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Additional Information

Real scale evaluation of vibration mitigation of sub-ballast layers with added tyre-derived aggregate

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Abstract

This paper represents a final stage in the assessment of granular sub-ballast materials mixed with tyre-derived aggregate (TDA) without binder material. The objective is to evaluate such mixtures through a full-scale test under real traffic conditions. An experimental track with three 30-metre long sections was constructed: one section was built with conventional sub-ballast; and the other two sections were built with mixtures containing increasing rubber content. This track was then monitored using accelerometers.

The results show a clear reduction in the acceleration peaks as rubber content increases. Moreover, the excited frequency bandwidth tends to become narrower and shifts to lower frequencies.

Keywords

Railways, sub-ballast, tyre-derived aggregate, vibration, experimental track, insertion loss

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Introduction

Scrap tyres are one of the most troublesome waste materials generated by modern societies. They are highly flammable, not biodegradable, and their composition may cause toxic leaching if stockpiled, or hazardous fumes if incinerated [1]. Every year more than three million tonnes of scrap tyres are disposed of only in Europe [2].

One of the most promising alternatives to deal with scrap tyres is to use them as construction material for large infrastructures such as roads and railways. Within this framework, the authors propose mixing tyre-derived aggregates (TDA) from scrap tyres with coarse aggregates to build the sub-ballast layer of new railway tracks, hence enabling the disposal of large quantities of such a problematic waste product.

Over the past 30 years there have been a numerous applications for TDA in civil engineering, particularly in road and railway engineering. However, the vast majority of such applications took the form of rubber-only layers in road embankments [3, 4], and bituminous mixtures with added rubber in slab tracks [5]. Focusing on railways engineering, there has been increasing interest in using scrap tyres when building new railway tracks, not only as a way of reusing a problematic waste material but also to provide benefits in the form of vibration alleviation. Most of this past research, however, has focused on rubber-sand mixtures [6], rubber-only layers [7, 8], or attenuation elements made of scrap tyres such as under sleeper pads [9, 10]. Other authors recently studied the performance of ballast mixed with rubber particles [11, 12] and found that adding 10% crumb rubber (by volume) to the ballast could reduce degradation and increase energy dissipation [13]. A thorough review on design and maintenance technologies for reducing ballast deterioration found some techniques based on adding rubber particles from scrap tyres to be particularly useful, although some concerns regarding costs and increased settlement were also indicated [14].

However, unbound mixtures such as the ones proposed in this paper (i.e. rubber and coarse aggregates) represent a new approach to the problem. More specifically, using such mixtures as a sub-ballast layer (instead of a rubber-only layer) is a relatively unexplored field of research that has only been indirectly studied with laboratory tests and computer modelling [15].

The aim of this research is to assess the potential use of unbound rubber-aggregate mixtures as sub-ballast layers. As a first step [16], the behaviour of these mixtures was studied through an extensive set of laboratory tests in order to characterise them and measure the main features required for sub-ballast materials by Spanish and international railway regulations (including resistance to degradation, bearing capacity, resilient modulus, etc.). The results obtained showed that adding between 1 and 10% of rubber particles to the mixture (in terms of weight) improves resistance to degradation (measured using the Los Angeles and Micro-Deval coefficients) and reduces bearing capacity. An addition of rubber limited to 5% provided an optimum balance between these two features [16]. These results were further tested on a small-scale experimental railway platform. Bearing capacity and the long-term deformation of these new mixtures were analysed in the laboratory, as well as on the aforementioned experimental platform [17], as these are key factors in the life cycle and maintenance needs of any railway track.

As a third step of research [18], the potential vibration attenuation provided by the rubber-aggregate mixtures was tested – once again both in the laboratory and on the experimental platform. Vibration generated by passing trains and transmitted to the environment is one of the main issues that may hamper the development of railways, particularly in urban areas, as shown by extensive research, both theoretical [19, 20] and practical [21, 22]. Authors have paid attention to different damping materials and techniques, including elastic mattresses [23], open and filled trenches [24], or layers made of tyre shreds [25], with somewhat irregular results.

The results obtained for vibration attenuation of the proposed mixtures show that adding up to 5% of rubber increases the damping ratio of the material and reduces the observed acceleration peak registered at one metre from the excitation source [18].

The new mixtures have been evaluated in the laboratory under carefully controlled conditions, as well as using an *ad hoc* experimental railway platform. The next step in this research, and the specific objective of this paper, is to assess the performance of the new mixtures (and particularly their behaviour with vibration) in a real railway track under real traffic conditions. Accordingly, 2.5% and 5.0% mixtures were used as sub-ballast in two sections of a new railway track built as part of the renovation of the marshalling yard at San Roque Station near Algeciras (southern Spain). The new track was then monitored to measure the vibration transmitted to the environment by passing locomotives and to compare the behaviour of the new track with respect to a section built with conventional sub-ballast material.

The paper is organised as follows: first, the testing setting is described, including the construction of the new track and the installation of the monitoring devices. The monitored data is then shown, thoroughly analysed, and discussed. Finally, the main conclusions are given.

Materials and methods

Description of test site

The main purpose of this paper is to test the proposed rubber-aggregate mixtures placed in a full-scale railway track under real traffic conditions and then analyse the vibration alleviation performance.

The experimental track chosen is part of the marshalling yard of the San Roque Freight Station located in Algeciras (southern Spain) as shown in Figure 1. This station was expanded through a renovation project ("*Proyecto Constructivo para la Renovación del Trayecto de la Línea Bobadilla-Algeciras, Subtramo pk 3+100 a pk 6+800.*") that resulted in the construction of three new operational tracks with a length exceeding 750 metres and longitudinal slope of less than 2‰. One of these new tracks (labelled 'track 14') was built using the new rubber-aggregate mixtures instead of conventional sub-ballast aggregate.

Figure 1. Experimental track location.

The geology the new tracks are built upon is a uniform layer of lumachelle loam and limestone belonging to the Pliocene (Tertiary Period). These are cemented materials with high bearing capacity and low deformation.

The experimental track stretch is 90 metres long (from PK 5+235 to PK 5+325), divided into three sections of 30 metres each (Figure 2):

- Section ‘Sub_Ref’ (PK 5+235 to 5+265) was built using conventional sub-ballast as a reference.
- Section ‘Sub_Mix 2.5’ (PK 5+265 to 5+295) incorporates modified sub-ballast with a rubber content of 2.5% (in terms of weight).
- Section ‘Sub_Mix 5.0’ (PK 5+295 to 5+325) incorporates modified sub-ballast with a rubber content of 5.0% (in terms of weight).

In addition to these three sections, another track stretch with conventional sub-ballast (‘Sub_Ref2’, starting at PK 5+325) was monitored as an additional reference.

The track was built with wooden sleepers placed every 60 cm. The sub-ballast layer in every case was 20 cm thick, with a ballast layer of 50 cm and a 60 cm foundation layer. The track gauge is 1668 mm. Figure 2 shows the track cross section. Figure 3 shows the finished tracks (labelled 14 and 16, the former being the track monitored).

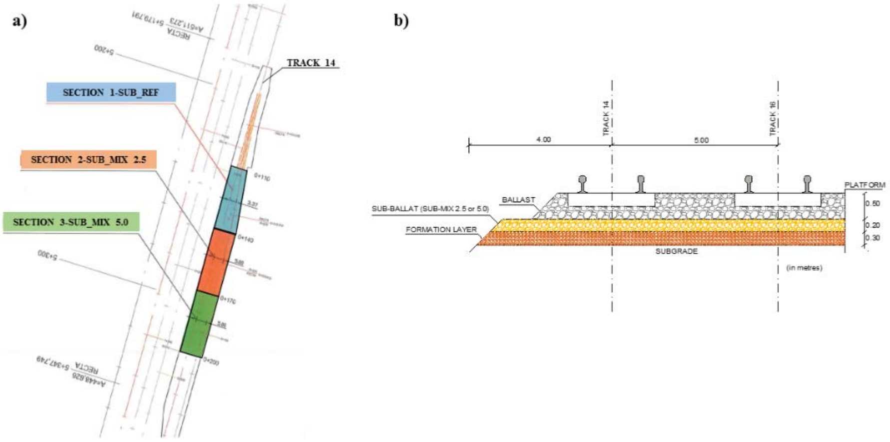

Figure 2. (a) Experimental track layout. (b) Track cross section.

Figure 3. Tracks 14 (left) and 16 (right) after construction.

Construction procedure

The construction procedure for the experimental track was of key importance, not only to achieve a functional and reliable infrastructure but also to assess the manipulation, storage, and placement of the new mixtures as designed during previous stages of research. Machinery used to handle and place conventional sub-ballast was chosen to control construction costs when using the new mixtures.

Some initial tests were carried out on the natural soil to measure its bearing capacity (by means of the CBR), compressibility modulus (E_{v2}), modified Proctor (MP) density, and optimum moisture content. If the natural soil density was found to be lower than 95% MP, compaction was then carried out so as to reach that threshold. Once the subgrade soil was properly compacted, selected aggregates were laid to create the formation layer. Bearing capacity and compaction of this layer were also measured during the construction process.

Selected aggregates supplied by Manilva Quarry in Málaga (Spain) and rubber particles supplied by a scrap tyre recycling plant in Aznalcóllar (Spain) were mixed on-site using an auto-loading mixer (Figure 4a). The mixing process was devised as follows to avoid segregation:

- Aggregates and rubber particles were first mixed without water until achieving a homogeneous mixture.

- Water was then added until reaching the optimum moisture content (6.1% for the ‘Sub_mix 2.5’ and 6.2% for the ‘Sub_mix 5’, as determined in preliminary laboratory tests). Hygroscopic moisture of both the aggregates and rubber particles was taken into account.
- All the materials were mixed once again until the final mixture was obtained. Final density and moisture was then checked using radioactive isotopes.

The resultant mixture was then directly poured over the formation layer and extended using a motor grader to form the sub-ballast layer (Figure 4b). This layer was then compacted using a road roller equipped with a smooth vibrating drum. In situ density was measured after 24 hours by means of radioactive isotopes and required to exceed the 98% MP threshold. The sub-ballast compressibility modulus was also measured using a static plate load test (ϕ 300 mm, see Figure 4c) and required to yield a second cycle value (E_{v2}) of over 120 MPa as demanded by Spanish railway regulations [26]. All of these requirements were fulfilled by all sections of the experimental track, including all rubber-aggregate mixtures, as well as the conventional sub-ballast used as reference.

Figure 4. Construction process. (a) Mixing process of the rubber-aggregate mixtures. (b) Subballast placement after mixing. (c) Subballast extended using a motor grader. (d) Static load plate test.

Finally, once the sub-ballast layer was completed, the rest of the track (i.e. ballast, sleepers and rails) was constructed using conventional methods and machinery, always in fulfilment of Spanish railway regulations.

Materials description

Table 1 shows the mean values of different parameters obtained from three conventional aggregate samples taken during the construction of the experimental track.

Table 1. Mean values obtained from aggregates and PF-7 requirements.

Parameters	**Mean Value**	**PF-7**
Maximum size (mm) (ASTM D6913)	16	–
% size below 0.063 mm (ASTM D6913)	6.6	3-9
Coefficient of uniformity, C_u (ASTM D6913)	22.7	$C_u \geq 14$
Coefficient of curvature, C_c (ASTM D6913)	1.6	$1 \leq C_c \leq 3$
Sand equivalent, *SE* (ASTM D2419)	62	SE >45
Atterberg limits (ASTM D4318)	NP	NP
Los Angeles coefficient, *LA* (ASTM C131)	27	LA<28
Micro-Deval, MD_H (ASTM D6928)	15.3	MD_H<22
Max. dry density Mod. Proctor (g/cm^3) (ASTM D1557)	2.222	–
Optimum moisture *PM* (W_{opt}) (%) (ASTM D1557)	5.9	–
Permeability, *K* (m/s) (ASTM D7760)	6.7E-7	K< 1E-6
Organic matter content (%) (ASTM D2974)	0.07	N/A

As the table shows, all parameters checked are within the limits required by Spanish regulations [26] and thus the aggregate is a suitable sub-ballast material. As for the rubber particles, samples were also taken and tested, obtaining the results shown in Table 2.

Table 2. Characterisation tests results for rubber particles.

Parameter	**Value**
Coefficient of uniformity, C_u (ASTM D6913)	3.0
Coefficient of curvature, C_c (ASTM D6913)	2.9
Permeability, *K* (m/s) (ASTM D7760)	2.5E-5
Relative particle density, *Gs* (ASTM C127)	1.112
Absorption (%) (ASTM C127)	3.20
Max. dry density Mod. Proctor (g/cm^3) (ASTM D1557)	0.525

These results are consistent with those obtained for the rubber particles used in previous research [16], which were provided by a different supplier.

In situ compaction and bearing capacity tests

In situ density was measured in the formation layer according to ASTM D3017 [27], ASTM D2922 [28] and BS 1377-5 [29]. Table 3 shows the location of each measurement, and the sub-layer monitored (as the formation layer was built in two consecutive sub-layers for better control of moisture and compaction). The lower sub-layer is labelled (1) and the upper layer is labelled (C). As the table shows, all results are within the limits required by Spanish regulations (PGP-2008, [30]).

Table 3. Density and compaction results in the formation layer.

Kilometric Point (Sub-layer)	Section	In situ density (g/cm^3)	In situ moisture (%)	MP density (g/cm^3)	MP moisture W_{opt} (%)	% Compaction
5+235 (1)	Subballast	1.86	15.0	1.88	13.9	99
5+255 (1)	Subballast	1.88	14.9	1.88	13.9	100
5+275 (1)	Sub_Mix 2.5	1.88	13.6	1.88	13.9	100
5+295 (1)	Sub_Mix 2.5	1.90	13.0	1.88	13.9	101
5+315 (1)	Sub_Mix 5.0	1.88	12.9	1.88	13.9	100
5+325 (1)	Sub_Mix 5.0	1.90	13.4	1.88	13.9	101
5+355 (1)	Subballast	1.89	14.0	1.88	13.9	101
5+375 (1)	Subballast	1.88	14.6	1.88	13.9	100
5+395 (1)	Subballast	1.89	14.2	1.88	13.9	101
5+415 (1)	Subballast	1.91	12.9	1.88	13.9	102
5+235 (C)	Subballast	1.91	13.2	1.90	14.7	101
5+255 (C)	Subballast	1.90	13.6	1.90	14.7	100
5+295 (C)	Sub_Mix 2.5	1.92	13.4	1.90	14.7	101
5+325 (C)	Sub_Mix 5.0	1.90	13.9	1.90	14.7	100
5+375 (C)	Subballast	1.91	14.1	1.90	14.7	101
5+415 (C)	Subballast	1.92	13.8	1.90	14.7	101

Bearing capacity was measured on top of the formation layer using a static plate load test [31] in the kilometric point PK 5+355. The second cycle compressibility modulus (E_{v2}) obtained was 91.8 MPa, which is far greater than the required value of 60 MPa [30]. The ratio between first and second cycle modulus was 2.22 (which is slightly over the required threshold).

Monitoring

The experimental track was monitored to evaluate the performance of the two rubber-aggregate mixtures (i.e. 2.5% and 5% of rubber content in terms of weight), as well as the conventional unmixed sub-ballast. The four sections aforementioned were equipped with several accelerometers. The main objective was to measure vibration levels generated by the passing trains and compare the attenuation given by each sub-ballast configuration.

Each of the four sections was equipped with four uniaxial piezoelectric accelerometers: one placed on the rail foot closer to the platform (S0), one on the sleeper (S1); and two embedded in the ballast (S2 was placed between the track and platform; and S3 was placed between the monitored track and the track next to it). Figure 5 shows the sensor configurations for each section. Please note that the S3 sensor in Section 4 experienced a malfunction during monitoring and thus did not provide any useful data.

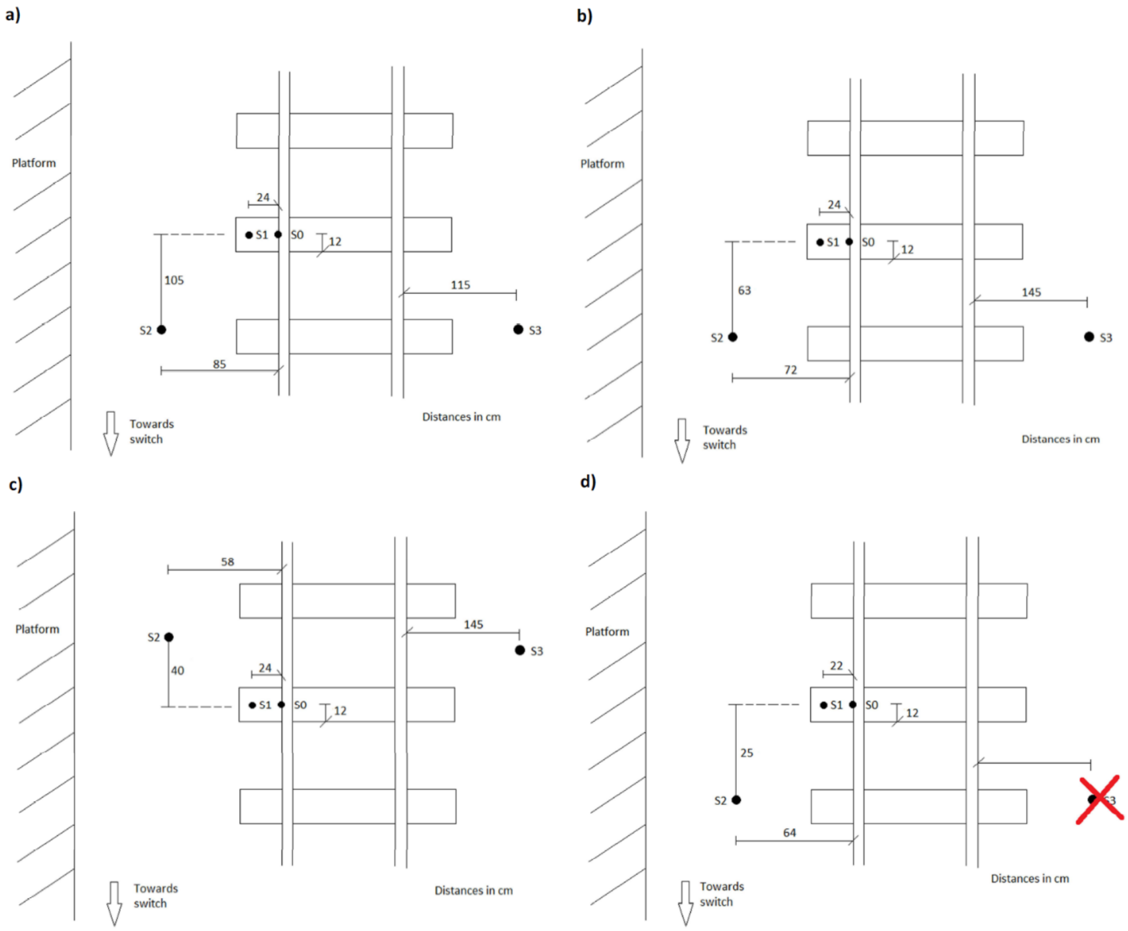

Figure 5. Sensors configuration. (a) Section 1: Sub_ref. (b) Section 2: Sub_mix 2.5. (c) Section 3: Sub_mix 5.0. (d) Section 4: Secondary subballast reference.

Table 4 shows the main characteristics of the sensors used. Sensors were connected to a data acquisition system model cDAQ-9133 (National Instruments) with a sampling frequency of 1652 Hz.

Table 4. Accelerometers' characteristics.

Sensor	Model	Series	Range (g)	Sensitivity (mV/g)
S0	MMF	KS76C-100	± 60	98.85
S1	MMF	KS76C-100	± 60	98.76
S2	MMF	KS76C-100	± 60	99.54
S3	PCB	352B-1000	± 5	990.00

Acceleration levels were measured at each section during the passing of vehicles at controlled speed, namely 10, 20 and 30 km/h (as the speed limit for the track is only 40 km/h). As the experimental track is part of a marshalling yard in a freight station with little traffic, a dedicated locomotive was used: a 79 tonnes Renfe Series 310 with an axle-load of 19.8 tonnes.

For each fixed speed four datasets were registered, two in one direction (towards Algeciras) and two in the opposite (towards Bobadilla). Table 5 shows a summary of all the monitoring events.

Table 5. Summary of measurements in the San Roque station.

Hour	Section	Direction	Speed (km/h)
11:00	1	Algeciras	10
11:02	1	Bobadilla	10
11:03	1	Algeciras	10
11:05	1	Bobadilla	10
11:06	1	Algeciras	20
11:07	1	Bobadilla	20
11:09	1	Algeciras	20
11:10	1	Bobadilla	20
11:11	1	Algeciras	30
11:12	1	Bobadilla	30
11:14	1	Algeciras	30
11:15	1	Bobadilla	30
11:44	2	Algeciras	10
11:45	2	Bobadilla	10
11:46	2	Algeciras	10
11:47	2	Bobadilla	10
11:49	2	Algeciras	20
11:50	2	Bobadilla	20
11:51	2	Bobadilla	20
11:53	2	Algeciras	20
11:55	2	Bobadilla	20
11:56	2	Algeciras	30
11:57	2	Bobadilla	30
11:58	2	Algeciras	30
11:59	2	Bobadilla	30
12:21	3	Algeciras	10
12:23	3	Bobadilla	10
12:24	3	Algeciras	10
12:26	3	Bobadilla	10
12:27	3	Algeciras	20
12:28	3	Bobadilla	20
12:29	3	Algeciras	20
12:31	3	Bobadilla	20
12:33	3	Algeciras	30
12:35	3	Bobadilla	30
12:37	3	Algeciras	30
12:38	3	Bobadilla	30
12:57	4	Algeciras	10
12:58	4	Bobadilla	20
12:59	4	Algeciras	30
13:00	4	Bobadilla	30

Vibration data gathered from the four monitored sections was processed and analysed. A Butterworth high-pass (1 Hz) filter was applied to remove errors due to the lack of accuracy of the sensors at very low frequencies, hence obtaining a smoother acceleration signal. Maximum and minimum acceleration peaks were then identified. Values thus obtained from each section were compared to evaluate the influence of the rubber content in the sub-ballast layer. To better carry out this comparison, a Continuity Index (CI%) was used as proposed by Gorisse [32]:

$$CI = \frac{a_m}{a_p} \times 100 \qquad (1)$$

Where a_m is the mean acceleration peak measured in each section built with one of the mixtures, and a_p is the mean acceleration peak measured in the pattern material (i.e. the unmixed sub-ballast). In this way, the mean acceleration peak registered at each position is normalised with regard to the equivalent acceleration peak from the pattern material [32]. Please note that a lower CI value means higher attenuation with respect to the pattern material.

Results and discussion

In this section the data gathered during the vibration monitoring is presented, analysed, and discussed. Table 6 shows the average value of the acceleration peak obtained for each section and sensor.

Table 6. Mean acceleration peaks. Units in m/s^2.

Section	S0: rail		S1: sleeper		S2: ballast next to platform		S3: ballast between tracks	
	Peak max	**Peak min**	**Peak max**	**Peak min**	**Peak max**	**Peak min**	**Peak max**	**Peak min**
Sub_Ref	19.456	-24.311	3.883	-4.471	0.272	-0.248	0.204	-0.202
Sub_Mix 2.5	21.228	-20.083	4.203	-4.651	0.235	-0.170	0.111	-0.172
Sub_Mix 5.0	11.038	-13.592	4.783	-4.598	0.230	-0.215	0.092	-0.090
Sub_Ref2	11.199	-14.346	7.289	-7.994	0.320	-0.255	--	--

Focusing on the ballast (S2 and S3), the mean acceleration peaks tend to decrease as the rubber content increases. This trend is observed on both sides of the track. This is further observed in Figures 6 and 7, which show representative acceleration signals recorded in the ballast at each section.

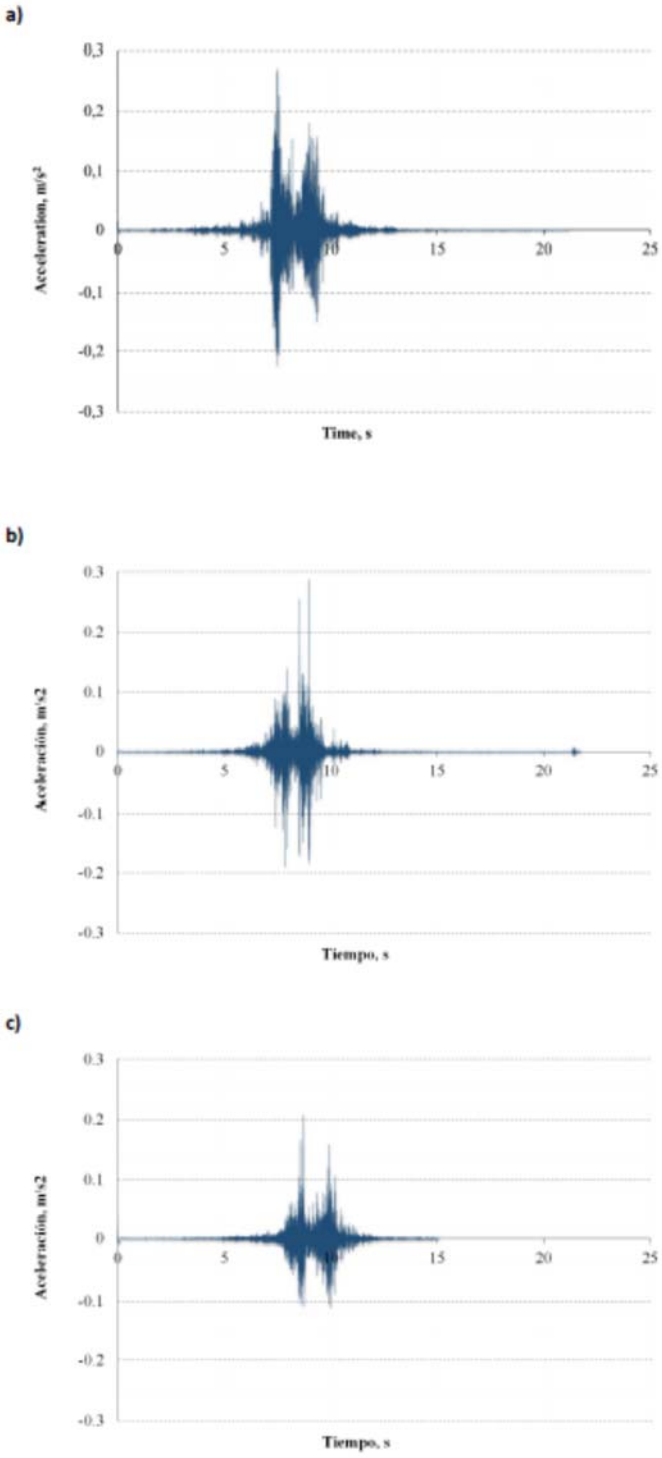

Figure 6. Acceleration signal in sensor S2. (a) Section 1: Sub_ref. (b) Section 2: Sub_mix 2.5. (c) Section 3: Sub_mix 5.0.

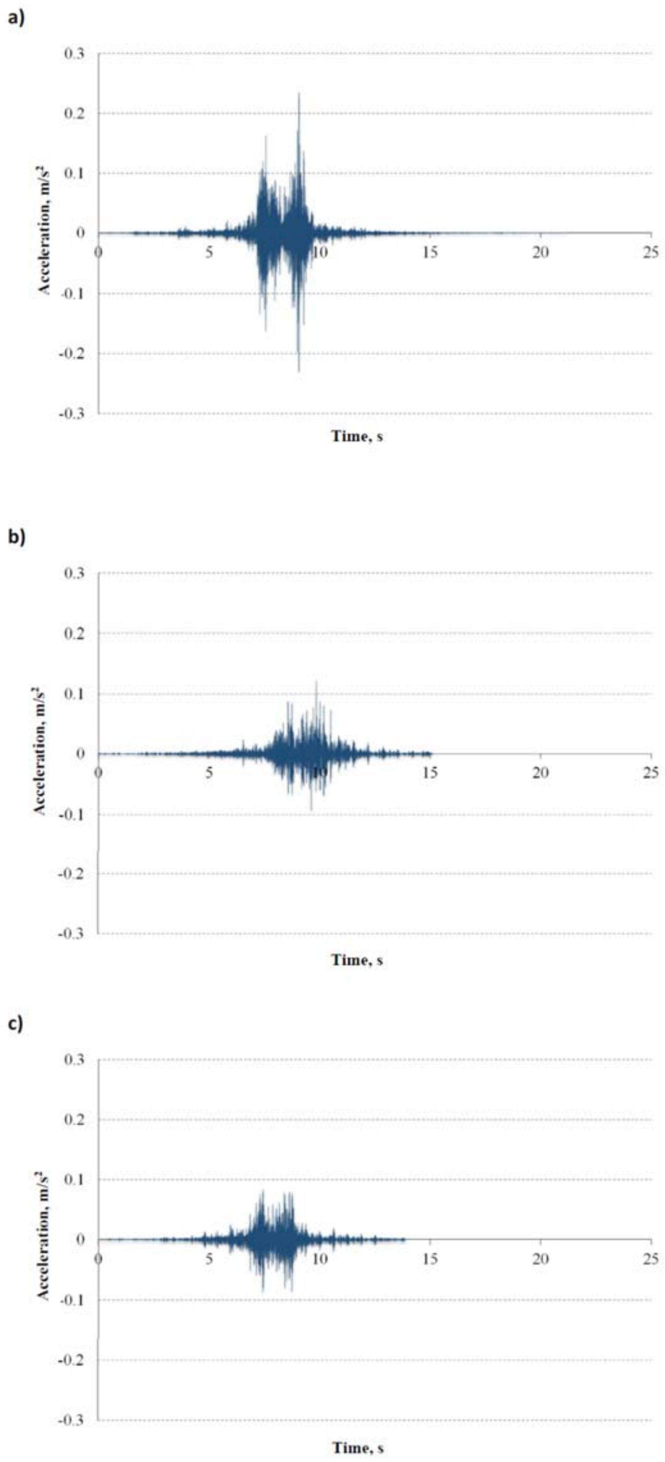

Figure 7. Acceleration signal in sensor S3. (a) Section 1: Sub_ref. (b) Section 2: Sub_mix 2.5. (c) Section 3: Sub_mix 5.0.

Figure 8 shows the corresponding acceleration levels measured in rail and sleeper at each section (when the locomotive passed by at 30 km/h), where the trend cannot be as clearly seen as in the ballast. Vibration peaks in the rail seem to be quite similar in the three sections, while they tend to increase in the sleeper as the rubber content increases. However, if mean acceleration peaks are considered (Table

6), vibration peaks seem to increase in the rail after the first reference section (Sub_Ref) to the Sub_mix 2.5%, and then are clearly lower in the Sub_mix 5.0% section and the second reference section. Levels for the sleeper tend to increase with the rubber content, but the highest average peak was recorded in Sub_Ref2.

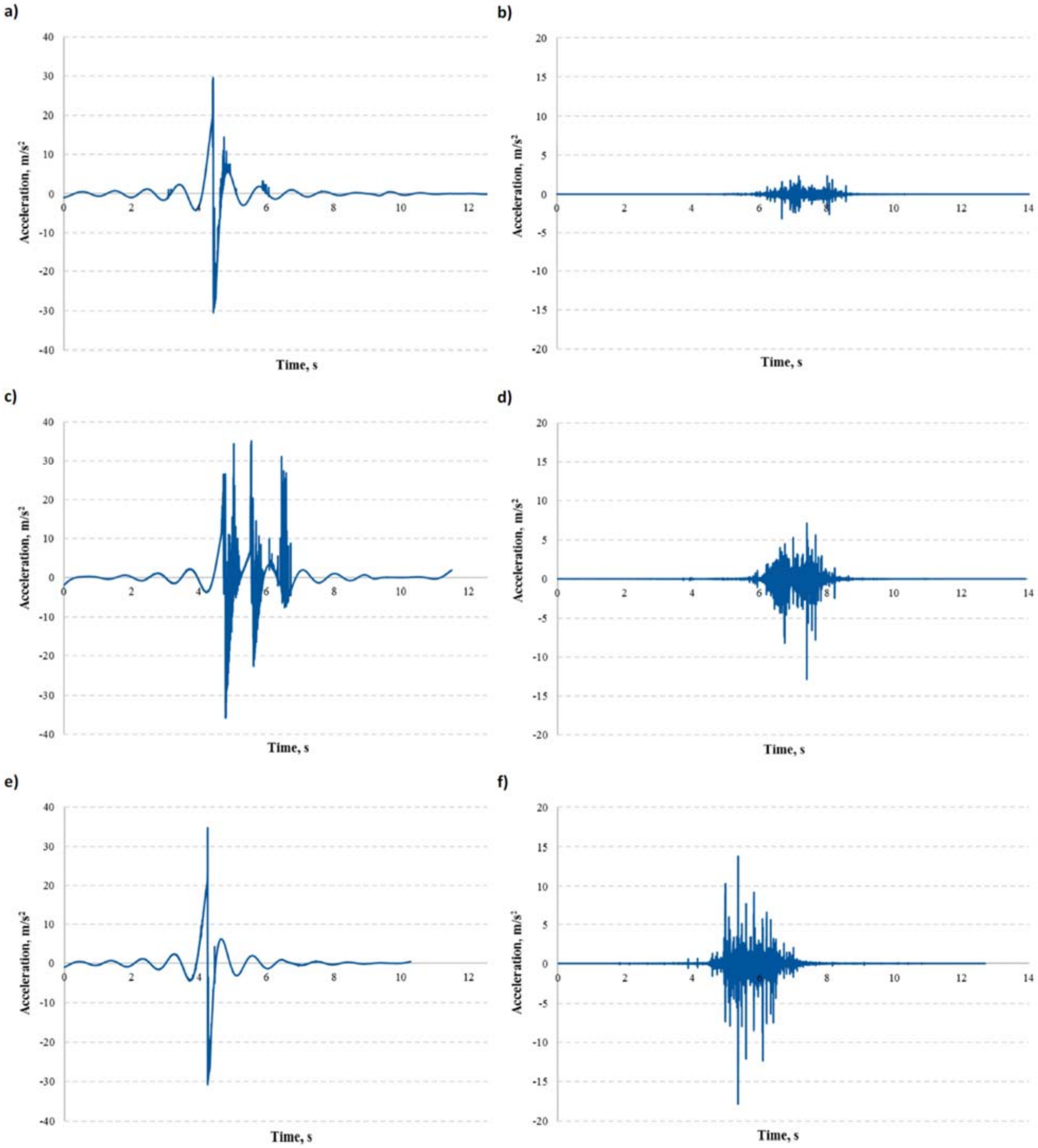

Figure 8. Acceleration signal in sensors S0 and S1. (a) Sub_ref, Rail (b) Sub_ref, Sleeper (c) Sub_mix 2.5, Rail (d) Sub_mix 2.5, Sleeper (e) Sub_mix 5.0, Rail (f) Sub_mix 5.0, Sleeper.

These results indicate that the addition of rubber reduces the vibration peak transmitted through the ballast and sub-ballast and into the ground, but this reduction comes at the cost of a slight increase in the vibration levels in the sleeper (while the rail seems to be unaffected). This may have an impact in the maintenance of sleepers, a circumstance that should be further studied.

It is worth noting that the levels measured are lower than those presented by other authors. For instance, Galvín and Domínguez [33] measured average acceleration peaks of about 20-25 m/s^2 on the sleeper, while Degrande and Schillermans [34] measured up to 40 m/s^2 on the sleeper and over 100 m/s^2 on the rail. However, both studies were focused on high-speed lines with trains running at 300 km/h along ballasted tracks with concrete sleepers. Martínez et al. [22] measured similar values. Brajovic et al. [35] measured accelerations on the sleeper within the range of 10-20 m/s^2 for trains running at 70 km/h along tracks with wooden sleepers, although in this case the trains were heavy freight vehicles. These results indicate that the levels measured for this paper may not be fully comparable to other studies, mainly because the experimental setting devised does not allow measuring vibration caused by whole trains at higher speeds, which is the most conventional framework for all the studies reviewed.

The attenuation observed in S2 (ballast between track and platform), measured in terms of CI between maximum peaks, is about 79% between the reference material (mean value of sections 1 and 4) and Sub_mix 2.5%; and about 86% between the reference and Sub_mix 5.0%. The attenuation observed in S3 (ballast between tracks) is about 68% between the reference material and Sub_mix 2.5% and 45% between the reference and Sub_mix 5.0%. This variation in the trend is perhaps because the accelerometer placed between the platform and the track (S2) is closer to the vibration source than S3. Moreover, the proximity of the platform (which is a rigid concrete structure) may interfere with the measurements by reflecting part of the incident vibration.

Overall there is a mitigation of the vibration levels measured in the ballast as the rubber content in the sub-ballast layer increases. This agrees with the results observed in small-scale field tests during previous stages of research [18]. The attenuation observed in the maximum acceleration peaks between both mixtures (with 2.5% and 5% of rubber content respectively) is within the same order of magnitude in both cases, as shown in Table 7.

Table 7. Continuity index values in the small scale field test [14] and real scale experimental track.

Material	CI (%) Small scale field test (at 1 metre from vibration source)	CI (%) Experimental track in Algeciras (Sensor S3)
Sub_Mix 2.5	71	79
Sub_Mix 5.0	46	45

The acceleration data was transformed using a FFT (Fast Fourier Transform) to obtain the corresponding vibration spectra. The main results are shown in Figure 9 (S2) and Figure 10 (S3).

As the figures show, vibration energy tends to be focused in a narrower bandwidth as the rubber content increases. Moreover, there is a shift to lower frequencies in the spectra corresponding to higher rubber contents, which points to a reduction in the resonance frequency. This trend is observed in both sensors, as the resonant frequency (f_0) in section 1 (Sub_Ref) is in the range 50-58 Hz, while it drops to 46 Hz in section 2 (Sub_mix 2.5%) and about 40 Hz in section 3 (Sub_mix 5.0%). These results are consistent with the observations made during the small-scale field test carried out in previous stages of research [18], as well as with other vibration measurements taken from railway tracks under real traffic conditions [22].

It is important to note that this reduction of the resonant frequency may become a problematic issue in high-speed lines, as it may indicate a reduction in the critical velocity of the track. The experimental setup used only considers relatively low speeds, and thus further research should be made to address this aspect of the new mixtures for high-speed lines.

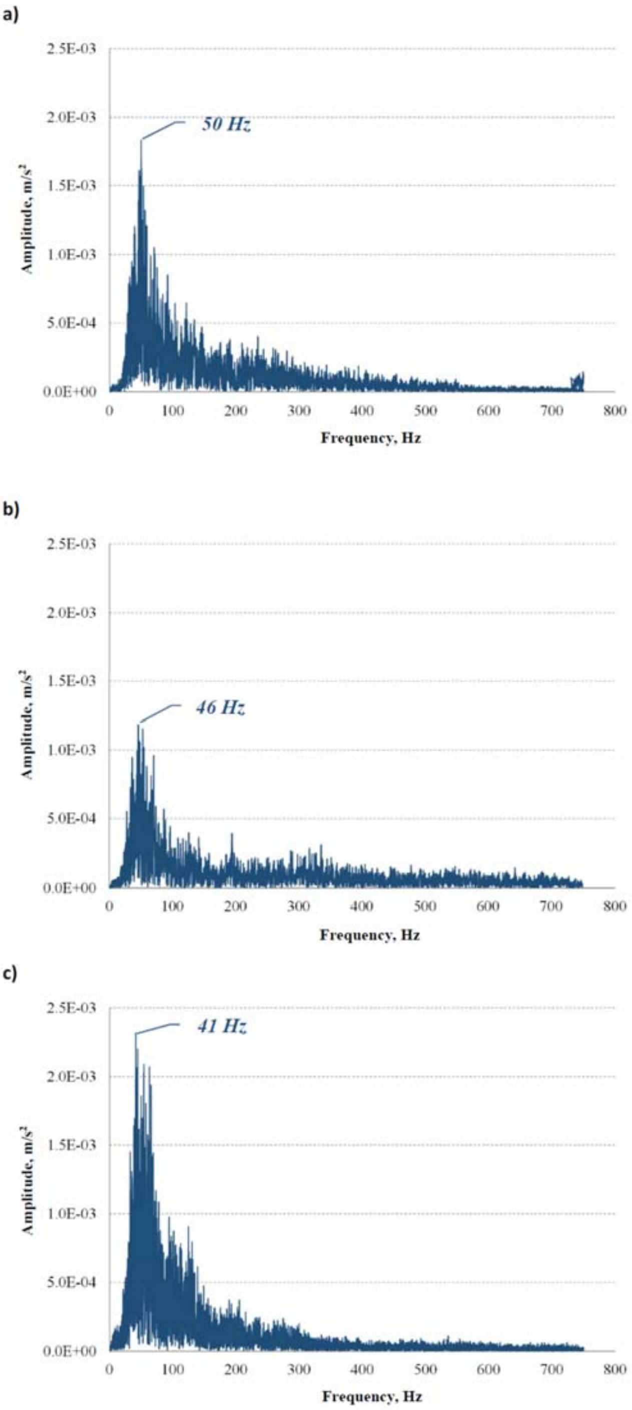

Figure 9. FFT spectra in sensor S2. (a) Section 1: Sub_ref. (b) Section 2: Sub_mix 2.5. (c) Section 3: Sub_mix 5.0.

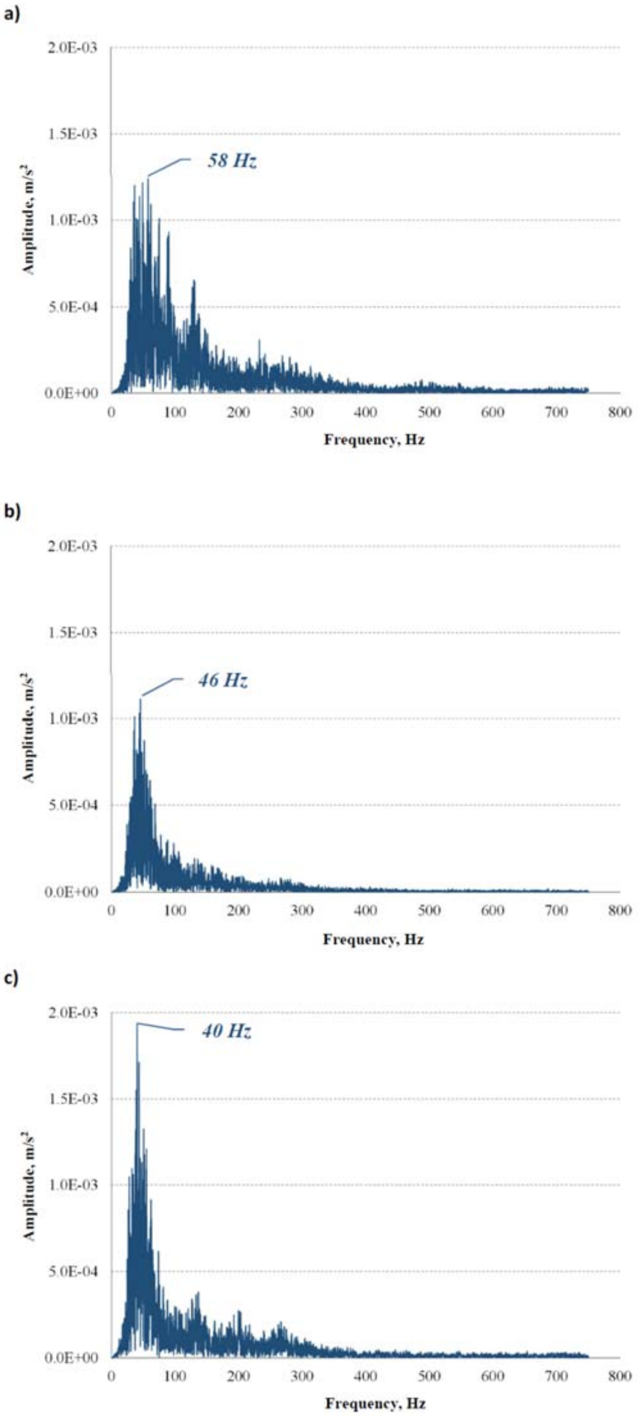

Figure 10. FFT spectra in sensor S3. (a) Section 1: Sub_ref. (b) Section 2: Sub_mix 2.5. (c) Section 3: Sub_mix 5.0.

To better assess the effect that the rubber content has on vibration alleviation, insertion loss has been calculated with regard to the pattern unmixed sub-ballast (Section 1). Figures 11 and 12 show the average insertion loss obtained in sections 2 and 3. As Figure 11 reveals, the 2.5% sub-ballast yields an average vibration reduction of less than 5 dB between 0 and 10 Hz. There is a small amplification between 10 and 45 Hz, and a noticeable reduction for higher frequencies that exceed 15 dB for lower speeds.

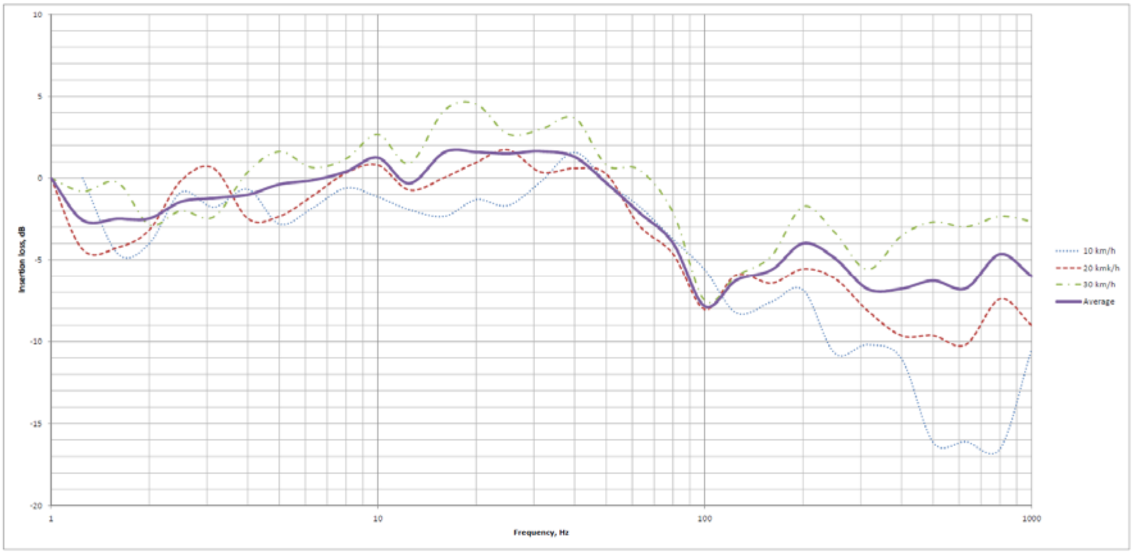

Figure 11. Insertion loss in Section 2 (Sub_mix 2.5) with regard to Section 1.

The 5% sub-ballast (Figure 12) shows a somewhat similar trend, although in this case, the reduction in the lower bandwidth is more irregular and there are two clear peaks of reduction at 100 Hz and 500 Hz. These results are consistent with previous research on the vibration reduction of ballast mixed with TDA [11].

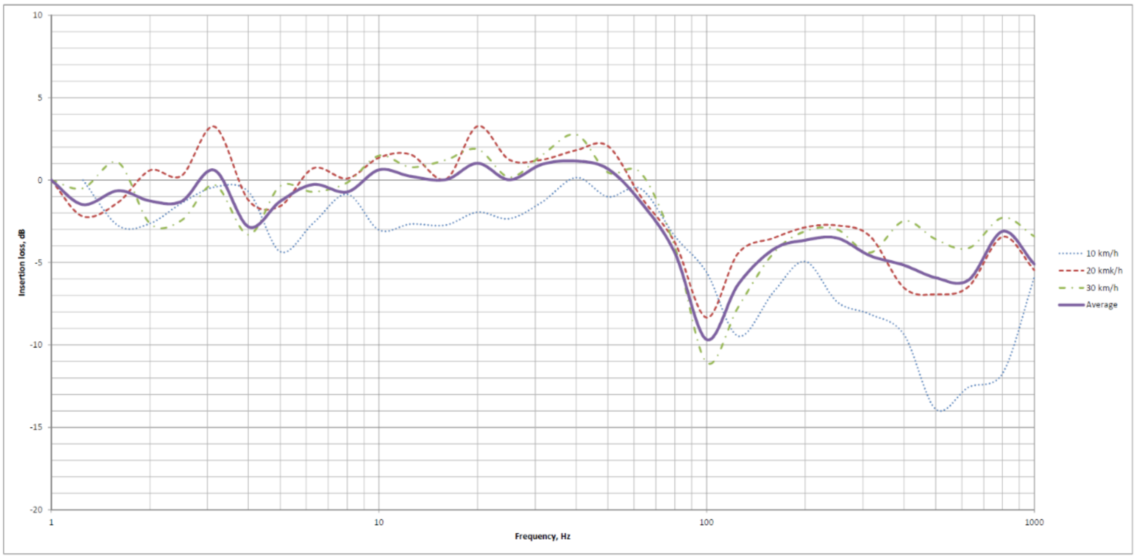

Figure 12. Insertion loss in Section 3 (Sub_mix 5.0) with regard to Section 1.

The results obtained show the feasibility of using sub-ballast made of rubber-aggregate mixtures to achieve vibration attenuation in railway tracks. This real scale test confirms the results obtained in laboratory and small scale tests during previous stages of research [16, 17, 18], and further supports this line of investigation. However, there are still some limitations of the experimental setup that should be addressed to completely determine the efficiency of this solution in terms of vibration mitigation. The most obvious drawback is that the monitored track is a conventional ballasted track with wooden sleepers and the trains used were freight locomotives passing at rather low speeds due to the speed limitation in the marshalling yards. Future tests should be carried out in other track infrastructures (e.g. slab tracks or ballast track with concrete sleepers) and with trains passing at higher speeds to ensure an experimental setting closer to real life conditions and comparable to other studies.

Conclusions

As a final stage in the research of the suitability of using new rubber-aggregate mixtures as sub-ballast, an experimental track was built and monitored under real traffic conditions. This track was divided into three 30-metre long sections. The first was built using conventional sub-ballast to be checked as a pattern, while the other two sections were built using a mixture of unbound granular material and rubber particles for the sub-ballast layer – with varying rubber content, namely 2.5 and 5% (in terms of weight). All sections were then equipped with accelerometers in different locations to measure the transmission of vibrations during the passing of a train locomotive at varying speeds.

The data thus gathered was then analysed and the following conclusions were drawn:

- In terms of time domain, the registered signals show a clear reduction in the acceleration peaks (in the ballast) as the rubber content increases. The overall reduction is about 20% when compared with the 2.5% mixture with the pattern sub-ballast (i.e. a Continuity Index of 79%), and about 55% when compared with the 5% mixture and the pattern (i.e. a CI of 45%). This result agrees with previous smaller scale experimental research. On the other hand, there is a slight increase in sleeper vibration in the sections built with mixed sub-ballast.
- The vibration spectra obtained show that, as the rubber content increases, the excited bandwidth tends to become narrower and shift to lower frequencies. Moreover, the resonant frequency (f_0) is also reduced with the addition of rubber, as it drops from 50-58 Hz in the

pattern material to 40 Hz in the 5% mixture. These results are also in agreement with previous research and bibliography.

- The average insertion loss obtained for the pattern section shows, for both mixes (i.e. 2.5% and 5%), a small reduction in the 0-10Hz bandwidth, a small amplification between 10 and 45 Hz, and a remarkable vibration mitigation in frequencies over 50 Hz (with peak reductions of about 15 dB).

In conclusion, the results obtained during this research, as well as from previous stages show that the use of rubber-aggregate mixtures is feasible. These new mixtures fulfil all the requirements set for sub-ballast layers and provide vibration attenuation while helping to reuse an otherwise problematic waste material. There are some restrictions in the experimental setup used (conventional ballasted track, wooden sleepers, and low speeds) that somewhat limit the scope of the conclusions, but the degree of mitigation observed indicates the potential of these rubber-aggregate mixtures and encourages further research and experimental testing under wider conditions (and particularly in high-speed railway tracks).

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