No.	kPa	kPa	kPa	kPa	No.
0	103.4	103.4	93.1	10.3	500-1000
1	20.7	20.7	18.6	2.1	100
2	20.7	41.4	37.3	4.1	100
3	20.7	62.1	55.9	6.2	100
4	34.5	34.5	31.0	3.5	100
5	34.5	68.9	62.0	6.9	100
6	34.5	103.4	93.1	10.3	100
7	68.9	68.9	62.0	6.9	100
8	68.9	137.9	124.1	13.8	100
9	68.9	206.8	186.1	20.7	100
10	103.4	68.9	62.0	6.9	100
11	103.4	103.4	93.1	10.3	100
12	103.4	206.8	186.1	20.7	100
13	137.9	103.4	93.1	10.3	100
14	137.9	137.9	124.1	13.8	100
15	137.9	275.8	248.2	27.6	100

The average deviator stress from the last five cycles and the recovered axial deformation (ε_r) were used to obtain the resilient modulus M_r from both the pattern and the mixtures. Additionally the evolution of the permanent axial deformation (ε_p) was also measured. Once the triaxial test was done, the final moisture content of each specimen was measured.

2.4. Permanent Deformation Test

The addition of rubber not only may affect the elastic properties of the subballast layer, but it is also important to evaluate its impact in the structural behaviour of said layer in terms of permanent deformation. According to the "Shakedown" theory (Werkmeister, 2011), when an aggregate experiences low level cyclic loads, permanent deformations tend to stabilise after a number of cycles. However, if the applied loads are high enough, permanent deformations rapidly increase even to the point of a gradual failure. Therefore, there is a limit of critical stress that marks the boundary between stable and unstable situations. This is the Plastic Creep Limit, and if the loads applied are below such limit, the deformations experienced by the material will fall within acceptable limits and failure will only take place after a large number of loading cycles (Cerni, 2012).

In order to obtain the Plastic Creep Limit (PCL), the methodology found in UNE EN 13286-7 was followed. Permanent Deformation Tests are carried out on a specimen with four different confining stresses, namely 20, 50, 70 and 100 kPa. The test starts by applying the lower deviator stress shown in Table 2 (the axial cyclic load is a 7 Hz senoid) and then increasing it sequentially until reaching failure. The PCL is then calculated by obtaining the stress combination (σ_1, σ_3) corresponding to the situation where the difference in the permanent deformation between the load cycles 3000 and 5000 is higher than 400 microstrain units ($\Delta\varepsilon_p = \varepsilon_{p5000} - \varepsilon_{p3000} > 400$ µstrain).

Afterwards, the axial stress σ_1 is plotted against the σ_1/σ_3 ratio for all the specimens tested of each mixture type. The curve thus obtained fits the following equation (1):

$$\sigma_1 = \alpha \left(\frac{\sigma_1}{\sigma_3}\right)^{\beta} \qquad (1)$$

Where σ_1 is the axial stress (kPa), σ_3 is the confining pressure (kPa), and α (kPa) and β are coefficients depending on material/mixtures. By obtaining this envelope the deformation behaviour of the mixtures can be predicted for each combination of stress.

Table 2: Stress levels during the multi-stage cyclic triaxial test. UNE EN 13286-7 Annex C

Confining Stress σ_3	**Minimum Deviator**	**Stress Ratio σ_d /σ_3**

kPa	Stress σ_d kPa	Subballast	Mix 1.0	Mix 2.5	Mix 5.0
20	5	1; 2; 3; 4; 5; 6; 7; 8; 9; 10; 11; 12; 13; 14; 15; 16; 17; 18; 19; 20; 21	1; 2; 3; 4; 5; 6; 7; 8; 9;10;11	1; 2; 3; 4; 5; 6; 7; 8	1; 2; 3; 4; 5; 6
50	5	1; 1.5; 2; 2.5; 3; 4; 5; 6; 7; 8; 9; 10; 11; 12; 13; 14; 15; 16; 17;18	1; 1.5; 2; 2.5; 3; 4; 5; 6; 7; 8; 9	1; 1.5; 2; 2.5; 3; 4; 5; 6; 7	1; 1.5; 2; 2.5; 3; 4
70	5	1; 1.5; 2; 2.5; 3; 4; 5; 6; 7; 8; 9; 10	1; 1.5; 2; 2.5; 3; 4; 5; 6; 7; 8; 9	1; 1.5; 2; 2.5; 3; 4; 5; 6	1; 1.5; 2; 2.5; 3; 4
150	5	1; 1.5; 2; 2.5; 3; 4; 5; 6; 7; 8; 9	1; 1.5; 2; 2.5; 3; 4; 5; 6; 7	1; 1.5; 2; 2.5; 3; 4; 5; 6	1; 1.5; 2; 2.5; 3; 4

These tests have been performed using the same equipment aforementioned. For each of the mixtures studied four cylindrical specimens have been made, each one with a diameter of 100 mm and 200 mm of height and compacted at 100% Modified Proctor with optimum moisture content. All specimens were protected after compaction by means of a 0.6 mm thick latex membrane. All tests were performed with double drainage during the application of the stress combination.

3. Results and Discussion

3.1. Characterisation Tests

The granular material is a well-graded gravel with silt (GW-GM) less than 10% of fine content, non-plastic nature, and a Sand Equivalent (SE) of 47%. Resistance to fragmentation (LA) and abrasion (MDH) are very low, 25 and 11 respectively.

Regarding the rubber particles, their Specific Gravity is 1.136 g/cm^3, 2.5 times lighter than the unbound granular material, while their absorption is 5.0%, much higher than the aggregate. For further details regarding the characterisation of the unmixed materials see Hidalgo et al. (2015).

3.2. Resilient Modulus

Table 3 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 [31] (National Cooperative Highway Research Program, 2004). 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. 3, where M_r is compared with Θ, which is the sum of principal stresses (2):

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

Table 3: Results from the cyclic load triaxial test.

Parameter	Subballast	Mix 1.0%	Mix 2.5%	Mix 5.0%
Dry Unit Weight, γ_d (g/cm^3)	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

The trend lines drawn for each mix as well as for the subballast correspond to the nonlinear 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 Eq. (3):

$$M_r = K_1 \Theta^{K_2} \tag{3}$$

Where K_1 and K_2 are non-linear parameters which depend on the material studied.

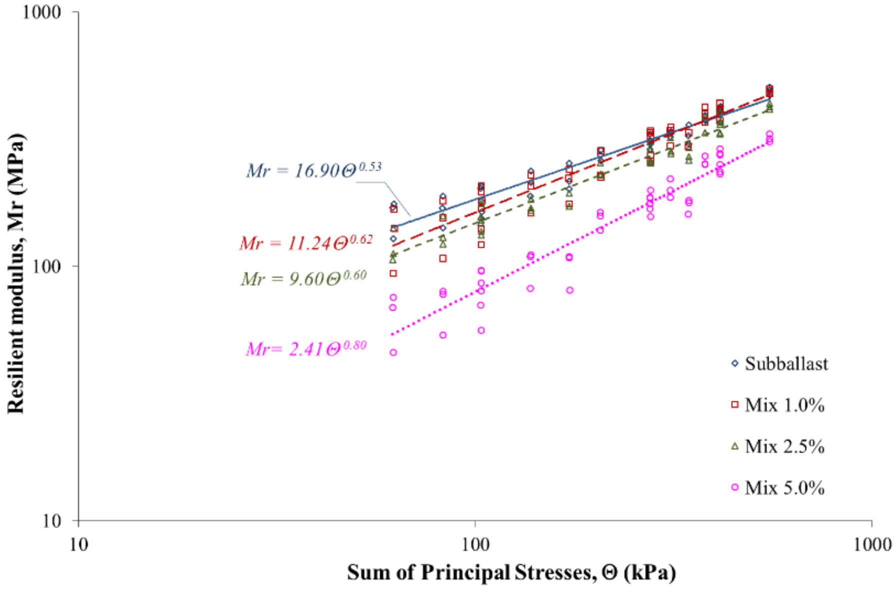

Figure 3. Resilient Modulus vs. Sum of Principal Stresses

From Figure 3 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 unbound granular material (Gudishala, 2004).

All mixtures except MIX 5.0 yield K_1 and K_2 parameters similar to those of an unmixed aggregated according to several previous studies (Rada and Witczak, 1981; Araya et al., 2011; Fortunato et al., 2012).

3.3. Permanent Deformation

Table 4 shows the average results obtained during the permanent deformation test for the four specimens of each mixture studied.

Table 4: Dry unit weight and moisture content before and after Permanent Deformation Test.

	Subballast	**Mix 1.0**	**Mix 2.5**	**Mix 5.0**
Max. Dry Unit Weight, γ_d^{PM} (g/cm^3)	2.35	2.28	2.24	2.18

Initial Moisture content, W_o (%)	6.20	6.20	6.20	6.20
Final Moisture content, W_f (%)	5.60	5.50	5.10	4.80

As that figure shows, the addition of rubber modifies the Plastic Creep Limit so that the mixtures with higher rubber content experience plastic creep with lower σ_1/σ_3 stress levels. The usual stress levels in subballast layers under railway tracks are below 100 kPa (Peña, 2003), with a σ_1/σ_3 ratio between 3 and 4 (as indicated by the red box in Figure 4). Taking into account these levels and the results shown in Figure 4, it is clear that the addition of rubber over 5% (in terms of weight) is undesirable as the resultant mixture may experience a combination of stress over the PCL, and thus the subballast layer will be more prone to failure under repeated loading.

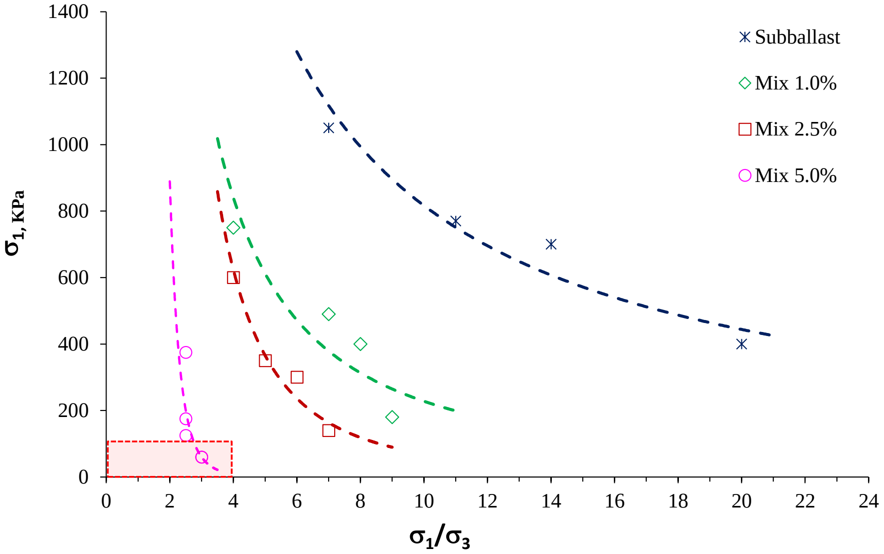

Figure 4 Plastic Creep Limits (PCL) for each mixture. The red box marks the usual stress values in a subballast layer.

Non-cohesive materials may be classified through their permanent deformability (UNE 13286-7:2008, Annex C.4). As shown in Figure 5(a), taking into account a common stress combination in the subballast layer, permanent deformation presents three different behaviours depending on the rubber content. The pattern material as well as the Mix 1.0% shows stable deformation behaviour – Range A: plastic accommodation. Mix 2.5% experiences plastic creep after a high number of load cycles – Range B: plastic creep. Finally, the Mix 5.0% reaches failure after a low number of load cycles – Range C: Progressive plastic collapse.

Figure 5(b) shows the maximum permanent deformation experienced by each mixture for a stress combination of 50 kPa (σ_3) and 100 kPa (σ_d). Adding rubber particles to the aggregate increases the mixture's permanent deformation due to the lower stiffness of rubber. The trend is approximately linear and may be defined by the following equation (4):

$$permanent\ deformation = a \cdot rubber + b \tag{4}$$

Where both the permanent deformation and the rubber content are in percentages (the latter with regards to the mixture total weight) and *a* and *b* are the equation parameters. As figure 5(b) shows, the values of *a* and *b* are 0.346 and 0.239, respectively, with a correlation coefficient (R^2) higher than 90%.

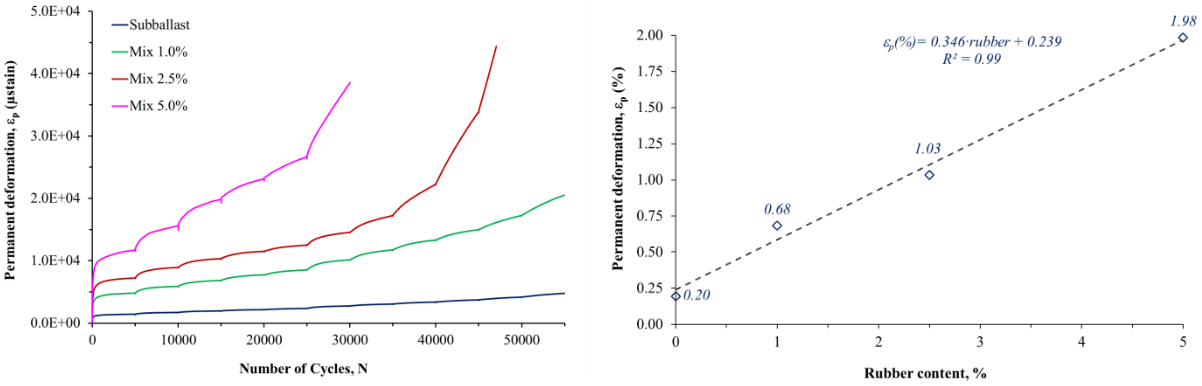

Fig.5 (a) Permanent deformation vs. Number of Cycles with confining pressure σ_3 50 kPa. (b) Permanent deformation vs. Rubber content with stress level σ_3 50 kPa and σ_d 100 kPa.

3.4. Optimum Rubber Content

Considering all the results obtained from the cyclic triaxial tests, and taking into account the usual stress levels measured in subballast layers, which are below 100 kPa (Peña, 2003), the percentage of rubber should be kept below 5% in terms of weight to avoid plastic creep and instability. This result is consistent with the optimum content obtained during previous stages of research (Hidalgo et al., 2015).

4. Conclusions

This paper is a continuation of a wider research project that aims to characterise rubber-aggregate mixtures and their potential use as subballast layers under railway tracks. The present paper focuses on the study of the stress-strain behaviour of such mixtures under cyclic loads. In order to assess this behaviour, several cyclic load triaxial tests were carried out for mixtures with varying percentage of rubber content.

The results obtained show that the resilient modulus (M_r) tends to decrease as the rubber content increases, although all the mixtures studied except the Mix5% yield a M_r higher than 100 kPa, which is an acceptable level for subballast layers.

Moreover, adding rubber reduces the Plastic Creep Limit of the mixture. Percentages higher than 5% in terms of weight may lead to unstable mixtures which experience large deformations after a small number of load cycles. The Mix5% showed a progressive plastic collapse for a stress combination of 50 kPa (σ_3) and 100 kPa (σ_d).

All these results show that the percentage of rubber should be kept below 5% in order to obtain a mixture with enough resilient modulus and below the Plastic Creep Limit. This threshold is consistent with the one obtained during previous stages of research with regards to the bearing capacity of the mixtures.

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