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

Design and development of new bituminous mixtures, based on waste recovery, to be used as the main component of slab tracks in urban tram lines.

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Abstract

This article aims to show the work carried out to develop a new slab tracks in urban tram lines that, thanks to the intrinsic viscoelastic behavior of the bituminous mixtures, which allows to mitigate the transmission of vibrations from its origin (the wheel-rail contact) to the ground, thus attenuating the condition to the environment and the arrival of these to the foundations of the adjoining structures. To achieve this objective, bituminous mixtures have been designed and studied, including the addition of plastics from recycled materials, thus seeking an improvement in their global properties, while achieving a revaluation of waste, with the economic and environmental advantages that this implies. This article presents the results obtained in laboratory tests carried out to evaluate the behavior of the material, the numerical modeling developed for design (Structural checks and vibratory considerations) and the execution and evaluation of a bituminous mixtures slab track pilot section. To evaluate the behavior of different bituminous mixtures to mitigate the transmission of vibrations, resistance to fatigue and stiffness tests were carried out according to current European standards. The numerical modeling developed was calibrated and validated for concrete slab tracks in tram projects previously to this study and it was adapted and used to design and optimize the structural section which was executed as pilot section. A bituminous mixtures slab track pilot section located in El Campello, Spain (Owner: TRAM Metropolitá D`Alacant. Generalitat Valenciana) was built, checked and monitored along the time. After more than five years, this pilot section continues to function properly and keeps its properties intact, thereby it can be considered that the success of the project has been achieved.

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1. INTRODUCTION

Asphalt mixtures highlight within the materials incorporated to the design of railway solutions due to their interesting structural properties and to their vibration's abatement capacity. In this context, the most extended use of asphalt mixtures is as subballast layer in the track infrastructure which has been already implemented with excellent results in high speed lines in Spain, Italy and Japan [1]. Moreover, Xei and Rose [2] performed a numerical experiment that revealed that, in poor terrains, an asphalt layer under the ballast minimizes the deflections, accelerations and stresses in the subgrade induced by the passing trains. Di Mino et al. [3] also considered asphalt layers in analytic models for the vibration prediction, demonstrating the good performance by comparing the results obtained with others from conventional ballasted tracks.

In order to prompt the vibration mitigation power provided by these bituminous layers, Zheng et al. [4] incorporated rubber powder to the mixture. Laboratory tests demonstrated that the rubber increases both the stiffness and the damping ratio of the mixture, improving simultaneously the structural and dynamic behaviour of the infrastructure. This effect was evidenced in the high-speed line Torino-Milan by D'Andrea et al. [5], where it was observed a vibration decrease in the range 50-100 Hz. Moghaddam et al. [6] incorporated recycled plastomers to the asphalt mixture, demonstrating an improvement of the SMA mixture properties.

In this context, the development of a new slab track system addressed to the vibration reduction in tram networks environment was posed. This track is composed of a slab exclusively made of an asphalt mixture which includes recycled plastics in the formulation. This paper studies the design and the dynamic behaviour of this new asphalt slab track. Firstly, the optimum dosage of the mixture is determined, and the dimensions of the cross section are calculated. Secondly, the dynamic performance of the track against vibrations induced by a passing vehicle is assessed. To accomplish this second part, a three-dimensional Finite Elements Model (FEM) is created and then calibrated and validated with acceleration records from a real track, which is constructed according to the requirements established in the previous stage. In order to confirm the versatility of this new solution, the track is tested in different scenarios in which the surface layer of the track is varied to assess the consequences of that on the dynamic behaviour.

Since the last part analyses the vibration response of the new asphalt slab track using a three-dimensional finite elements model, it should be mentioned the previous work developed by Kourioussis et al. [7] in which the accelerations near the Brussels tram track were calculated using an integrated numerical model. Another interesting example of the FEM applied to acceleration prediction in concrete slab tracks can be found in Fang et al. [8], who compared the dynamic behavior of different slab tracks.

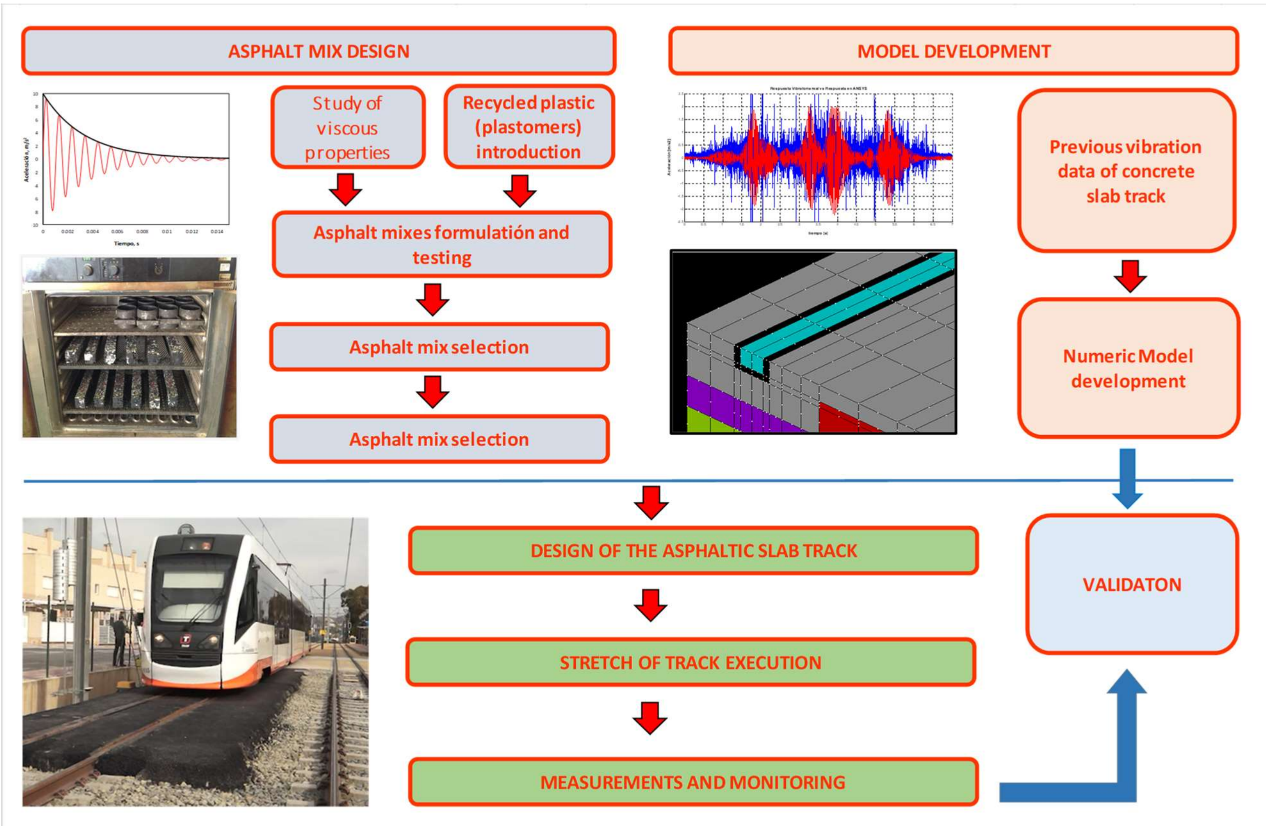


Figure 1. Work Plan

2. DETERMINATION OF OPTIMAL MIXTURE

The election of the optimum dose of the asphalt mixture that constitutes the new track must consider three fundamental aspects: sufficient vibration mitigation capacity; meet durability and strength requirements and be economically viable.

2.1 Vibration mitigation capacity

Considering a viscoelastic behavior, the complex stiffness modulus E^* of the asphalt mixtures can be defined as the sum of the real modulus E' which has into account the elastic component and the imaginary modulus E'' representing the viscous part:

$$E^* = E' + iE''.$$

The quotient of the imaginary and the real component is known as the loss factor η and is equal to the tangent of the phase angle Φ:

$$\tan(\Phi) = \eta = \frac{E''}{E'}.$$

The vibration attenuation capacity of a material is given by its damping ratio ξ, which is calculated as the loss factor divided by two:

$$2\xi = \eta.$$

The relation between the phase angle and the damping ratio was studied by Billigri et al. [9]. Since the objective in this case is also to achieve an asphalt mixture with a high damping ratio, different dosages of the mixtures, in which the content and the properties of the aggregates, filler, binder and plastics are varied, are developed determining the phase angle in each one according to the standard UNE-EN 12697 [10] for the determination of the fatigue strength on asphalt mixtures.
The selected temperature was 20°C according to climate conditions in the experimental stretch location. The excitation frequency was 5 Hz, approximately equal to that of the bogie passage induced frequency of a tram vehicle at low speeds. Finally, five different microdeformation values selected based on the expected values for the infrastructure layers of a tram tack were tested. Results in Fig. 2 show that highest values were obtained for the specimens containing a 0.5 % of plastic waste for both, asphalt concrete AC20 (S20) and stone mastic asphalt (SMA16). Moreover, the phase angle obtained for SMA16 mixtures was higher than those obtained for the AC20 (S20).

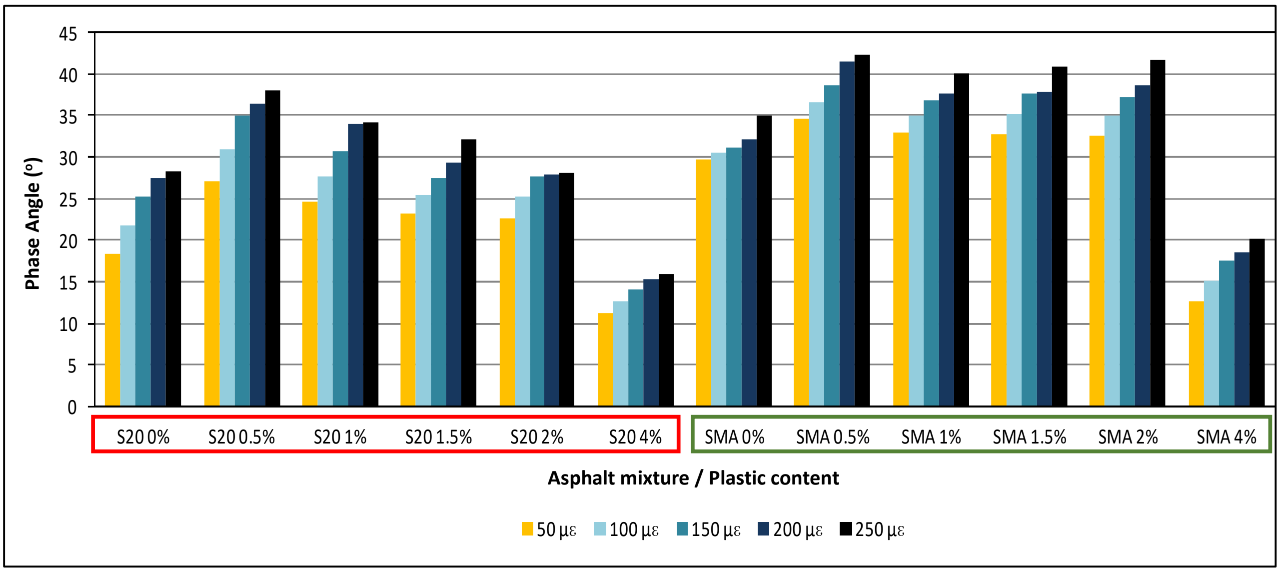


Figure 2. Phase angle values for the different mixtures tested

2.2 Mechanical properties of the mixtures

Besides providing high damping ratio, the asphalt mixture of the new asphalt slab track must fulfil several requirements to ensure the structural stability and durability. These requirements are specified in the PG-3 document [11] for road works and have been adequately adapted to the needs of the current project.
Within the tests performed on the asphalt mixtures, it should be cited the Marshall stability and flow, fatigue strength and density tests. All these tests have been developed in agreement to the standards UNE-EN 12697 [10] for asphalt mixtures.

In Fig. 3, the values obtained for the Young's modulus are displayed. This parameter is crucial for the design since a high value may cause a reduction in the thickness of the layers, achieving material cost savings and obtaining the same strength against the loads produced by the vehicles.

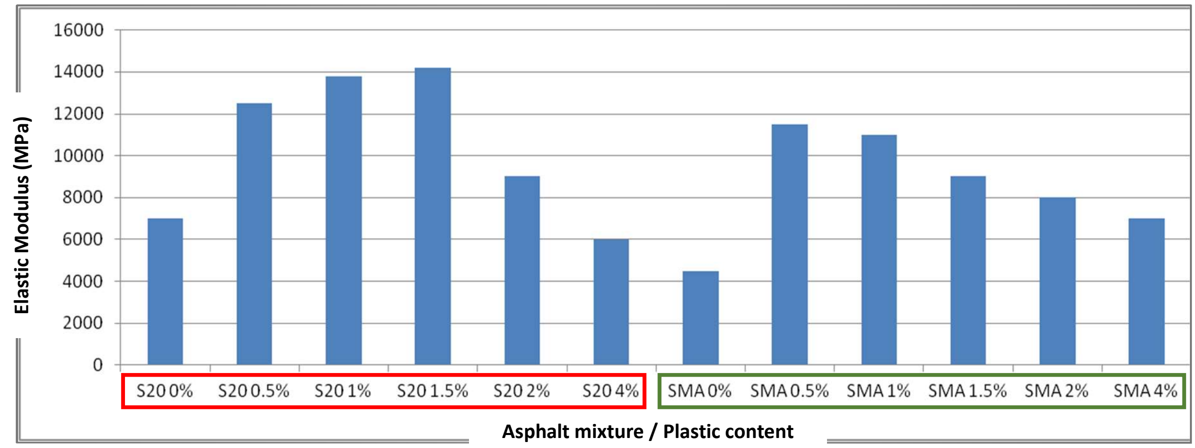


Figure 3. Young's modulus for the different asphalt mixtures tested

There is not a great difference between the mixtures that obtained the best damping results; the Young's modulus of the mixture AC20-0.5 % is 12200 MPa while in the case of the SMA16-0.5 % reaches 11800 MPa.
Marshall stability and flow, relative density and air voids on the mixtures are presented in Fig. 4. In all the cases, the minimum specifications of the standards are satisfied.

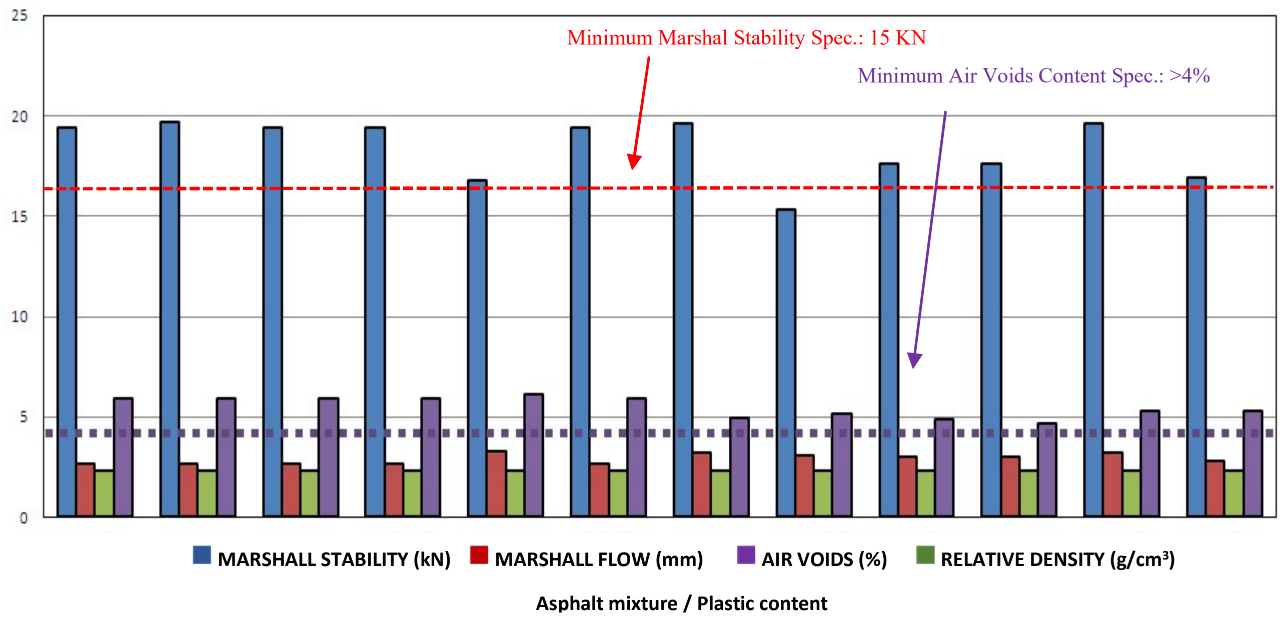


Figure 4. Results of Marshall stability and flow, relative density and air voids

2.3 Economic appraisal

The economic criteria used for the appraisal of the different asphalt mixtures have only considered the fabrication costs. It is supposed the rest of the costs (i.e. transportation, compaction, etc.) are similar in all the cases as any of the asphalt mixture requires specific methods different from the conventional ones.

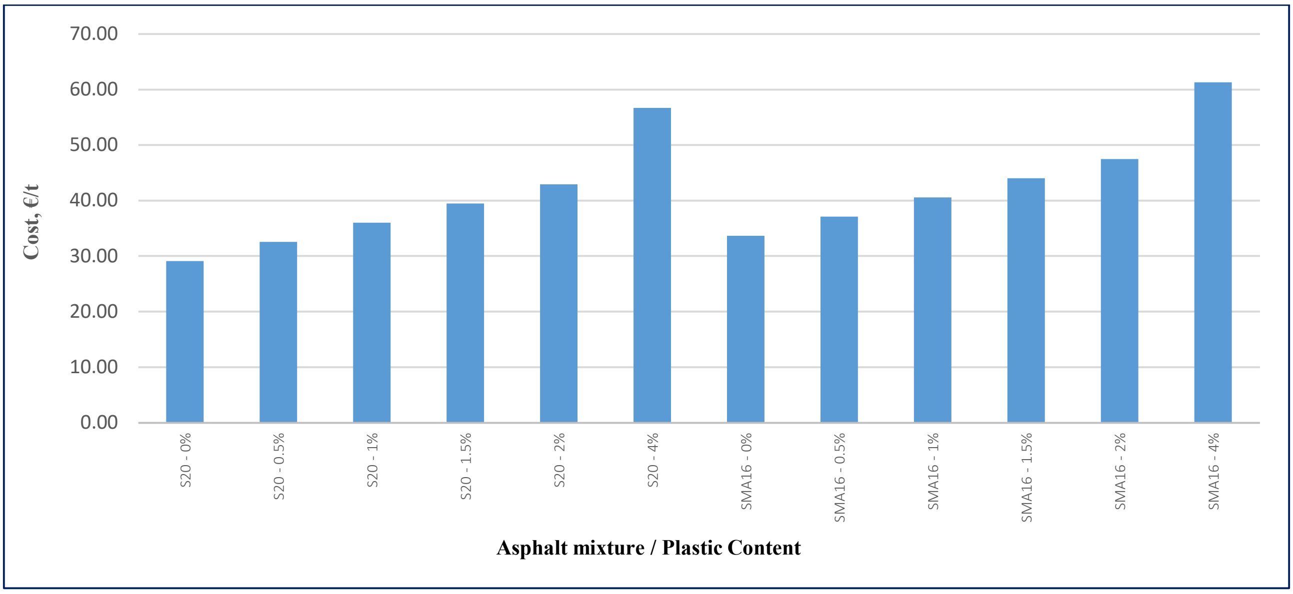


Figure 5. Fabrication cost of the different asphalt mixtures

In Fig. 5, it can be seen how the cost per ton increases with the percentage of plastic. In addition, for the same plastic content, the SMA16 mixtures are slightly more expensive than the S20 because of the higher binder content of the first ones.
In order to select the optimal asphalt mixture, the PRESS multicriteria decision method was performed [12], considering up to 6 variables in the process with the relative weights shown in Table 1.

Table 1. Variables and weights considered in the PRESS method

Variable	Weight
Viscous behavior	0.30
Structural behavior	0.20
Marshall stability	0.10
Marshall flow (deformation)	0.10
Void ratio	0.05
Economic cost	0.25

As deduced from Table 1, the higher weight has been assigned to the viscous behavior. This property is represented by the phase angle and it determines the vibration mitigation power of the asphalt mixture. The next attribute in importance is the economic cost. Finally, the structural behavior represented by the Young’s modulus and the stability, flow and voids results obtained from the Marshall tests were considered.
The multicriteria decision making method revealed that the SMA16-0.5 % is the optimal solution.

3. DESIGN OF THE ASPHALTIC SLAB TRACK

Once the most suitable asphalt mixture has been determined, the next step is to design of the cross section of the track, calculating the optimal thicknesses of the different layers that guarantee the good performance of the infrastructure over its life span and minimize the construction costs.

3.1 Design criteria

Thicknesses calculation of the asphalt mixture layers in the track structure is performed according to fatigue requirements. In Fig. 6, a representative cross section of the track is presented. It can be seen two different layers of SMA16-0.5 % (surface and intermediate); the graded aggregate that supports the intermediate layer and the sandy natural ground.

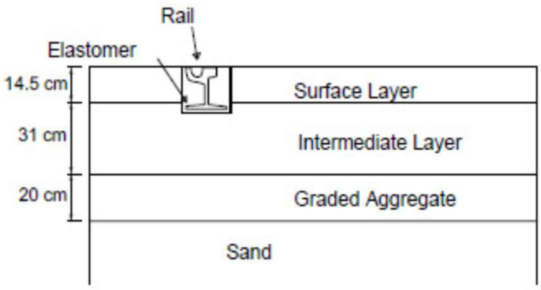


Figure 6 . Cross section of new asphalt slab track

Table 2. Mechanical properties of the track elements

	E (MPa)	υ	ρ (kg/m^3)
Rail	210000	0.30	7830
Elastomer	26.67	0.48	900
Asphalt mixture	11500	0.33	2400
Graded aggregate	170.92	0.30	1700
Sand	50	0.30	2000

The mechanical properties of the different materials in the track are summarized in Table 2. The Young's modulus of the sand is marked with an asterisk because it is a priori unknown. It has been assigned a low value in order to ensure that the calculated dimensions of the asphalt mixture are larger than the minimums required. It is a secure method to guarantee the adequate structural behavior of the track against the stresses induced by the vehicles.
Constructing a finite elements model in which the thicknesses of the bituminous layers are variable, the strains produced on the different materials can be calculated. These strains are caused by the passage of the operating trains. The following strains must be checked in the studied track:

- Maximum horizontal tensile strain in the bottom fiber of the intermediate asphalt layer $\varepsilon_{h\ SMA}$.
- Maximum vertical compressive strain in the upper fiber of the graded aggregate layer $\varepsilon_{\upsilon\ GA}$.
- Maximum vertical compressive strain in the upper fiber of the natural ground $\varepsilon_{\upsilon\ Soil}$.

The fatigue equations have been calculated based on lab tests. These equations link the strain produced in each load cycle *N* with the number of cycles that can be produced without collapsing the material and are presented in the following equations for the mixture SMA16-0.5 % Eq. (4); the graded aggregate Eq. (5) and the sand Eq. (6) :

$$\varepsilon_{h\ SMA} = 9.10853 * 10^{-3} * N^{-0.2871} \quad (4)$$

$$\varepsilon_{h\ GA} = 21600 * N^{-0.28} \quad (5)$$

$$\varepsilon_{h\ Sand} = 15800 * N^{-0.25} \quad (6)$$

From the information previously presented, the design process is as follows: given an asphalt mixture thickness, the different strains in the defined checkpoints are calculated using a finite elements model. These obtained strains are introduced into the fatigue equations, checking that the number of load cycles N_i is higher than the critic number of cycles N_{crit} estimated for a life span of 50 years and a potential traffic level for each one of the materials. The minimum thickness of the SMA16-0.5 % mixture that satisfies this requirement is chosen as the optimal design. In this case, the optimal thickness resulted of 45.5 cm divided into the surface layer (14.5 cm) and the intermediate layer (31 cm) as depicted in Fig. 6. These results have been calculated considering that the vehicles operating in this case are Vossloh 4100 and Bombardier Flexity Outlook. The design iterative process is outlined in Fig. 7.

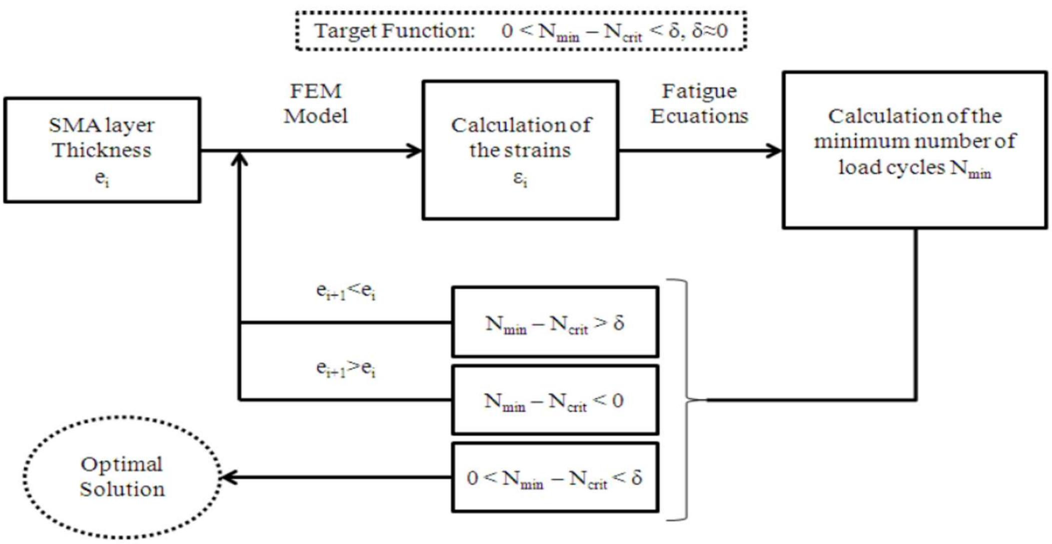
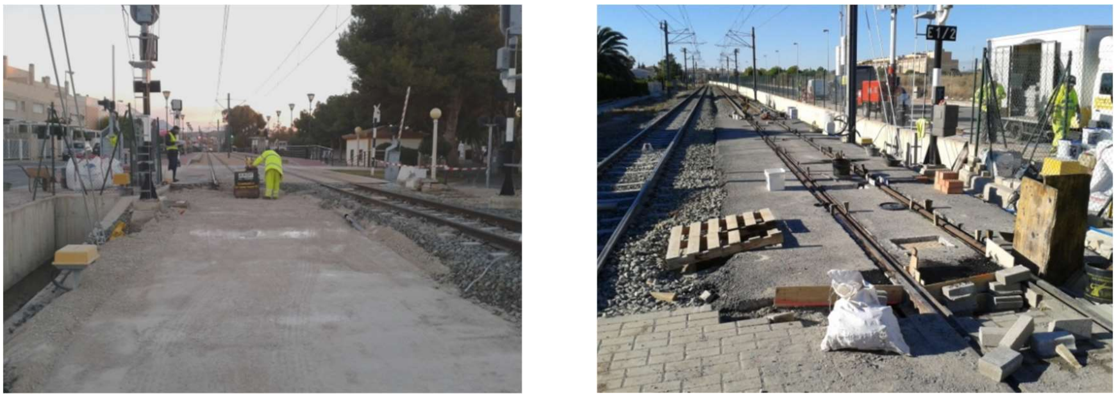


Figure 7. Diagram of the asphalt layer thickness optimization process

4. CONSTRUCTION OF THE STRETCH OF TRACK

After determining the dosage of the mixture and the optimal dimensions of the cross section, a stretch of the new asphalt slab track is constructed in a real operating line (Fig. 8). The chosen line is located in the Alicante (Spain) TRAM network, Poble Espanyol station.



a) b)
Figure 8. a) Compaction of the graded aggregates and b) Rail alignment before the elastomer pouring

It is a straight stretch at the end of the station, where a 20 m stretch of the former ballasted track was replaced by the new slab track. To do so, the rail, sleepers, ballast layer and the rest of granular layers were completely removed, matching the top of the sand stratum in Fig. 6. Then, a 20 cm layer of graded aggregate was placed and compacted, applying a tack coat on the surface to improve the adherence between the aggregates and the asphalt mixture.
The intermediate layer was compacted in two stages because of its high thickness while the surface layer was directly compacted after the placement. The channel that contains the rail was excavated using a trencher machine.
Once the rail channel was completed, the rail was placed ensuring the longitudinal and transversal alignment and the tops were welded to the existing track.
The elastomer used to fill the rail channel was a usual commercial system, in which, the elastomeric material is poured in liquid state providing a total coating of the rail.

4.1 Dynamic behavior of the stretch of track

The acceleration results that allow the assessment of the vibration mitigation power of the new asphalt slab track are presented in this section. For this purpose, real accelerations induced by a passing train are measured on the real stretch. These acceleration data sets allow creating a three-dimensional finite elements model with the same dimensions that the model described in Section 3 for the design of the optimal cross section. A data acquisition campaign was done using three axial accelerometers shown in Fig. 9 and placed at 0.2 and 0.7 m from the outer side of the rail. Once the dynamic model is calibrated and validated, the acceleration results can be calculated in any point of the domain.

Figure 9 . Stretch of asphaltic track and accelerometers

According to said data acquisition campaign, using three axial accelerometers, following results were obtained:

Table 3. Acceleration peaks and average values at 0.7 m from the rail (no elastomer influence)

	Peaks (0.7 m) Concrete Slab	Peaks (0.7 m) Asphalt Slab	Average (0.7 m) Concrete Slab	Average (0.7 m) Asphalt Slab
Measurement 1	1.92 m/s^2 – 5.00 m/s^2	1.51 m/s^2 – 3.35 m/s^2	3.46 m/s^2	2.43 m/s^2
Measurement 2	7.73 m/s^2 – 10.95 m/s^2	1.28 m/s^2 – 2.52 m/s^2	9.34 m/s^2	1.90 m/s^2

According to these results, there is a about 58% of reduction in both, peak values and average values.

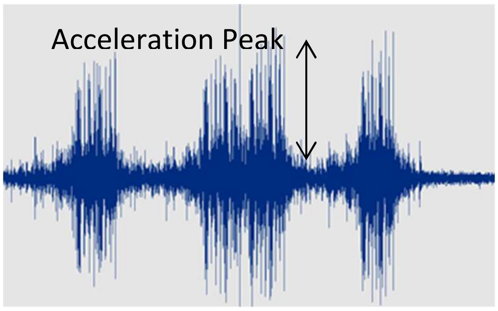


Figure 10. Detail of Acquisition data by three axial accelerometers

4.2 Finite elements model

Previously to the calculation of the dynamic response of the slab track, it is necessary to assemble the finite elements model. The cross section depicted in Fig. 6 has been schematically represented, assigning to the different materials in the track the mechanical properties in Table 2.
The dimensions of the model have been chosen so as to study accelerations in the range 2-50 Hz [13]. The symmetric half of the model is represented in Fig. 10 as appears in the software.
Since in any case it is considered a flawless track, the main mechanism of vibration generation is the 50 kN quasi-static load. This load is induced by the passage of a vehicle which operated on the track stretch during the data acquisition campaign.

4.2.1 Calibration

As explained before, the Young's modulus of the sand in Table 2 has been supposed to design safely the track but the real value of this parameter may differ from 50 MPa. Moreover, the global Rayleigh damping coefficient β which represents the contribution of the stiffness matrix to the vibration damping of the system is an unknown input.

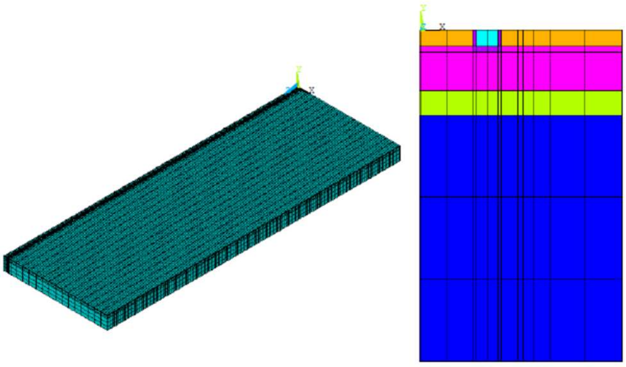


Figure 11. Representation of the symmetric half of the stretch of track in the model

With the aim of determining the approximate value of these two inputs, a calibration process is performed. The calibration of the model was done from real acceleration registers, instead from experimental modal analyses as in the case of Ribeiro et al. [14].
The procedure followed is an iterative method in which pairs of values for the Young's modulus of the sand and the global Rayleigh damping coefficient β are proposed. Then, the different vibration responses are obtained from the finite element model. These solutions are compared with the real acceleration data sets and the combination that yields the closer results to the real registers will be chosen as the correct. The overlapping of the real and the calculated accelerations is shown in

Fig. 11, calculated with a combination of E_{sand} = 144 MPa and β = 0.001 in the point located at 0.2 m from the outer side of the rail.

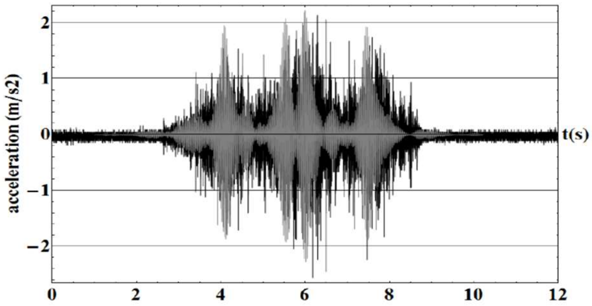


Figure 12. Calibration. Real (black) and calculated (grey) accelerations

4.2.2 Validation

The real and the calculated responses must be compared in a different point from that used in the calibration in order to validate the model. This point is located at a distance of 0.7 m from the outer side of the rail since real acceleration data sets are available at this point.

The magnitude of the peaks calculated with the model and the time distribution match the records registered by the accelerometer. In addition, the tail times are mostly overlapped in both cases, giving an idea about the time elapsed between the beginning of the excitation perception and the moment in which the wheel that produces it passes through the section in which the accelerometer is placed producing the peak. These validation criteria based on morphological aspects have been also employed by Costa et al. [15], comparing vibration velocities calculated and measured on a sleeper. A numerical model able to reproduce accurately the dynamic behavior of the studied track is available. From this model, the dynamic response of the track in different scenarios can be calculated in the next subsection.

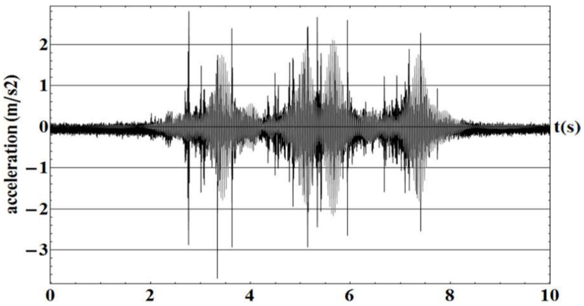


Figure 13 . Validation. Real (black) and calculated (grey) accelerations

4.2.3. Dynamic behavior of the new asphalt slab track with different surface layers

One of the advantages of the new track is that the surface layer can be made of different materials without affecting the vibration attenuation power of the whole track. In this manner, a better environmental integration can be achieved in the different locations of the track. It is possible because the most part of the excitation induced by the train is in vertical direction and reaches the infrastructure through the rail foot that lies directly on the intermediate layer as depicted in Fig. 6. Consequently, the influence of the materials located over the rail foot plane is not significant on the overall mitigation power of the track.

To prove that, the SMA16-0.5 % surface layer will be replaced in the previously developed model by other materials which are often used in tram tracks: concrete, cobblestones and a conventional asphalt mixture. The mechanical properties of these materials are shown in Table 3.

Table 4 . Mechanical properties of the track elements

	E (MPa)	υ	ρ (kg/m^3)
Concrete	22500	0.25	2400
Cobblestone	3000	0.30	2300
Conventional asphalt mixture	1500	0.30	2400

The surface layer is represented in the FEM model in Fig. 13 in orange colour. The mechanical properties of the elements of this layer will be modified according to Table 3 to represent the different materials in the surface layer and subsequently analyse the dynamic behavior.
The graphs in Fig. 14 show how the absolute values of the acceleration decrease and the accelerogram shape blurs as the measuring point moves away from the excitation source.
While at the points located at 0.7 m from the rail the effect of each train bogie is manifest, in the farther points the peaks become flat resulting in compact accelerograms with lower values as observed by Galvín and Domínguez [16] in high speed lines. In this manner, the damping capacity of the different materials that the waves traverse is evidenced.
On the other hand, responses slightly differ at 0.7 m from the outer side of the rail for the different materials but are almost identical in the point located at 5 m from the rail. It is because at the nearby points the accelerations have been obtained on the different materials of the surface layer. Their different mechanical properties produce such variations on the vibration responses obtained at these points. However, at a distance of 5 m from the rail the surface material is the same in the three cases and therefore, the results calculated at these points very similar.

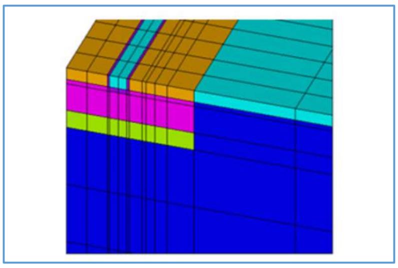


Figure 14. Detail of the surface layer elements in orange, intermediate layer in purple and graded aggregate layer in light green.

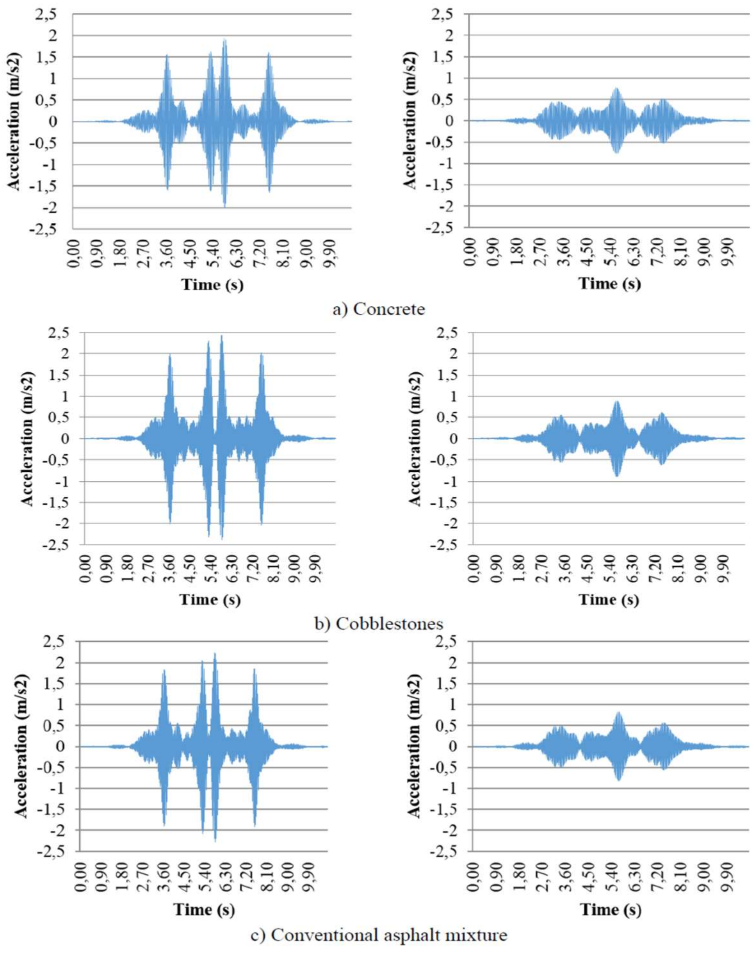


Figure 15. Acceleration registers at 0.7 m (left) and 5 m (right) from the rail head for the surface layer made of a) concrete, b) cobblestones, c) conventional asphalt mixture

The similar responses obtained for different materials of the surface layer ensure the integration capacity of the new asphalt slab track in the different urban environments. Thus, it is an effective, environmentally friendly and versatile solution as the new asphalt mixture with plastic waste presents an excellent behavior against vibrations induced by railway vehicles and can be also adapted to different scenarios varying the materials of the surface layer.

5. CONCLUSIONS

The aim of this research was obtaining a new solution able to attenuate the vibrations produced by a train in service in a tram track. Thus, the optimal dosage of an asphalt mixture containing plastic waste and providing high vibration attenuation power has been calculated. Moreover, the design process of the different layers of the track has been presented based on the fatigue equations. In any case, the ground properties at the track location must be updated to achieve the optimal design.

After the design stage, an experimental stretch has been built within an operating line and real accelerations induced by a train passage have been recorded. Using these registers, a three-dimensional finite elements model has been calibrated and validated to represent accurately the dynamic behavior of the asphalt slab track designed. Furthermore, these registers can be used to establish future comparisons between the performance of this track and other typologies (i.e. ballasted and concrete slab tracks).

With the 3D FEM model, calibrated and validated, the dynamic behavior of tracks with different surface layers has been simulated, finding that outside the track structure the vibration responses are identical. This result ensures the universality of the asphalt slab track since it can be adapted to the different urban environments merely modifying the surface layer.

6. ACKNOWLEDGEMENTS

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