CHARACTERISATION OF AN UNBOUND GRANULAR MIXTURE WITH WASTE TYRE RUBBER FOR SUBBALLAST LAYERS

Carlos Hidalgo Signes[1], Pablo Martínez Fernández[2], Elías Medel Perallón[3], Ricardo Insa Franco[4, *]

Abstract. Scrap tyres are a solid waste material produced in large quantities. One potential way of disposal is to use rubber particles from shredded tyres as a construction material. Within this context, this paper presents a comprehensive set of laboratory and field tests carried out to evaluate the characteristics of coarse aggregates mixed with rubber particle. The main objective is to assess whether these mixes could be used to form the subballast layer in new railway lines. All the technical features usually required for subballast were tested, including degradation, bearing capacity, density, resilient modulus, etc. The results show that adding between 1 and 10% of rubber (in weight) improves resistance to degradation. On the other hand, bearing capacity is reduced, but still well over the usual range for common subballast if the rubber content is limited to less than 5%. Moreover, the extension and compaction of these mixes can be done using conventional construction equipment.

Keywords: Railways subballast; waste tyres; unbound granular materials; resilient modulus

[1] Geological Engineer. Laboratory technician, Geotechnical Laboratory, Department of Geotechnical and Geological Engineering. Universidad Politécnica de Valencia (UPV). Camino de Vera, s/n, 46022, Valencia, Spain. Email: chidalgo@trr.upv.es

[2] Civil Engineer. Researcher, Department of Transport Engineering and Infrastructure. Universidad Politécnica de Valencia (UPV). Camino de Vera, s/n, 46022, Valencia, Spain. Email: pabmarfe@cam.upv.es

[3] Laboratory technician, Roads Laboratory, Department of Transport Engineering and Infrastructure. Universidad Politécnica de Valencia (UPV). Camino de Vera, s/n, 46022, Valencia, Spain. Email: emedelp@tra.upv.es

[4] PhD Civil Engineering. Railways professor, Department of Transport Engineering and Infrastructure. Universidad Politécnica de Valencia (UPV). Camino de Vera, s/n, 46022, Valencia, Spain. Email: rinsa@tra.upv.es

[*] Corresponding author. Phone: +34 96 387 70 07 Ext. 73767

1. Introduction

Nowadays scrap tyres represent a certain challenge for our societies. They are produced in increasingly large quantities and their disposal is rather difficult. If burned, they release toxic particles (including carcinogens) and greenhouse gases, a risk that is also present if stockpiled (Sharma et al., 2000). Another traditional option is to dispose them in landfill sites, but this alternative is being banned for their risks, including pollution of ground waters. In fact, at European level it is completely forbidden (Directive 1999/31). Therefore, alternative ways of scrap tyres disposal should be developed to address this severe environmental issue.

Among the options proposed in the past years, using shredded scrap tyres as raw material for construction seems to be very promising, as it will allow the disposal of this residue in large quantities under new roads and railways lines. However, these options should be studied in depth so as to ensure that rubber additions do not reduce the properties of the other materials involved or compromise the behaviour of the whole infrastructure.

Within this context, the present paper aims to test the behaviour of unbound mixes made of coarse aggregates and rubber chips from scrap tyres and compare them with traditional subballast materials made only of coarse aggregates. The objective is to assess whether these new mixes fulfil all the requirements established by Spanish Railway Regulations and, if so, to determine which percentage of rubber content would yield the bests results. In this way, this new mix may substitute traditional subballast materials, providing both a promising option for scrap tyres disposal as well as a material whose properties satisfy all the technical constraints.

2. Literature review

As explained before, the use of scrap tyres in civil engineering has been proposed and studied over the past few years. First attempts were carried out in the USA, as this country was the first to deal with the accumulation of large quantities of scrap tyres. Out of these experiences and the need of a working framework, the American Society for Testing and Materials developed a Standard (ASTM D6270-98) which regulates the use of this waste material in different civil engineering applications. In Europe, the Waste Framework Directive 2008/98/CE defined strategic objectives for scrap tyres collection, processing, reuse and recycling. This Directive, transposed to national legislations, encourages reusing this waste material in new applications, including public works.

In Spain, between 2006 and 2012, the company responsible for managing scrap tyres (SIGNUS) handled about 1.15 million tonnes, of which about 58% were reused as raw material, 33% were burned (mainly for cement production and energy generation) and only 9% were retreaded. Of the total used as raw material, only a 4% (about 27000 tonnes) was used in civil engineering, the rest used in diverse applications such as artificial grass fields, pavements, etc. (SIGNUS, 2012). This is far from the expected goal of using at least 100000 tonnes in earth works, as established by the Spanish National Plan for Scrap Tyres 2007-2015. Therefore, there is a clear drive for encouraging the use of tyre shreds in civil engineering, and this will only be achieved if the material is conveniently tested and accepted as a valid construction material. This is the main motivation behind this paper.

There are different ways of using scrap tyres particles in civil engineering. They can be laid as a standalone layer, or can be mixed with other materials such as bitumen, cement or granular soils. The way the tyres are processed (as shreds, chips, buffings, etc.) is also of particular importance, as studied by Edinçliler et al. (2010). Another important aspect is the potential environmental impact that the use of tyre shreds may have. According to Sheehan et al. (2006), the risk to aquatic ecosystems posed by leakage from tyre shreds used in road platforms is rather low, providing there is a certain buffer distance between the infrastructure and the water body.

As an example of rubber-only layer, in 1998 a 10 metre high embankment was built in Portland, Maine (USA) with a core made entirely of scrap tyres shreds (Humphrey and Blumenthal 2010).

The measured settlement was lower than predicted from previous laboratory tests (4% on average at the top of the core) (Humphrey et al., 2000).

In 2001, a 0.3 metre thick layer of rubber tires was placed between the ballast and sub-ballast of a railway track, in the network operated by the Santa Clara Valley Transportation Authority (VTA) in California (USA), providing some reduction of vibration levels for frequencies over 31.5 Hz (Wolfe et al., 2004).

A more recent example is the 2007 joint project between 'Universidad Politécnica de Cataluña' (UPC), ACCIONA I+D and IBERINSA. An embankment was built in the M-111 road in the province of Madrid (Cano et al. 2011). Up to 270000 scrap tyres were used (i.e. about 2200 tonnes), and a settlement of about 2% of the total embankment height was measured.

Rubber shreds from scrap tyres can be also added to bituminous and concrete mixes. Several studies have been carried out over the past years following this line of research; particularly in Italy were bituminous sub-ballast layers have been widely used for 30 years. Examples of this range from purely theoretical approaches (Di Mino et al., 2012) to computer modelling through finite elements (Wang and Zeng, 2004) and laboratory and field tests (Buonnano and Mele, 2000). The latter studied the bearing capacity, durability and vibration damping of mixes with a rubber content between 4% and 8%, showing an overall better performance when compared to mixes without rubber.

It is evident that there is extensive literature regarding the use of rubber-only layers and rubber-modified bituminous layers in civil engineering. The mixture of rubber particles with coarse aggregates to form layers of unbound material is far less studied, hence only a few examples have been found.

In terms of laboratory tests, Feng and Sutter (2000) studied the shear modulus and damping coefficient of rubber-sand mixes by means of Resonant Column Test, but failed to obtain any significant result. More interesting and recent is the work of Nahkaei et al. (2012), who carried out triaxial tests for different mixes of soil and rubber. These tests showed that the higher the content of rubber from scrap tyres, the lower the shear modulus. Additionally, the damping coefficient tends to drop when the content of rubber is increased for pressures between 50 and 100 kPa. The opposite effect is observed for pressures between 200 and 300 kPa.

From a more practical point of view, rubber and sand mixed in equal proportion were used to form the 2 m height embankment core in the State Road 31 in Lakeville, USA (Salgado et al. 2003; Yoon et al. 2005). After 200 days of ordinary traffic only 12 mm of settlement were detected and there were no problems of stability. The magnitude of the settlement is similar to others measured in both railway (Melis, 2006) and road (Vipulanandan et al., 2002) embankments without the addition of tyre shreds.

These few works reviewed show both the potential of unbound coarse aggregates mixes as construction material and the relatively low experience regarding such mixes when compared with other alternatives. Therefore, the study of unbound rubber-coarse aggregates mixes in order to better determine its properties and assess its reliability is well justified. Particularly the study of the substitution of traditional granular sub-ballast with unbound mixes is of particular interest, as most of the previous experiences have focused on roads instead of railways.

3. Materials and methods

In this section a description of all the laboratory and field tests carried out is given.

3.1. Material selection and sampling

The first step to design and test new unbound mixes was to select the proper materials. Rubber from scrap tyres was provided by a company specialised in scrap tyres treatment. This company was a member of SIGNUS, an organization formed by the main tyre producers in Spain and devoted to their proper management and disposal. The material delivered was required to be free of steel wires, present a low percentage of fibres and a particle size lower than 20 mm.

The aggregate was provided by an aggregate treatment company, on the condition that the material delivered would fulfil the requirements of the *Pliego de Prescripciones Técnicas Generales de Materiales Ferroviarios PF-7: Subbalasto* (2006) and the *Pliego de Prescripciones Técnicas Tipo para los Proyectos de Plataforma PGP-2008* issued by the Spanish Ministry of Public Works and ADIF (Railway Infrastructure Manager) respectively.

Once both materials were received and stored in the laboratory, samples were taken for the different tests to be carried out. Selection was made according to the ASTM D75/D75M-09. Figure 1 shows the different samples taken, where NFU20 refers to tyre shreds with a maximum size of 20 mm, NFU2 refers to a maximum size of 2 mm and NFU1 refers to a maximum size of 1 mm. Materials were mixed in terms of weight instead of volume as this is the most practical and common way to control mixtures of aggregates in-situ. Measuring volumes is usually inaccurate and even unfeasible in construction sites.

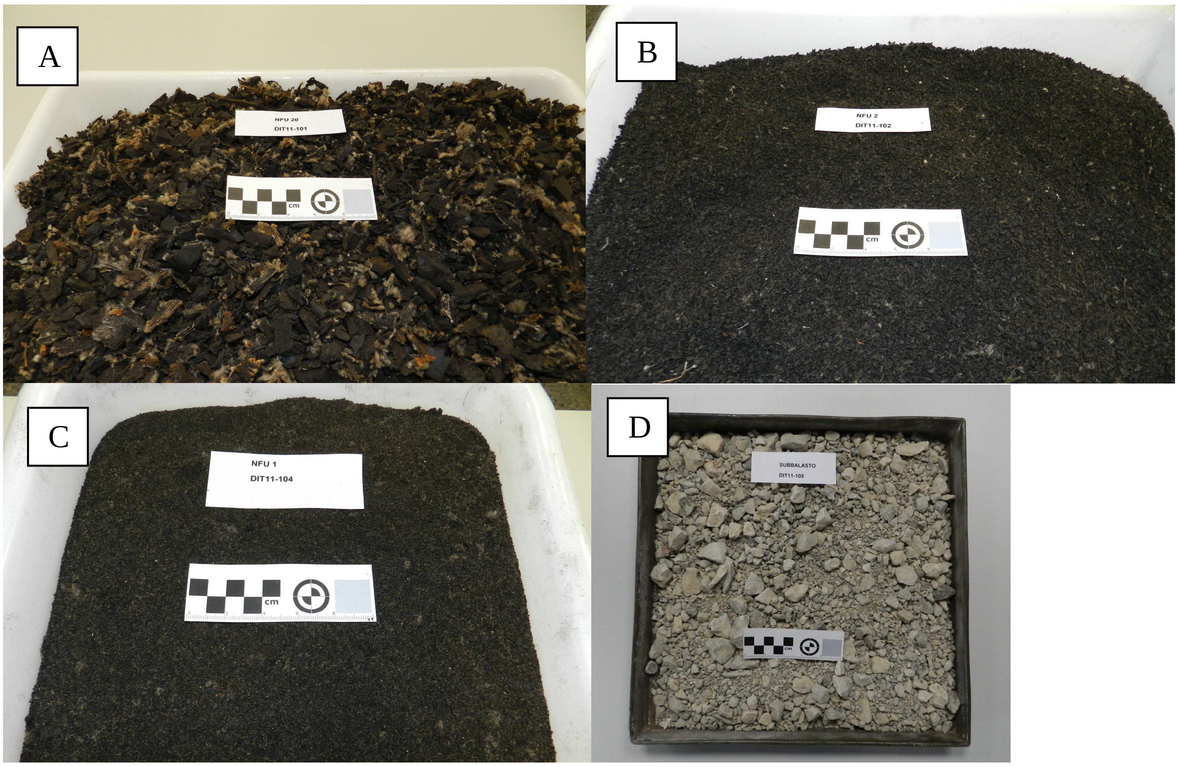

Fig. 1: Soil and rubber samples taken for laboratory and field tests. A) Rubber 20. B) Rubber 2. C) Rubber 1. D) Common Subballast.

The material defined as Platform is an aggregate chosen to be used as a base in the experimental railway track built for field testing (see Sect. 3.3). It is sampled and tested to ensure that it fulfils the properties required for such materials in actual railway tracks, but it is not the object of this study.

3.2. Laboratory tests

Several laboratory tests were carried out to identify the properties of the soil and rubber materials (Table 1). One of the aggregate samples was chosen as a traditional subbalast pattern to be compared with the new mixes. Samples were prepared with the maximum dry density using energy of Modified Proctor.

Table 1: Laboratory and field tests carried out.

Laboratory Test	**Standard**	**Subballast**	**Rubber**	**Mix**
Gradation of Soil	ASTM D6913	X	X	X
Atterberg limits	ASTM D4318	X		X
Loss on drying	ASTM D4959	X	X	X
Specific gravity	ASTM C127	X	X	
Water Absorption	ASTM C127	X	X	
Sand equivalent value (SE)	ASTM D2419	X		
Resistance to degradation (Los Angeles Coefficient – LA)	ASTM C131	X	X	X
Resistance to abrasion micro-Deval (MDH)	ASTM D6928	X	X	X
Percentage of fractured particles	ASTM D5821	X		
Organic matter content	ASTM D2974	X		
Modified Proctor compaction	ASTM D1557	X	X	X
CBR (Standard)	ASTM D1883	X		X
Direct shear test (Consolidated Drained)	ASTM D3080/D3080M	X		X
Triaxial compression test (Consolidated Drained)	ASTM D7181	X		X
Cyclic load triaxial test	AASHTO T 307-99	X		X
Field Test	**Standard**	**Base ground**	**Platform**	**Subballast**
Density "in situ" (radioactive isotopes)	ASTM D3017:2001 ASTM D2922:2001	X	X	X
Static load plate (ϕ 300 mm)	BS 1377-9		X	X
LFWD (ϕ 300 mm)	ASTM D4694		X	X

Additionally, four different aggregate-rubber mixes were prepared, varying the percentage of rubber from 1.0%, 2.5% to 5% and 10% respectively (in terms of weight, Table 2). All mixes were prepared using a laboratory planetary mixer, first mixing the aggregate and the rubber shreds during 2 minutes until achieving a homogeneous mix and then adding water and mixing for one more minute. All mixes were tested and the results were later compared to those obtained for traditional subballast.

Table 2: Rubber-Soil mixes analysed.

Mix	% Aggregate	% Rubber 20	% Rubber 2	% Rubber 1
1.0% Mix	99.0	0.4	0.4	0.2
2.5% Mix	97.5	1.0	1.0	0.5
5.0% Mix	95.0	2.0	2.0	1.0
10.0% Mix	90.0	4.0	4.0	2.0

It is important to note that the definition of the percentages of rubber was relatively complex because there is not a clear consensus between all the papers reviewed. Authors tend to try several different rubber contents (in terms of weight or volume) with respect to different criteria and objectives, or even arbitrarily (Speir and Witczak, 1996). Taking this into account, a first round of CBR tests were carried out and it was found that a rubber content above 10% (in weight) yielded a CBR below 20 and caused problems of bulking. Using this result as a preliminary criterion, a maximum rubber content of 10% was chosen, and the other three configurations (1%, 2.5% and 5%) were also chosen so as to assess the influence of the rubber within the range considered.

Regarding the tests in Table 2, the cyclic load triaxial test is not required by the PF-7 (2006), but it was nevertheless performed so as to obtain the resilient modulus. This parameter provides some information about the elastic behaviour of a confined material permanently deformed by dynamic loads (Garnica et al., 2001) and is widely used to characterise aggregate materials (Tutumluer and Seyhan, 1999). The test was carried out according to AASHTO T307-99 (2003) at a controlled temperature of 25 ºC. Cylindrical specimens were made with 100 mm diameter and 200 mm height and a maximum particle size of 20 mm. For each mixture, four specimens were prepared and tested and average results were obtained. The test consisted on 15 load cycles under varying conditions of confining pressure and deviator stress as described in AASHTO T307-99 (2003). The specimens were dynamically compacted using a 2.5 kg hammer falling from 305 mm, with 100 blows per layer. This yields a compaction energy of 2.632 J/cm^3.

3.3. Field tests

In addition to laboratory tests, an experimental railway platform was built so as to test the placing of the new mixes and their performance on field. This platform consists on a 10x10 m square, excavated to a depth of 35 cm. This depth is completely filled with a layer of aggregate of the material labelled as ‘platform’ during the lab tests. This material fulfils all the requirements from PF-7 (2006). This layer represents the railway platform. Over this foundation a second, 30 cm thick layer is laid, representing the subballast. This top layer is divided in four sections, each one with a different material, as shown in Fig. 2. The different materials used are the same tested in laboratory.

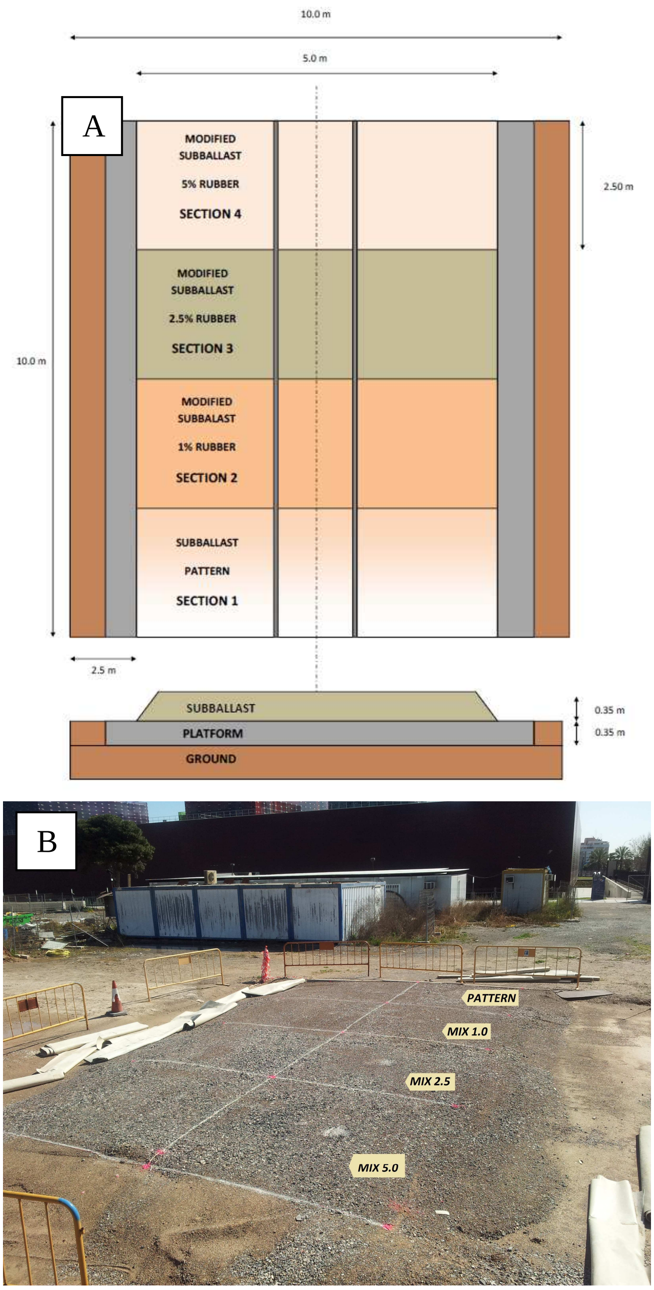

Fig. 2: Experimental railway platform. A) Platform layout (the vertical dotted line represents the track central axis). B) Completed platform.

The first section is made of traditional granular subballast, hence providing a pattern for comparison. The other three sections are made of a mix of aggregate and 1, 2.5 and 5% rubber respectively. The mixes were prepared following the same procedure described for laboratory tests, although with bigger quantities and larger equipment. A 50 Kg scale with a precision of 5 g was utilised to control the weight of each component of the mix, and a 500 litres portable mixer was then utilised to prepare all mixes. Each mixing operation lasted at least 5 minutes to ensure homogeneity.

Each of the four sections of the platform is 10 m wide and 2.5 m long. These dimensions were chosen according to the specifications of the manufacturer of the testing devices as well as the recommendations of the German ZTVE-St 94. The requirements of each of the tests to be carried out in the platform were also taken into account, paying special attention to the Static Load Plate test and the Light Falling Weight Deflectometer (LFWD) test. Certain recommendations such as the ones given by the Service d'Études sur les Transports, les Routes et leurs Aménagements (SETRA) technical note 114 propose larger dimensions for a test board, but at this stage of research a balance between technical requirements and economic constraints was needed. Therefore the specified dimensions (10x10 m) were finally chosen as a reasonable agreement, considering also that this is a first approach to the characterisation of this kind of mixes.

It was decided not to build a 10% mix section due to bulking problems. This is further explained in Sect. 4.

The purpose of this experimental platform is twofold: On the one hand, material placing and compaction by conventional means is tested so as to check if the new mixes add any difficulty to the construction process. On the other hand, density and bearing capacity are measured in the four sections in order to assess the differences between the pattern material and the new mixes.

The construction process encompasses the following steps (Fig. 3):

- Cleaning and clearing of the area and perimeter, including access paths.
- Soil excavation of 35 cm depth and compaction (95% modified Proctor) of the ground underneath by means of road roller. Samples were taken from the natural soil nearby to identify the maximum density in the laboratory. In-situ density was checked by means of radioactive isotopes.

- Placing and compaction (98% modified Proctor) of the ‘platform’ layer. This layer was laid in two sub-layers of 20 cm, each one conveniently compacted and humidified. Density was once again checked in-situ after compaction.
- Site survey in order to accurately define the four sub-sections of the platform.
- Placing and compaction (98% modified Proctor) of subballast and in-situ density measurement.

Fig. 3: Experimental platform construction process. A) Site before cleaning and clearing. B) Excavation. C) Site survey. D) Placing and compaction.

The tests carried out in this experimental site are listed in Table 1. Both the static and dynamic (LFWD) load plate tests were carried in parallel with two circular plates of 300 mm of diameter (Fig. 4). This plate size ensures that the stress bulb is contained between the subballast and platform layers and thus it is not affected by either the natural ground underneath or the platform boundaries.

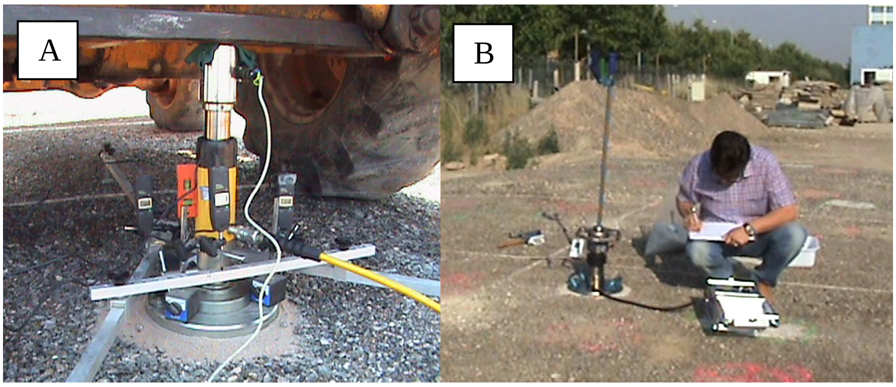

Fig. 4: Field tests. A) Static load plate test. B) LFWD.

The static load plate test consisted on the following loading steps (all values in MPa):

1st loading step: 0.00, 0.08, 0.16, 0.24, 0.32, 0.40, 0.45, 0.5

1st unloading step: 0.25, 0.12, 0.00

2nd loading step: 0.08, 0.16, 0.24, 0.32, 0.40

2nd unloading step: 0.25, 0.12, 0.08, 0.00.

The equipment used for the test was a backhoe of 8.9 tonnes. In order to increase the weight, the backhoe was equipped with a 1 tonne hammer device and the bucket was loaded with 2 tonnes of granular material, hence yielding a total weight of 11.9 tonnes.

The LFWD test was carried out with a mass falling freely over the load plate, applying an impact force of 7.07 ± 0.07 KN over 17 ± 1.5 ms. Only the static load test is required by Spanish Railway Administrator (PF-7 and PGP-2008) to control subballast placing during construction. This test yields a static deformation modulus (E_{v1} and E_{v2}). The purpose of carrying out also a dynamic load plate test (which yields a different, dynamic deflection modulus E_{vd}) is to compare both moduli and observe the relation between both of them, as this is not well established in the literature. Results from these tests are also compared to the ones obtained in the laboratory.

4. Results and discussion

4.1. Laboratory results

The results obtained from the laboratory tests for both the aggregate material and the rubber particles are detailed in Table 3.

Table 3: Laboratory results for aggregate and rubber materials.

Aggregate material		
Parameter	**Results**	**PF-7 Requirement**
Uniformity Coefficient (Cu)	80	Cu ≥ 14
Coefficient of Curvature (Cc)	1.4	1 ≤ Cc ≤ 3
Sand Equivalent (SE)	47	SE > 45
Atterberg Limits	Non-plastic	Non-plastic
Los Angeles Coefficient (LA)	25	LA< 28
Micro-Deval (MDH)	10.5	MDH < 22
Coefficient of permeability (K) (m/s)	3.05E-7	K< 1E-6
Specific gravity (g/cm^3)	2.773	--
Water Absorption (%)	0.71	--
Dry Unit Weight, Modified Proctor (g/cm^3)	2.360	--
Optimal Moisture (W_{opt}) (%)	6.2	--
Organic Matter Content (%)	0.09	Free Content
Rubber particles		
Parameter	**Results**	
Uniformity Coefficient (Cu)	1.4	
Curvature Coefficient (Cc)	0.9	
Coefficient of permeability (K) (m/s)	2.1E-5	
Specific gravity (g/cm^3)	1.136	
Water absorption (%)	5.00	
Dry unit weight modified proctor (g/cm^3)	0.567	

First of all, the tests carried out for the subballast show that the material chosen presents a grain size well within the soil gradation curves required by the PF-7 regulations (Fig. 5). The Coefficient of Uniformity (C_u) is 80.0, much higher than the one demanded ($C_u \geq 14$). The Sand Equivalent (SE) is 47, the threshold value established by regulations. Specific gravity of the material is 2.773 g/cm^3. The CBR obtained for a sample compacted at 100% Modified Proctor (dry density 2.360 g/cm^3 and optimal moisture 6.2%) is greater than 100. Additionally, the triaxial shear test gave a null effective cohesion and an effective friction angle of 40º.

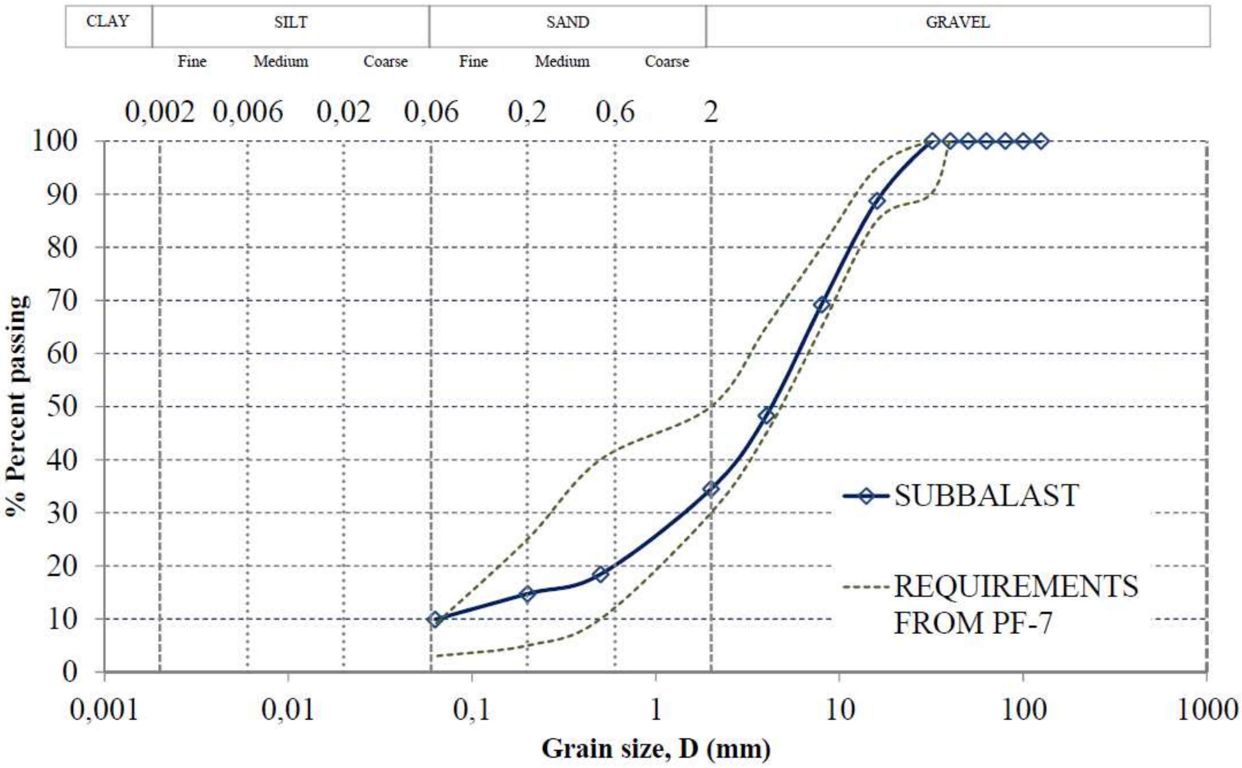

Fig. 5: Soil gradation for the subballast material.

Up to this point the characteristics of the material are good enough for it to be used as subballast. Additionally, the resistance to fragmentation (LA) is 25, which is lower than required (LA<28). The micro-Deval test yields a result of 10.5, again below to the threshold value (MD < 22). Therefore, this aggregate material does fulfil all the requirements expected for a subballast layer. This good result is quite uncommon for calcareous soils, which are the most abundant in the eastern regions of Spain. The reason is the high content of dolomite in the chosen soil, which provides greater resistance to fragmentation. Usually, when new tracks are built in eastern Spain, the calcareous soil excavated on site needs to be disposed of and replaced by a more competent material, hence increasing the cost and environmental impact of the construction.

Considering now the different rubber-aggregate mixes studied, the first noteworthy result is that all the mixes are within the required gradation curves (Fig. 6). It is clear then that a 10% (or lower) addition of rubber in terms of weight will not compromise the viability of the mixed material in terms of size gradation.

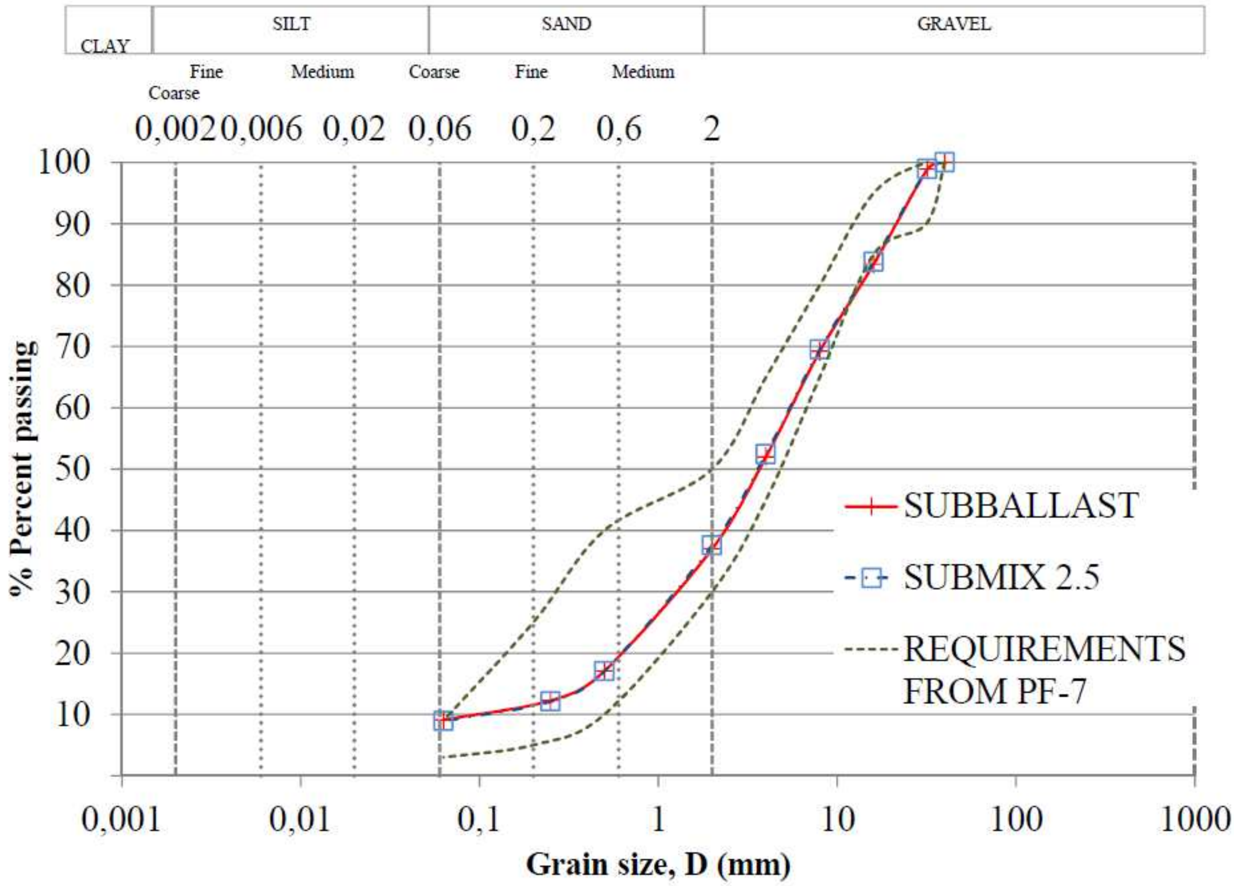

Fig. 6: Soil gradation for the subballast and the 2.5% mix.

Focusing now in the degradation, all the mixes present an enhanced behaviour compared to the unmixed soil, as the addition of such an elastic material as rubber reduces the wear of the mixture. Fig. 7 shows the results of both the Los Angeles test and Micro-Deval test. Both figures show a clear trend of degradation reduction with an increase of rubber content. For a 10% addition of rubber, the LA shows a reduction of 20% (from 25 to 20) and the MD is reduced from 10.5 to 8.4 (20 %), a result that improves the requirements aforementioned. Therefore, an addition of 10% rubber to a more calcareous soil, which usually does not reach the degradation thresholds, may turn an otherwise invalid material for subballast into a suitable one, according to Spanish norms.

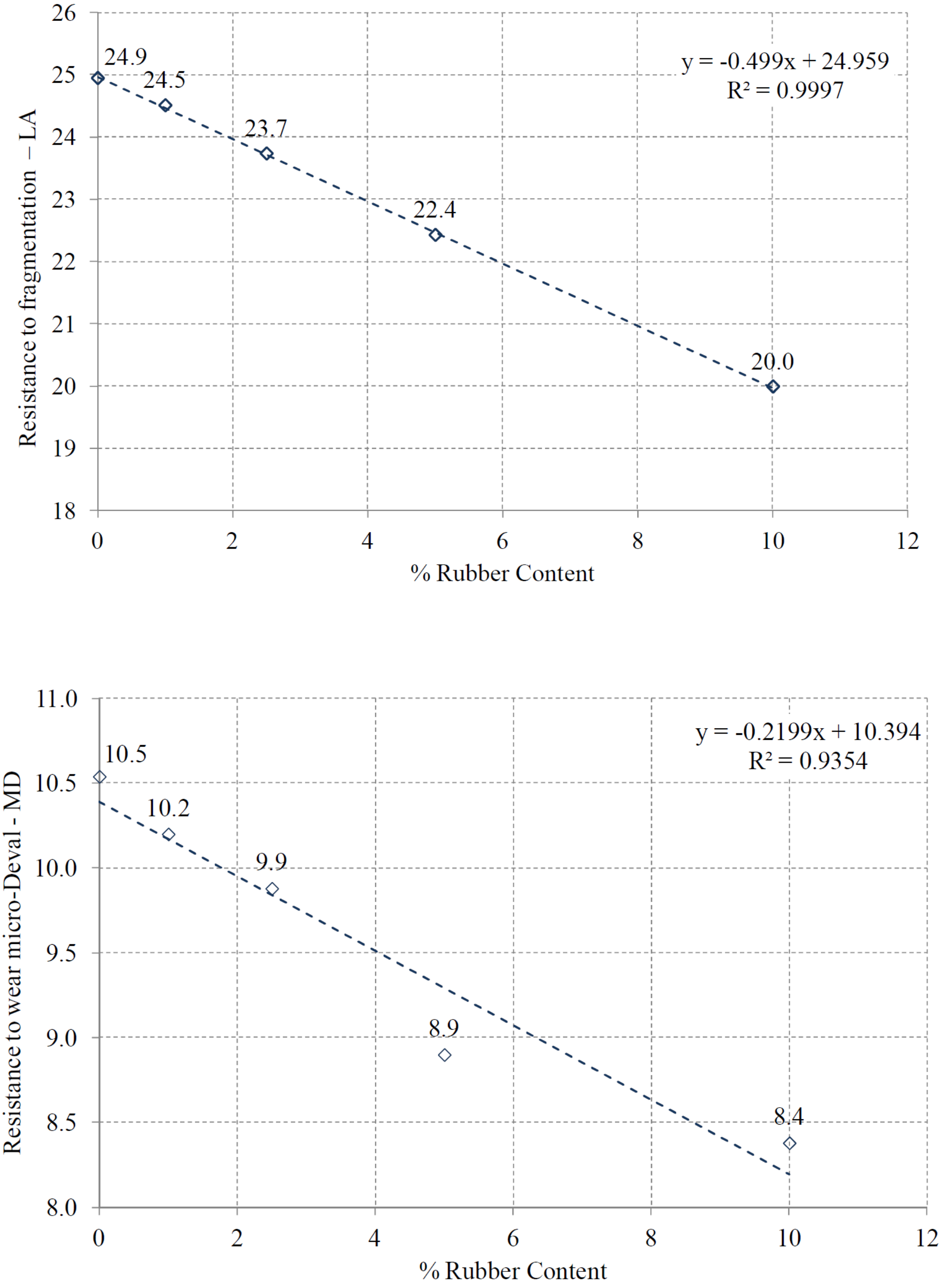

Fig. 7: Los Angeles coefficient (up) and Micro-Deval (humid) coefficient (down).

It could be argued that the Los Angeles and Micro-Deval tests may not be completely appropriate to assess the degradation of rubber-soil mixes, as they were first conceived to measure the abrasion of common, unmixed aggregates. However, it is not the objective of this study to discuss the reliability of these tests (which would require a paper on its own) but to assess the suitability of the rubber-soil mixes under the parameters and tests required by Spanish regulations. These regulations, which are quite similar to the common practice in the railways sector across Europe, are based on existing standard procedures such as the Los Angeles and Micro-Deval tests, and thus the mixtures studied in this paper were assessed according to such standards. However, their aptness is a rather important issue that requires further research and discussion.

That being said, the addition of rubber has other effects that should be taken into account before setting an optimal percentage. First of all, the more rubber added, the lower the density of the material, and this may be an advantage to certain extent as a more light material is obtained. However, during the CBR test it was found that an addition higher than 10% (in weight) induces bulking, hence increasing dramatically the energy required for compaction. For this reason the experimental platform was built with a maximum 5% of rubber content in one of its four sections, as explained before. Therefore, a rubber addition over 10% of the aggregate weight is not appropriate.

Considering now the bearing capacity, the addition of rubber tends to reduce the CBR. An addition of 2.5% (in weight) yields a threefold reduction when compared with the pattern material (Fig. 8). Previous research made for sand and rubber mixes covering a wide range of rubber content (from 10% to 50% in terms of volume) observed a completely different result (Hataf and Rahimi, 2006). This is because rubber particles are of greater size than sand particles and provide certain degree of entanglement when mixed, hence increasing the bearing capacity and shear strength of the sand.

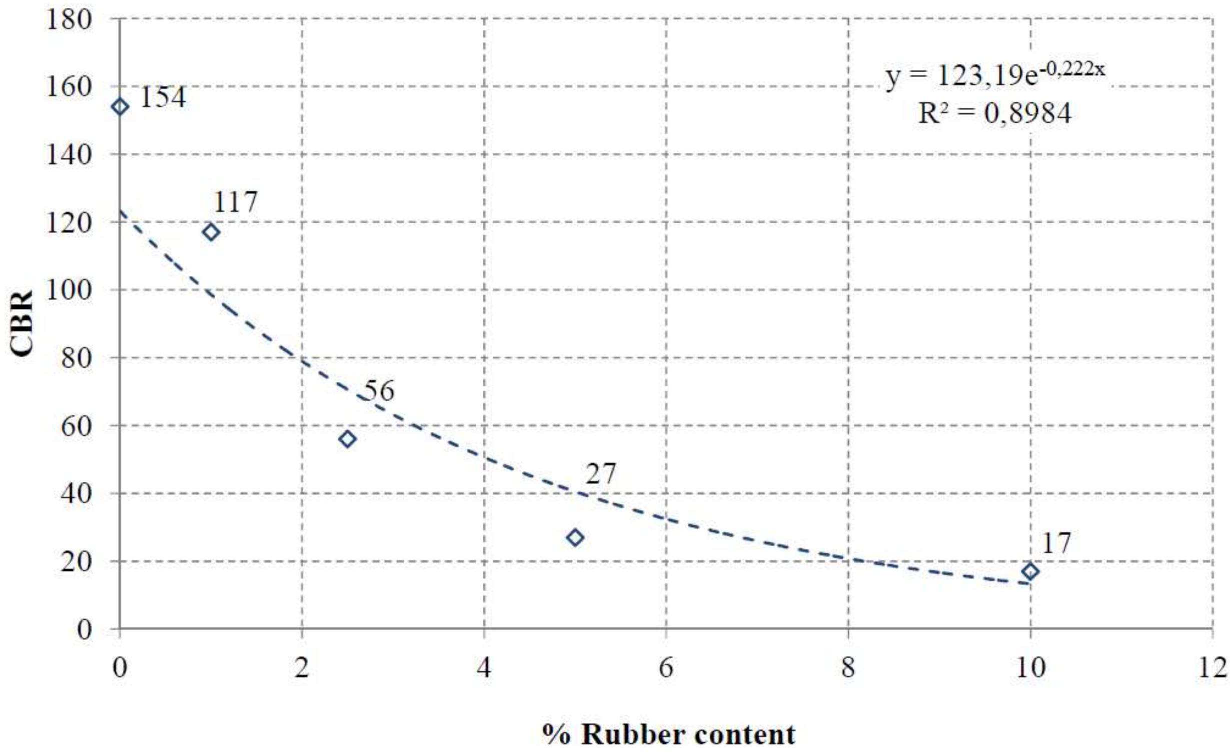

Fig. 8: CBR results against rubber content.

This is not the case in the mixes studied for this paper, where rubber particles are smaller than those of the aggregates used for subballast.

It is worth noting that this test and all the following were performed ensuring a 100% Modified Proctor density for all the samples.

Nevertheless, despite this trend of reduction, all the mixes studied yielded a CBR index high enough to be used for railway platforms, except the 10% mix (the required CBR is 20 or better). This mix could be still used, however, for platform layers under the subballast layer in railway lines with low average daily traffic.

Therefore, the addition or rubber provides two main effects. On the one hand, the elastic behaviour and resistance to degradation is improved. On the other hand, bearing capacity is reduced, but it is still within the usual range for a subballast material. This is particularly remarkable because the Spanish railway regulations do not take into account the CBR as a measure of the subballast bearing capacity, relying instead on the static load plate test carried out in situ.

Taking into account all these results, adding rubber to the soil up to about 7.5% in weight will yield a more elastic and less prone to degradation material while ensuring a high enough bearing capacity, hence solving the aforementioned usual problem of high degradation found in calcareous soils which are rather common in South-West Spain.

With regards to the cyclic load triaxial test, Fig. 9a shows that the resilient modulus (M_r) decreases with the addition of rubber. This was expected as density is reduced when rubber is added and that directly affects the resilient modulus. The modulus used for this comparison corresponds to a confining pressure of 34.5 kPa and a deviator stress of 103.4 kPa, (NCHRP, 2004). The average results are also detailed in Table 4, including moisture content and strain levels.

Table 4: Average results from the cyclic load triaxial test.

	Subballast	**1.0% Mix**	**2.5% Mix**	**5.0% Mix**
Dry Unit Weight, γd (g/cm3)	2.32	2.30	2.25	2.17
Resilient Modulus, Mr (MPa)	249.6	192.3	167.4	92.8
Permanent Strain, ε_p (%)	0.233	0.275	0.400	0.750
Resilient Strain, ε_r (%)	0.042	0.051	0.057	0.103
Initial Moisture content, W_o (%)	6.2	6.2	6.2	6.2
Final Moisture content, W_f (%)	4.8	4.5	5.1	5.1

It is usually required, for materials to be used as support layers, that the resilient modulus is at least over 100 MPa (Brown and Pappin, 1985), therefore the addition of rubber should be limited to less than 5% in weight. However, the resilient modulus depends on the level of stress, and this is taken into account in Fig. 9b, where M_r is compared with Θ, which is the sum of principal stresses (1):

$$\Theta = \sigma_1 + 2\sigma_3 \tag{1}$$

The trend lines drawn in Fig. 9b for each mix as well as for the pattern material correspond to the non-linear Bulk Stress Model usually used (Araya et al., 2012) to study the resilient deformation of unbound granular materials such as the ones considered in this study. This model is ruled by the following equation (2):

$$M_r = k_1 \cdot \Theta^{k_2} \tag{2}$$

Where k_1 and k_2 are non-linear parameters which depend on the material studied (Mohammad et al., 1994). From Fig. 9b it is clear that, at lower stress levels, the difference in the resilient modulus due to the addition of rubber is much higher than that found and higher stress levels. However, it is worth nothing that for all samples the resilient modulus increases with the stress level; hence the addition of rubber does not alter the typical behaviour of an aggregate material (Gudishala, 2004).

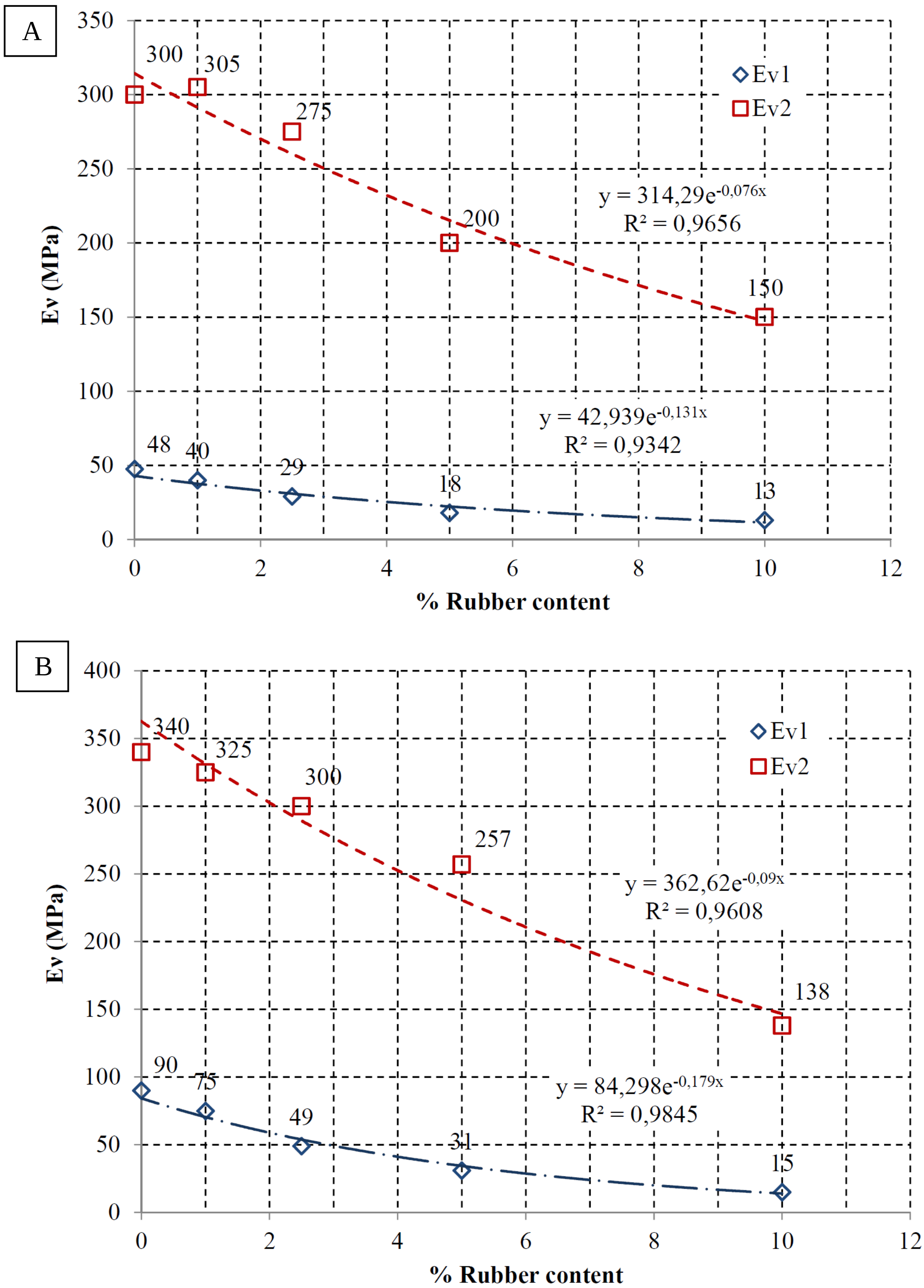

Fig. 9: A) Resilient modulus vs. % rubber content. B) Resilient modulus vs. Sum of principal stresses.

Another interesting result is shown in Fig. 10, which compares the resilient strain (Fig. 10a) and permanent strain (Fig. 10b) with the number of cycles for each mix studied. Both the resilient and permanent strain increases with the number of cycles and the content of rubber. For the 5% mix the maximum resilient strain after 2000 cycles is 8E-4 (in unit fraction), while the permanent strain is above 1.2 %.

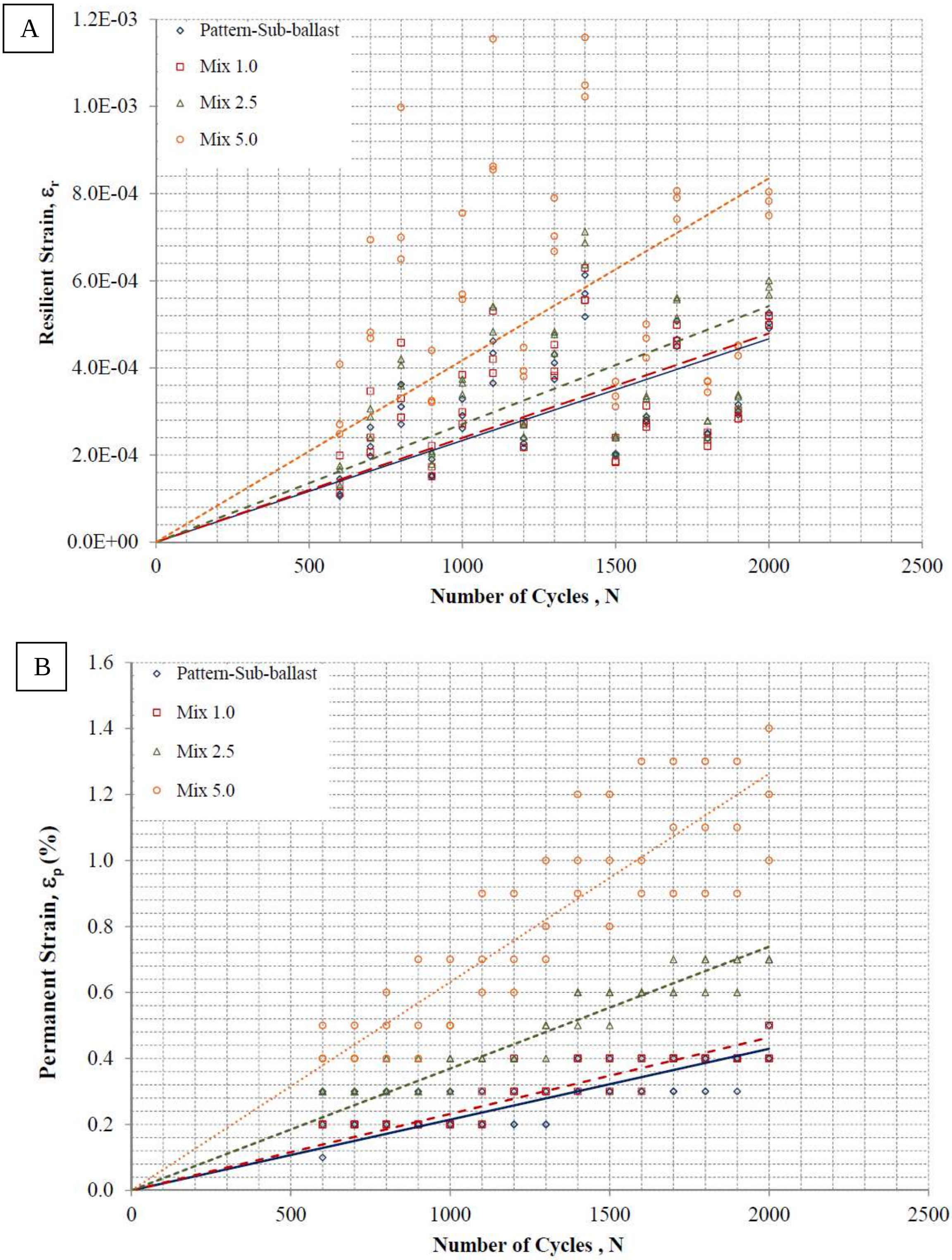

Fig. 10: A) Resilient strain (unit fraction) vs. number of cycles. B) Permanent strain (%) vs. number of cycles.

The shear tests carried out showed that all the mixes behave similarly to the pattern material. The parameters obtained were the same (Cohesion = 0 kPa, Effective Friction angle = 47º), and the only difference observed was that the increase in rubber content increases also the horizontal deformation needed to reach the same shear stress. Therefore, the addition of rubber within the range considered in this study (i.e. lower or equal to 10% in weight) does not alter the shear strength of the soil.

Finally, in both the CBR and cyclic load triaxial tests it has been observed that mixtures with higher rubber content retain more moisture after being subjected to load cycles. This is likely due to their higher compressibility.

4.2. Field results

The results of the field tests performed in the experimental platform are listed in Tables 5 and 6. The tests carried out in the natural ground underneath the experimental platform yield an in situ humidity of 6.8% and a dry density of 1.95 g/cm^3. The degree of compaction is above 98%.

Table 5: Field tests results for the platform material under each section.

	In situ dry density (g/cm^3)	In situ humidity (%)	Modified Proctor density (g/cm^3)	Modified Proctor humidity (%)	% Compaction	Dynamic deflection modulus E_{vd} (MPa)
Pattern	2.185	6.5	2.280	6.6	95.8	89.3
1.0% Mix	2.185	6.9			95.8	
2.5% Mix	2.241	6.7			98.3	
5.0% Mix	2.234	6.2			98.0	

Table 6: Field tests results for the subballast materials in each section.

	In situ dry density (g/cm^3)	In situ humidity (%)	Modified Proctor density (g/cm^3)	Modified Proctor humidity (%)	% Compaction	Static deformation modulus E_{v2} (MPa)	Dynamic deflection modulus E_{vd} (MPa)
Pattern	2.262	6.4	2.360	6.2	95.8	232	147
1.0% Mix	2.240	7.5	2.300	6.2	97.4	195	118
2.5% Mix	2.197	6.7	2.260	6.2	97.2	160	75
5.0% Mix	2.120	6.9	2.160	6.2	98.1	84	47

As for the different mixes, from table 6 it is clear that, as the rubber content increases, the percentage of compaction attained increases too, as the density to be reached according to the Modified Proctor Tests is also reduced. Therefore, the addition of rubber may ease the compaction process made with conventional equipment (i.e. road roller). Additionally, both the static and dynamic moduli tend to decrease when more rubber is added, a result already observed during the cyclic load triaxial test. It is worth comparing the results from that test and the dynamic modulus obtained from the LFWD, as the former is a rather complex and expensive test whereas the latter is much more common and affordable. This comparison is shown in Fig. 11, and the correlation between the Resilient Modulus (M_r) and the Dynamic Deflection Modulus (E_{vd}) found is:

$$M_r = 4.416 \cdot E_{vd}^{0.81} \tag{3}$$

With a R^2 coefficient of 0.94. This result may be useful to further characterise this kind of mixed materials by means of more cost-effective testing devices such as the LFWD, particularly when more expensive systems such as the cyclic load triaxial test are not available.

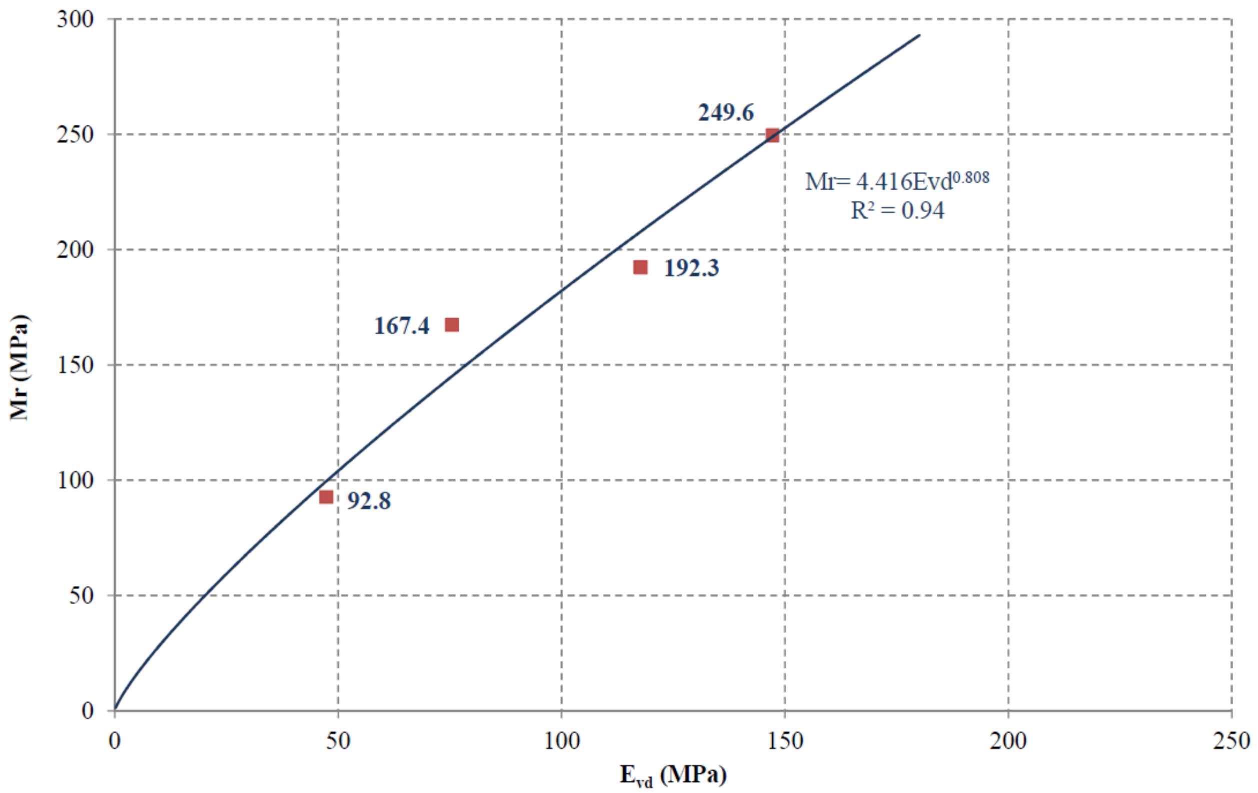

Fig. 11: Correlation between resilient modulus and dynamic deflection modulus.

Another noteworthy result is that all the mixes tested, except the 5 % mix, yield dynamic modulus (E_{vd}) greater than 50 MPa, which is the threshold required by the German Railways normative NGT

39 (1997) for subballast layers. The static modulus (E_{v2}) is well over the 120 MPa threshold required by the PF-7 (2006) except, once again, for the 5 % mix (Fig. 12).

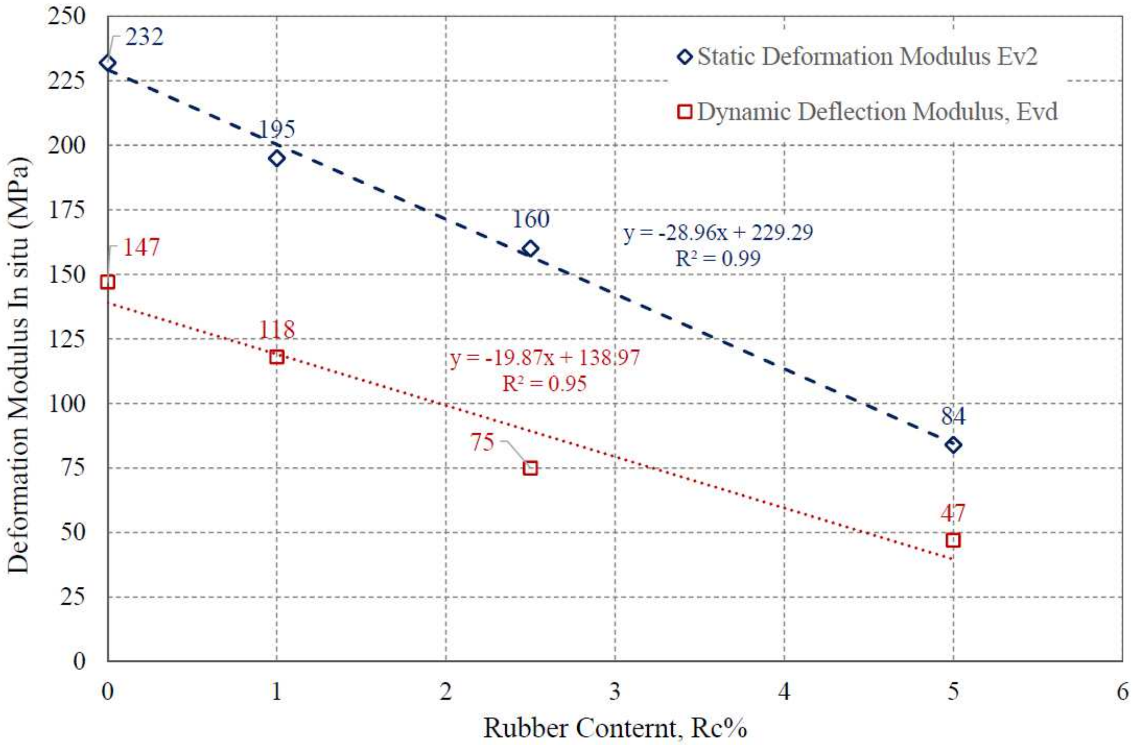

Fig. 12: Static modulus E_{v2} and Dynamic modulus E_{vd} vs. % rubber content.

All the tests performed (both in laboratory and in the field) are standard procedures defined in ASTM and British norms.

5. Conclusions

From the results discussed in the previous section, a few conclusions may be drawn. First of all, the addition of rubber particles to a granular material enhances the resistance of the resultant mix against degradation, improving the standard wear coefficients used to test that characteristic (Los Angeles and Micro-Deval). Nevertheless, these standard procedures might not be completely apt for the kind of unbound rubber-aggregates mixes studied.

On the other hand, density and bearing capacity are reduced, but the CBR index obtained is still over 20 (which is a usual minimum for this kind of material) unless the addition of rubber is equal to 10% of the total weight.

The resilient modulus (M_r) obtained from the cyclic load triaxial test also shows the same trend: the more rubber added, the lower the modulus. This difference is more evident for lower stress levels. In any case, it was found that the content of rubber should be limited to less than 5% (in weight) in order to ensure enough bearing capacity and resilient modulus.

Furthermore, the addition of rubber within the range considered (≤ 10% in weight) does not alter the resistant parameters of the soil obtained from a shear tests. Nevertheless, more deformation is required to reach the maximum shear stress.

From all these results it can be concluded that the addition of a small percentage of rubber to a coarse aggregate may improve the material in terms of resistance to degradation while maintaining its bearing capacity and resilient modulus in acceptable levels. In order to ensure such balance, rubber particles should be added in a proportion lower than 5% in weight. In this way, materials otherwise invalid for their use as subballast in railway platforms may be enhanced and used while fulfilling all the requirements set on Regulations. This may bring an economic advantage in terms of cost reduction, as there would be no need of dispose of the previously inacceptable material and obtain a better and more expensive soil. Moreover, the generalization of this use for rubber particles will allow the recycling of large quantities of scrap tyres, whose accumulation represents an environmental threat to modern societies.

All these potential advantages should encourage further research in this topic, focusing particularly in some aspects that are still not well known, such as the effect of the rubber particle size and the applicability of some of the procedures and thresholds defined in the regulations to materials that are certainly different to those these limits were fixed for. Another important aspect is that the test board used for the field tests was, as explained before, relatively small and not completely in accordance with certain recommendations. In order to better study the behaviour of the mixes, they will be tested in an actual railway platform with real traffic conditions during future stages of research.

Finally, modifying the elasticity of the subballast layer may provide a certain level of attenuation of the vibration caused by the trains. This is a rather important feature as the mitigation of vibration has become a key issue regarding the environmental impact of railway networks; hence it should be studied in the future.

Acknowledgments

The authors wish to thank GUEROLA for providing the soil samples from its quarry, EMRO for providing the rubber particles and Ángel Morilla Rubio, Manolo Medel Perallón and Esther Medel Colmenar for their help during the field tests.

References

AASHTO (2003). T307-99-UL. 'Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials.'

Araya, A.A., Huurman, M., Molenaar, A.A.A., Houben, L.J.M. (2012). 'Investigation of the resilient behavior of granular base materials with simple test apparatus.' *Materials and Structures*, 45, pp. 695-705.

ASTM (1998). D6270-98. 'Standard Practice for Use of Scrap Tires in Civil Engineering Applications.'

ASTM (2001a). D3017. 'Standard Test Method for Water Content of Soil and Rock in Place by Nuclear Methods (Shallow Depth).'

ASTM (2001b). D2922. 'Standard Test Methods for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth).'

ASTM (2005). D1883. 'Standard Test Method for CBR (California Bearing Ratio) of Laboratory Compacted Soils.'

ASTM (2006a). C131. 'Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine.'

ASTM (2006b). D5821. 'Standard Test Method for Determining the Percentage of Fractured Particles in Coarse Aggregate.'

ASTM (2007). D4959. 'Standard Test Method for Determination of Water (Moisture) Content of Soil By Direct Heating.'

ASTM (2009a). D75/D75M-09. 'Standard Practice for Sampling Aggregates.'

ASTM (2009b). D6913. 'Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis.'

ASTM (2009c). D2419. 'Standard Test Method for Sand Equivalent Value of Soils and Fine Aggregate.'

ASTM (2009d). D4694. 'Standard Test Method for Deflections with a Falling-Weight-Type Impulse Load Device.'

ASTM (2010a). D4318. 'Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils.'

ASTM (2010b). D5084. 'Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter. Method B and C.'

ASTM (2010c). D6928. 'Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus.'

ASTM (2011a). D3080/D3080M. 'Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions.'

ASTM (2011b). D7181. 'Standard Test Method for Consolidated Drained Triaxial Compression Test for Soils.'

ASTM (2012a). C127. 'Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate.'

ASTM (2012b). D7760. 'Standard Test Method for Measurement of Hydraulic Conductivity of Tire Derived Aggregates Using a Rigid Wall Permeameter.'

ASTM (2012c). D1557. 'Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3 (2,700 kN-m/m^3)).'

ASTM (2013). D2974. 'Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils.'

ADIF (2008). 'Pliego de Prescripciones Técnicas Tipo para los Proyectos de Plataforma PGP-2008 (Techical Specifications for Railway Platform Projects PGP-2008).'

Brown, S.F. and Pappin, J.W. (1985). 'Analysis of Pavements with Granular Bases.' *Transportation Research Record*, 1022, pp. 52-59.

BS (1990a). 1377-5. ‘Methods of test for soils for civil engineering purposes. Compressibility, permeability and durability tests.’

BS (1990b). 1377-9. ‘Methods for test for soils for civil engineering purposes In-situ tests: Determination of the vertical deformation and strength characteristics of soil by the plate loading.’

Buonanno, A. and Mele, R. ‘The use of bituminous mix sub-ballast in the Italian State Railways’. *2nd Eurasphalt & Eurobitume Congress*, Barcelona, 20-22 September 2000.

Cano, H., Estaire, J. and Rodríguez, R.. ‘Terraplén Experimental construido con Neumáticos Troceados (Experimental embankment built with shredded tyres). ’ *Jornada Técnica Sobre Experiencias Recientes en Estructuras de Tierra para Infraestructuras Viarias.* Madrid, 10 February, 2011.

CEDEX (1991). NLT-148/91. ‘Toma de muestras de roca, escorias, grava, arena, polvo mineral y bloques de piedra empleados como materiales de construcción de carreteras (Sampling of rocks, slags, sand, mineral dust and stone blocks used for road construction).’

CEDEX (1998). NLT-357:98. ‘Ensayo de carga con placa (Load plate test).’

Di Mino, G., Di Liberto, M., Maggiore, C. and Noto, S. (2012). ‘A dynamic model of ballasted rail track with bituminous sub-ballast layer.’ *Procedia-Social and Behavioral Sciences*, 53, 366-378.

Edinçliler, A., Baykal, G. and Saygılı, A. (2010): ‘Influence of different processing techniques on the mechanical properties of used tires in embankment construction.’ *Waste Management,* 30, 1073-1080.

European Commission (1999). Directive on the Landfill of Waste 1999/31/EC. *Official Journal of the European Union*, 182, 1-19.

European Commission (2008). Waste Framework Directive 2008/98/EC. *Official Journal of the European Union,* 312, 3-30.

Feng, Z. and Sutter, K. (2000). ‘Dynamic properties of granulated rubber/sand mixtures.’ *Geotechnical Testing Journal,* 23 (3), 338-344.

FGSV: Earthworks and Foundation Engineering Task Force (1994): ZTVE-StB 94. ‘Supplementary Technical Terms and Conditions of Contract and Guidelines for Earthworks in Road Construction.’

Garnica, P. A., Pérez, G. N., and Gomes, L. A. (2001). ‘Módulo de Resiliencia en Suelos Finos y Materiales Granulares. (Resilient Modulus in Fine Soils and Aggregate Materials).’ *Publicación Técnica*, 142, Secretaría de Comunicaciones y Transportes (SCI), Instituto Mexicano del Transporte (IMT). Sanfandila, México.

German Railways (1997). NGT 39. 'Richtlinie für die Anwendung des Leichten Fallgewichtsgerätes im Eisenbahnbau. (Directions of Application of Light Drop-Weight Tester in Railways).'

Gudishala, R. (2004). 'Development of resilient modulus prediction models for base and subgrade pavement layers from in situ devices test results.' PhD Thesis. SriKrishna Devaraya University, Andhra Pradesh, India.

Hataf, N. and Rahimi, M. M. (2006). 'Experimental investigation of bearing capacity of sand reinforced with randomly distributed tire shreds.' *Construction and Building Materials*, 20 (10), 910-916.

Humphrey, D. N., Whetten, N., Weaver, J. and Recker, K. 'Tire shreds as lightweight fill for construction on weak marine clay.' *Proceedings of the International Symposium on Coastal Geotechnical Engineering in Practice*, Balkema, Rotterdam, 2000.

Humphrey, D. N. and Blumenthal, M. (2010). 'The Use of Tire-Derived Aggregate in Road Construction Applications.' *Green Streets and Highways 2010*, 299-313.

Melis, M. (2006). 'Terraplenes y balasto en Alta Velocidad Ferroviaria (Embankment and ballast in High Speed Railways).' *Revista de Obras Públicas*, 3464, 7-36.

Mohammad, L.N., Puppala, A., and Alavalli, P. (1999). 'Effect of Strain Measurements on Resilient Modulus of Granular Soils.' *Dynamic Geotechnical Testing, Second Volume*, ASTM STP 1213, pp. 202-221.

Nakhaei, A., Marandi, S. M., Sani Kermani, S. and Bagheripour, M. H. (2012). 'Dynamic properties of granular soils mixed with granulated rubber.' *Soil Dynamics and Earthquake Engineering*, 43, 124-132.

National Cooperative Highway Research Program (2004). 'Research Results Digest. Laboratory Determination of Resilient Modulus for Flexible Pavement Design.' Available at: http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rrd_285.pdf (accessed 01/04/14).

RENFE (1982). N.R.V. 2-1-0.0. 'Obras de Tierra, Calidad de la Plataforma. (Earthworks, platform quality).'

Salgado, R., Yoon, S. and Zia Siddiki, N. (2003). 'Construction of Tire Shreds Test Embankment.' *Joint Transportation Research Program. Technical Report Nº: FHWA/IN/JTRP-2002/35.* Available at: http://docs.lib.purdue.edu/jtrp/42/ (accessed 11/02/2013).

SETRA (2005). Informative Note 114. 'Éléments techniques pour la conception et la realization de planches d'essais de compactage dans les chantiers de terrassements (Technical elements for the conception and construction of compaction test boards on earthwork sites).'

Sharma, V.K., Fortuna, F., Mincarini, M., Berillo, M. and Cornacchia, G. (2000). 'Disposal of waste tyres for energy recovery and safe environment.' *Applied Energy*, 65 (1-4), 381-394.

Sheehan, P. J., Warmerdam, J. M., Ogle, S., Humphrey, D. N. and Patenaude, S. M. (2006). 'Evaluating the risk to aquatic ecosystems posed by leachate from tire shred fill in roads using toxicity tests, toxicity identification evaluations and groundwater modeling.' *Environmental Toxicology and Chemistry*, 25 (2), 400-411.

SIGNUS (2012): Activity Report 2012. Available at: http://www.signus.es/ (accessed 02/07/2014).

Spanish Ministry of Public Works (2006). 'Pliego de Prescripciones Técnicas Generales de Materiales Ferroviarios PF-7: Subbalasto (General Technical Specifications for Railway Materials PF-7: Subballast).' *Boletín Oficial del Estado*, 103, 16891-16909.

Speir, R. H. and Witczak, M. W. (1996). 'Use of shredded rubber in unbound granular flexible pavement layers.' *Transportation Research Record*, 1547, 96-106.

Tutumluer, E., and Seyhan, U. 'Laboratory determination of anisotropic aggregate resilient moduli using a new innovative test device.' *78th Annual meeting of the transportation research board specialty session on "Determination of resilient modulus for pavement design."* Washington DC, USA, 1999.

Vipulanandan, C., Bilgin, Ö., Jeannot, Y., Vembu, K. and Bahadir, M. (2009). 'Prediction of embankment settlement over soft soils.' *Project Report Nº FHWA/TX-09/0-5530-1.* Available at: http://d2dtl5nnlpfr0r.cloudfront.net/tti.tamu.edu/documents/0-5530-1.pdf (accessed 30/06/2014).

Wang, J. and Zeng, X. (2004). 'Numerical simulation of vibration attenuation of high-speed train foundations with varied trackbed underlayment materials.' *Journal of Vibration and Control*, 10, 1123-1136.

Wolfe, S. L., Humphrey, D. N. and Wetzel, E. A. (2004). 'Development of tire shred underlayment to reduce groundborne vibration from LRT track'. *Geotechnical Engineering for Transportation Projects: Proceedings of Geo-Trans 2004*, 750-759. ISSN: 0-7844-0744-4.

Yoon, S., Prezzi, M., Zia Siddiki, N. and Kim, B. (2005). 'Construction of a test embankment using a sand–tire shred mixture as fill material.' *Waste Management*, 26, 1033–1044.