10]; stiffness modulus (EN 12697-26) [11] and triaxial test (EN 12697-25 method B) [12]. Additionally, to evaluate the performance of the mixtures according to their specific application in railway tracks, it will be developed innovative tests to determine the resistance to punching deformations due to the contact with ballast particles; the resistance to cracking due to traffic loads; and their effect on the global track behaviour through full-scale laboratory tests. Particularly, the present paper shows some initial results analysing the influence of the binder and type of mixture on the performance of the bituminous sub-ballast.

3. INFLUENCE OF TYPE OF BITUMEN AND TYPE OF MIXTURE ON SUB-BALLAST PERFORMANCE

From the initial results of the cited research project, this paper evaluates the influence of replacing the conventional bitumen commonly used in sub-ballast for railway with a modified binder for high performance asphalt (HPA), but both binders used to manufacture the same type of mixture with similar aggregates and design parameters (mixture type AC 22 – EN 13108-1) [13]. Additionally, it was assessed the effect of replacing the common type of mixture used as sub-ballast, studying then the performance of a mixture with finer aggregates and commonly applied in pavement surfaces, like the type SMA (Stone Mastic Asphalt – EN 13108-5) [14]. Table 1 summarizes the main characteristics of the mixtures used in this study.

Table 1: Materials used for the design of the mixtures analysed

Mixture name	Mixture type	Aggregates type	Bitumen type	Bitumen content	Additives
Reference	AC 22 S	Fines: Limestone Coarse: Limestone	B50/70	4.25 %/mix	-
HPA	AC 22 S		CRMB	4.25 %/mix	-
SMA	SMA 11	Fines: Limestone Coarse: Ophite	B50/70+CR+P	5.30 %/mix	Fibers

In order to assess the effect of the bitumen properties on the mechanical performance and durability of bituminous sub-ballast, it was studied a crumb rubber modified bitumen (CRMB) to obtain a high-performance asphalt mixture (HPA) from using the same design criteria as the reference mixture (a dense mixture type AC 22), but replacing the conventional B50/70 binder with the high performance bitumen. Also, another polymer modified bitumen was used in this study, but in this case to obtain a SMA to analyse the influence of the type of mixture to be used as sub-ballast instead of a AC 22. For this last case, the bitumen was type B50/70, but modified crumb rubber and polyethylene. The conventional bitumen used for the reference mixture presented a penetration value at 25°C of 52 dmm (EN 1426) and a softening point of 50°C (EN 1427) while the modified binders for the HPA and SMA, which were respectively a crumb rubber modified binder (CRMB) and a conventional B50/70 but including 10% of crumb rubber and 5% of recycled polyethylene (over bitumen weight) – B50/70+CR+P, presented penetration values of 25 dmm and 26 dmm, and softening point of 63°C and 78°C, respectively.

The reference mixture and the HPA (both a dense mixture type AC 22 S) were manufactured with limestone aggregates, using a granulometric curve that fit the requirements of the Standard EN 13108-1. Also, both mixtures used similar dosage of bitumen (4.25% over the total weight of the mixture), which was stablished as optimal from the Marshall test (EN 12697-34). On the other hand, the SMA was manufactured with limestone aggregates for the fine fraction (0/6 mm) while the course one (6/12 mm) was composed of ophite aggregates since this type of mixture commonly use aggregates with higher resistance to fragmentation in the course fraction. The properties of the aggregates and the granulometric curve was used in consonance with the Standard EN-13108. For this last mixture, the dosage of bitumen was 5.30% (over the total weight of the mixture) while textile fibers (around 0.3% over bitumen weight) were used in order to allow the higher content of bitumen of the mixture and increase its resistance to cracking.

To evaluate the influence of the design of the bituminous sub-ballast on its mechanical performance, firstly, it was applied characterization tests like determination of air void content (EN 12697-8) [8]; Marshall (EN 12697-34) [9]; water sensitivity (EN 12697-12) [10]; and stiffness modulus (EN 12697-26 annex C) at 20°C [11]; to later develop a punching test and a fatigue cracking test. In the first case, the test consisted of applying 100,000 cycles at 5Hz under a stress of 250 kPa (regarded as an unfavourable loading condition that can occur over the sub-ballast layer) [2] on the contact between the sub-ballast specimen and a standard ballast plate (formed by ballast particles glued to a metallic plate to simulate ballast surface). This test was carried out over squared specimens of 300 mm x 300 mm and a height of 60 mm, at a temperature of 40°C (which can be considered appropriate to evaluate the resistance of sub-ballast layer to plastic deformations under unfavourable conditions). On the other hand, the fatigue cracking was evaluated through the UGR-FACT test [15] at a temperature of 20°C. This test was carried out at a frequency of 5 Hz and a stress around 400 kPa over the specimens (200 mm in length, 60 mm in width, and 60 mm in height), reproducing tensile and flexion efforts on the specimens as those expected in the material during its service life.

Table 2 shows the physical properties of the mixtures, the results of the Marshall test and the water sensitivity test. It can be seen that the HPA presented quite similar values of density to the reference mixture, leading to a slightly increase in air void content, but still around 3% as recommended for this type of mixture as bituminous sub-ballast, according to other experiences [2]. The value of stability for the HPA is in the order of the reference mixture while the use of a high performance bitumen allowed for lower deformation. In the case of the other type of mixture (SMA), this was designed with higher air void content (4.5%) as commonly done for its application in pavements, which could be the reason for obtaining lower value of stability joined to the fact of using finer aggregates. Nonetheless, it was seen that the values of deformation were lower than in the other mixtures studied.

Also, results reflect that the replacement of conventional bitumen (reference mixture) with a high-performance one (HPA) led to the increase in tensile strength and resistance to water action. However, in the case of the other type of mixture (SMA), despite the fact of using also a high-performance bitumen, it showed values of tensile strength slightly lower than the other mixtures (particularly in comparison with the HPA), which must be due to the use of other type of granulometric composition. Nonetheless, this mixture showed similar (or even better) values of resistance to water action.

Table 2: Main physical and mechanical properties.

Property	Reference	HPA	SMA
Maximum density (Mg/m^3)	2.64	2.60	2.73
Bulk density (Mg/m^3)	2.57	2.52	2.60
Air void content (%)	2.6	3.2	4.5
Marshall stability (kN)	13.3	11.7	8.7
Marshall deformation (mm)	3.6	2.9	2.5
Indirect Tensile Strength at 15°C (kPa)	2,159.9	2,572.9	1823.3
Indirect Tensile Strength Ratio –ITSR (%)	86.0	94.9	90.5

Figure 4 displays the results of stiffness modulus at 20°C for the different types of mixtures. It was seen that the use of a high-performance binder to manufacture the AC 22 considered for bituminous sub-ballast, led to a considerable increase in the bearing capacity of this material which could allow for the improvement of the strength of the sub-structure in reference to the tracks with conventional bituminous sub-ballast (and then, more than in the tracks with traditional granular sub-ballast). Regarding the other type of mixture (SMA), it recorded quite similar values of stiffness to the reference mixture AC 22, which denoted that could be appropriate to be used as bituminous sub-ballast in comparison with the reference mixture and according to some standards (like PF-7) [16] into the application of this material in railways.

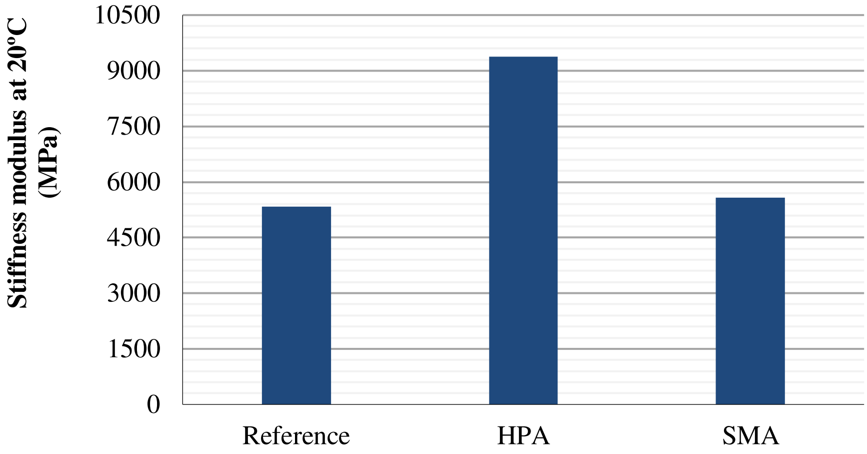

Figure 4: Results of stiffness modulus

Figure 5 shows the deformation of the mixtures at the end of the test due to cyclic punching efforts transmitted by ballast particles. It is seen how the alternative mixtures (HPA and SMA) allowed for an important increase in the resistance to permanent deformations, reflecting slight difference between them, which could be related to the fact that both used high-performance bitumen (modified binders). Then, it can be seen that the use of these high-performance mixtures could lead to a reduction higher than 50% of the final deformation, and then, reducing the global track deformation and susceptibility to failure due to irregularities.

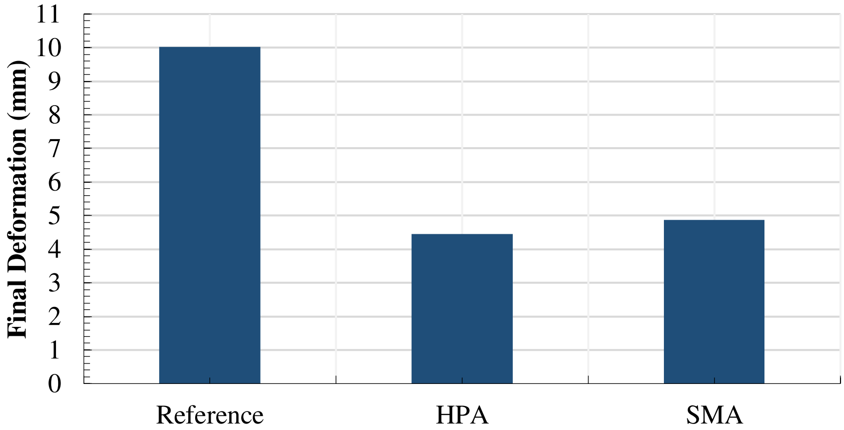

Figure 5: Final deformation of the specimens after the punching test.

Figure 6 presents the results of the UGR-FACT tests, displaying the number of cycles to material failure under fatigue test at 20°C. It is seen that the replacement of the conventional bitumen used in the AC 22 mixture (reference) with a high-performance binder (HPA) allowed for a considerable increase in the fatigue life of the specimens. Similarly, although with lower effect, the use of alternative types of mixtures with finer aggregates and with modified binder, also led to a remarkable increase in the number of cycles required to material failure. Then, these results denote that the application of other alternative mixtures, properly designed and including high-performance binders, could result in important improvement of railway tracks quality and durability.

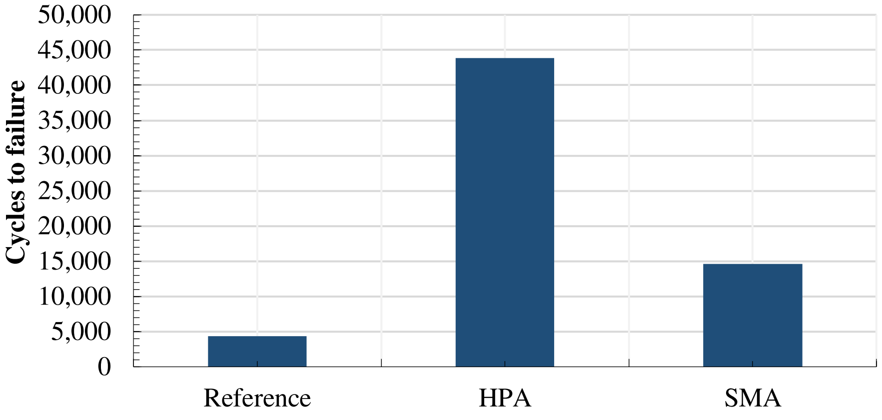

Figure 6: Results of the UGR-FACT test.

4. CONCLUSION

The present paper aim to study the potential use of high-performance bitumen and asphalt mixtures for their application in railway tracks in order to improve the mechanical response and service life of the infrastructure. For this purpose, this study reviews the importance of the sub-structure on track performance and the role of bituminous sub-ballast, while assessing (through laboratory tests) the influence of replacing the conventional mixture used as sub-ballast with other types of mixtures and using high performance binders. From this study, the main conclusions are the following:

-It is demonstrated that the strength of the sub-structure of railway track play an essential role on the mechanical response and durability of the infrastructure. Stronger sub-structures could improve the performance of the track.

-The use bituminous sub-ballast is demonstrated to allow for increasing the bearing capacity of the track section while reducing settlement and improving other essential properties of railway tracks.

-The use of innovative high-performance binders and asphalt mixtures could lead to higher benefits for the track behaviour and durability, which demands for further research to develop more appropriate materials to respond to the current and future requirements for the railway.

-Initial laboratory results have proved that the replacement of conventional bitumen with modified one could allow for increasing the mechanical performance of the same type of asphalt mixture conventionally used as sub-ballast. Particularly, it was improved the resistance to deformations due to ballast punching while also increasing the fatigue life of the material.

-Similarly, this study demonstrated that the application of other type of mixture could be considered to improve the performance and durability of the sub-ballast, and therefore, of the global railway track.

5. ACKNOWLEDGMENTS

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