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Friction resistance for different ballast-sleeper interfaces

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ABSTRACT: Laboratorio de Geotecnia-CEDEX runs a large direct shear test apparatus that facilitates the assessment of granular materials such as ballast, ensuring compliance with established standards concerning sample size and equipment specifications. This paper details the outcomes of shear resistance tests conducted on ballast, which was prepared under conditions that replicate those found in actual railway tracks, in conjunction with an array of sleeper types, with the aim to determine the sleeper resistance due to the strength of the ballast-sleeper interface. Although the predominant practice in Spain involves the use of concrete sleepers, there is an increasing focus on the sustainability of alternative sleepers constructed from plastic and synthetic materials. The results of this investigation suggest a significant potential for enhanced sustainability and cost-effectiveness in railway projects.

KEYWORDS: Ballast, sleeper, friction resistance.

1 INTRODUCTION

The interaction between railway sleepers and the underlying ballast layer plays a key role in the structural integrity and long-term performance of railway infrastructure. Among the various mechanical parameters governing this interaction, the frictional resistance at the sleeper-ballast interface is of particular importance, as it contributes directly to the track capacity to maintain geometric stability under dynamic and environmental loads. Understanding this frictional behaviour is crucial for developing more resilient, sustainable and safer railway systems.

One of the primary reasons for studying this interface is its crucial role in resisting both lateral and longitudinal movements of the sleeper. In continuously welded rail (CWR) tracks, thermal expansion and contraction of the rails can produce substantial transversal forces, which must be counteracted effectively to prevent rail buckling or displacement.

According to the literature, the lateral resistance of sleepers on the ballast layer is linked to the friction that occurs both at the base and the sides of the sleeper, as well as on the shoulder of the ballast bench. Another widely accepted assertion is that one of the greatest contributions arises from the resistance to friction between the sleeper bottom and the ballast (Santana & Estaire, 2019).

It is reasonable to assert that the choice of material used in the manufacture of sleepers, among other parameters, has a significant impact on the ballast-sleeper interface resistance with the ballast. Numerous studies have been conducted to explore the variations in lateral resistance of sleepers, employing both single tie push tests (STP tests) and discrete element method (DEM) modelling. These investigations examine the effects of different construction materials for sleepers, variations on sleeper bottom surface or the placement of under-sleeper pads [Zakeri & Bakhtiary (2014), (Bakhtiary et al. (2015), Jing and Aela (2019), Mayuranga et al. (2024)].

Recognizing the relevant role of resistance at the sleeper bottom in ensuring lateral stability, the objective of this study is to evaluate the friction resistance associated with different types of sleepers that are supported by ballast.

2 MATERIALS AND METHODOLOGY

2.1 *Ballast*

According to the technical regulations of the Spanish railway administrator (ADIF), ballast is made up of particles derived from crushed rock. It serves as support for the track structure and helps cushion and distribute the loads generated by passing trains, among other important functions. The regulations also specify, that for high-speed tracks, the ballast layer must have a uniform grain size, be of siliceous origin, and possess high resistance.

The ballast-sleeper interface resistance is significantly influenced by the properties of the ballast itself (Jing and Aela, 2019). Accordingly, the regulations established by various railway administrators require that the ballast possesses high friction angles and adequate strength to ensure durability and prevent breakage (Sadeghi et al., 2016).

In this project, the ballast layer was placed in its optimal state. Ballast was obtained from a quarry that was officially approved by ADIF for high-speed rail tracks. The type of ballast used in this study was the same as in other previous tests, with its main characteristics detailed in Santana and Estaire (2019). Figure 1 shows the ballast used in the present study.

Figure 1 Image of the ballast used in this study.

2.2 *Sleepers*

The sleepers are support elements constructed from timber, concrete, metal or other types of materials, that serves as the foundation element upon which the rails are laid, establishing a link between the rails and the underlying ballast. The sleepers maintain the track gauge and rail inclination, effectively distribute the loads generated by passing trains, and preserve the overall stability of the track structure.

In Spain, the most used sleeper for high-speed railway lines is the AI-04 type, a mono-block prestressed concrete sleeper. However, in specific situations, it may be necessary to use other types of sleepers made from materials other than concrete. Synthetic sleepers offer technical and environmental advantages over traditional materials, combining durability and resistance to degradation with the use of recycled polymers, thereby supporting sustainability in railway infrastructure. The following is a general overview of the advantages and disadvantages of the different types of sleepers.

The use of timber sleepers offers certain advantages, including: the flexibility of the material, allowing greater load absorption; reduced weight, improving transport and handling; high resistance; and ease of adaptation to new positions (boxing). On the downside, they are expensive due to the lack of quality timber, have a short useful life, and are susceptible to degradation due to moisture, pests, or fire.

Concrete sleepers have the advantage of a longer service life because they are not affected by external agents and are better suited to fastening systems. On the other hand, they tend to be more expensive, their greater weight makes them more difficult to handle, and they have higher electrical conductivity.

Synthetic sleepers are an innovative solution for high-speed rail systems, particularly in sections exposed to harsh environmental conditions, structural constraints, or sustainability criteria. Currently, their usage is not widespread across all rail lines; however, research and development efforts are progressing toward enhanced models characterized by increased rigidity, improved mechanical compatibility, and reduced environmental impacts. These advancements aim to optimize the performance and longevity of rail infrastructure while addressing ecological concerns.

This study investigated five types of sleepers made of the following materials: concrete, akoga timber, Fibre reinforced Foamed Urethane, plastic and reinforced plastic. Their main characteristics are shown in Table 1.

Table 1 Usual physical range values for different types of sleepers.

Material	Length (m)	Height [a] (mm)	Weight (kg)
Concrete	2.6	242	320
Timber	2.6	140-160	70-120
FFU (synthetic)[b]	2.6	100-120	70-120
Plastic	2.6	150-160	85-110
Reinforced plastic	2.6	150-160	110-130

[a] Measured under the rail axis.
[b] Fibre reinforced Foamed Urethane (FFU)

Due to the dimension constraints of the shear box, the sleepers were cut. Table 2 presents the percentage of the bottom surface area of the sleepers, along with the weight of the tested sleepers.

Table 2 Percentages of the tested sleeper lower area versus the original area and weights of the sleepers tested

Material	Bottom surface area relative to the total (%)	Weight (kg)
Concrete	29.4	95.5
Timber	36.5	37.5
FFU (synthetic)	36.2	28.5
Plastic	36.5	27.5
Reinforced plastic	36.7	44.5

Figure 2 displays a photograph of the five sleepers studied in this research, along with their corresponding lengths prior to insertion into the shear box for the tests. The bottom sleeper surface is predominantly smooth across all cases, except the plastic sleeper, which exhibits a distinct morphology, as shown in Figure 3.

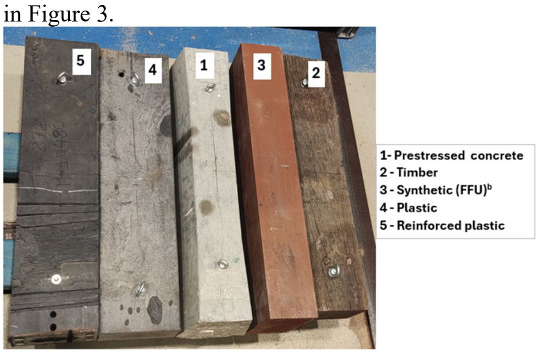

Figure 2 General aspect of the five types of sleepers tested.

Figure 3 Detail of the base of the plastic sleeper.

2.3 *Large shear test box*

The shear tests conducted in this study were carried out using a large-scale shear box belonging to Laboratorio de Geotecnia (CEDEX). This shear box has a shearing surface area of 1x1 m and can accommodate particles with a maximum diameter of up to80 mm. The apparatus can apply a maximum vertical load of 1000 kN to the specimen. The shear box allows for a horizontal displacement of up to 30 cm, providing an adequate range to capture the peak shear strength during testing. Additionally, a horizontal load of up to 1000 kN can be imposed, with the load controlled at a constant displacement rate to ensure consistent loading conditions throughout the test. More details are described in Santana and Estaire (2019).

3 LARGE SHEAR TESTS PERFORMED

3.1 *Test description*

This study involved conducting shear tests on the interface between the ballast layer and five types of sleepers. The lower half of the shear box was filled with the specified ballast material. To simulate the conditions of a high-speed track the ballast layer was compacted to a weight density of 16.7 kN/m³, which aligns with typical densities observed on actual railway tracks (16.0 – 17.5 kN/m^3). The compaction process involved placing the ballast material in three layers, with each layer compacted using a small vibrating hammer to ensure uniform weight density.

The procedure implemented in these tests were aligned to the methodologies established in our previous research. The ballast layer was carefully levelled on the shear plane of the box, and the sleeper to be tested was positioned on top, as shown in Figure 4. It is noteworthy that, due to the dimensions of the box, the sleepers had to be cut to fit within the 1 m long box.

Figure 4 General aspect of the test set-up when concrete sleeper is used.

Four normal stress levels were used in these tests: 25; 50; 100 and 150 kPa. The lower values simulate the normal stresses due to the weight of the 30 cm of the ballast layer, while the higher values reproduce the normal stresses due to the load of a passenger train axle.

3.2 *Test results to determine ballast-sleeper interface resistance*

Figure 5 shows examples of graphs obtained during some of the shear tests when using different sleepers (concrete and FFU).

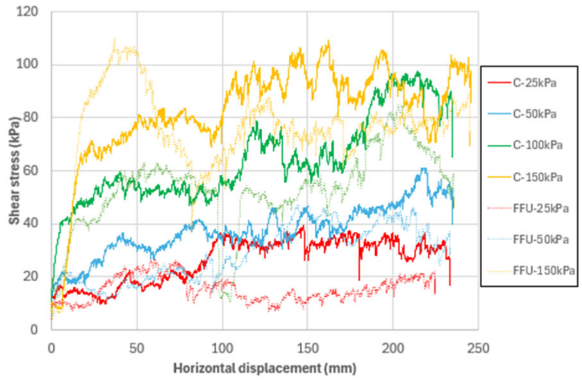

Figure 5 Results obtained for shear tests between ballast and concrete (C) and synthetic (FFU) sleepers at large shear test.

All curves shown in Figure 5 firstly experience an increase in the shear stress that reaches a maximum at a horizontal displacement of approximately 100 mm, then they drop and increase again to values even higher than the previous maxima.

When analysing the shear plane after the tests, in many cases, some fractured ballast particles were seen between the sleeper and one of the edges of the box (as shown in Figure 6). This phenomenon is assumed to explain why there is an increase in the shear stress, after the first drop. Due to this, the shear resistance was chosen, in all the tests, as the maximum shear stress that appears for horizontal displacements below around 100 mm.

Figure 6 Details of ballast particle breakage after shear tests at the shear box edge.

All the bottom sleepers, regardless of their construction materials, showed drag marks after the tests (Figure 7). This indicates that ballast particles became embedded in the sleepers during the shearing. Additionally, no significant breakage of ballast particles was observed beneath the sleepers during the tests.

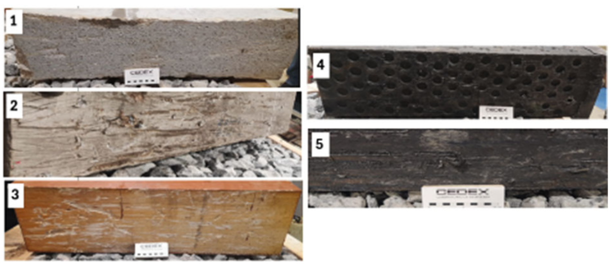

Figure 7 Aspect of the bottom of the sleepers after the tests.

3.3 *Test results to determine ballast strength*

In addition to the sleeper-ballast shear resistance tests, the shear strength of the ballast itself was determined by direct shear tests. To do so, the ballast specimen was prepared under the same conditions used in the sleeper-ballast tests. Ballast was compacted to achieve weight densities ranging from 16.1 to 16.5 kN/m^3. Normal stresses applied were 25; 50 and 100 kPa. Figure 8 shows the curves obtained which are clearly smoother than the ones shown in Figure 5.

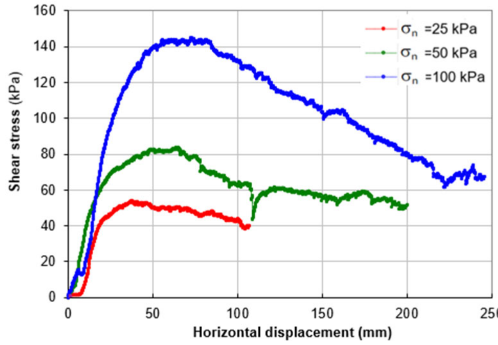

Figure 8 Shear stress-horizontal displacement curves obtained in ballast shear tests.

It can be observed that, for the three normal stresses used in the tests, the shear stress initially increases and then decreases gradually. The maximum shear stress occurs at displacements of approximately 40 mm, 50 mm, and 70 mm for normal stresses of 25 kPa, 50 kPa, and 100 kPa, respectively.

4 INTERPRETATION OF THE SHEAR TEST RESULTS

The initial step in interpreting shear tests involves selecting the shear strength for each normal stress used in the tests. Subsequently, it is standard practice to plot these pairs of values (normal stress against shear strength). This graphical representation facilitates the application of theoretical models to derive the corresponding resistance values. Our experience in large shear box tests for ballast suggests that the parabolic model is the most appropriate for this type of evaluation (Estaire and Santana, 2018).

The shear strength of the ballast was evaluated using this procedure. Figure 9 displays the pairs of normal and shear strength values obtained in the tests. To compare the results of the current study, they are represented by blue squares, while those of previous studies are shown with orange circles.

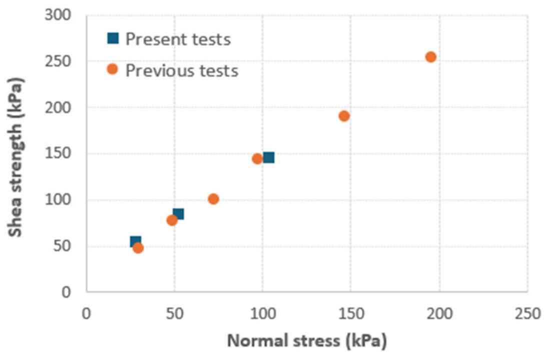

Figure 9 Pairs of normal stress and shear strength values obtained from the large direct shear test on ballast.

This figure suggests that the results of this study align very well with previous research, reducing the uncertainty in the results.

To compare the resistance of the ballast-sleeper interface with the ballast strength, Figure 10 presents the pairs of normal stress and shear strength values used, along with the standardised failure envelopes based on a parabolic model. Additionally, 0 presents the range of friction coefficient values for each test, along with the coefficient 'a' of the parabolic model, since coefficient 'b' was set to 0,825 for all the tests, to facilitate the comparison among them (when the stresses are expressed in kPa).

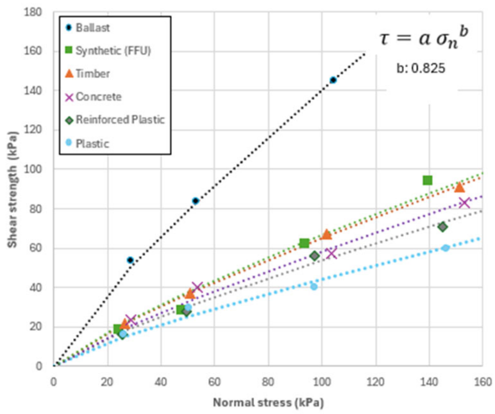

Figure 10 Interpretation of test results with a parabolic model.

Table 3 Coefficient of interface ballast-sleeper friction and values of the coefficients of the parabolic model for all the tests.

Material	Coef. of interface friction (tag δ)	Interface Friction angle (δ) and ratio [$\delta/\varphi_{ballast}$]	Parameters parabolic model (a / b) [τ, σ in kPa]
Concrete	0.54–0.81	28.4-39.0 [0.57]	1.31/0.825
Timber	0.60–0.81	31.0-39.0 [0.60]	1.46/0.825
FFU (synthetic)	0.60–0.76	31.0-37.2 [0.60]	1.49/0.825
Plastic	0.41–0.61	22.3-31.4 [0.45]	0.99/0.825
Reinforc. plastic	0.49–0.62	26.1-31.4 [0.50]	1.20/0.825
Ballast	1.39-1.88	54.3-62.0 [1.0]	3.14/0.825

Regarding the coefficient of friction, the values obtained align closely with those reported in the research conducted by Safari (2016). Furthermore, it is observed that, in all cases, the coefficient of friction tends to decrease with increasing normal stress during the tests.

Standardizing the curves enables a comparison of ballast-sleeper resistance based on the coefficient 'a'. The table indicates that the FFU sleeper has the highest recorded value for this parameter, while the plastic sleeper has the lowest. Table 4 presents the percentage variations in coefficient 'a', using the concrete sleeper as a reference, alongside the ballast strength.

Table 4 Percentage of resistance of each type of sleeper compared to concrete-ballast resistance and to ballast strength.

Material	Resistance Ratio 1	Resistance Ratio 2
Concrete	100	42
Timber	111	46
Synthetic (FFU)	114	47
Plastic	76	32
Reinforced plastic	92	38
Ballast	240	100

[1] Ratio 1: resistance of x sleeper/resistance of concrete sleeper (%)
[2] Ratio 2: resistance of x sleeper/resistance of ballast layer (%)

The results indicate that timber and FFU sleepers provide greater resistance to friction with ballast compared to concrete sleepers. Additionally, unreinforced plastic sleepers show shear resistance that is around 75% of that of concrete sleepers. When comparing the resistance of the sleepers to that of the ballast itself, it is evident that the resistance values for all types of sleepers are below 50%.

Safari (2016) examines various parameters, including the settlements that occur between different types of sleepers and ballast. The study indicates that settlements are lower in concrete sleepers compared to wooden or plastic sleepers. This is attributed to the rougher surface of the bottom surface of the concrete sleepers, which promotes greater interlocking and reduces the rearrangement of ballast particles.

In the present work, a visual analysis of the bottom sleeper surfaces after shear testing indicates that the marks are significant for normal stresses of 150 kPa. While this analysis is somewhat subjective, it is evident that the ballast sinks into both the wooden and synthetic sleepers, and in the case of the plastic sleeper, particle ballast even remove material.

5 SUMMARY

The main ideas developed in this paper are:

- Some shear tests to determine the shear resistance in the interface between the sleeper bottom and the ballast layer were performed with different types of sleepers.
- Five types of sleepers were used in the tests, constructed with the following materials: concrete, akoga timber, synthetic materials (Fibre reinforced Foamed Urethane) plastic and reinforced plastic.
- The tests were performed in a direct shear test box with a shearing plane of 1x1 m, filled with ballast compacted to get the usual weight density used in high-speed lines.
- The tests were interpreted using a parabolic model and to obtain the secant coefficients of ballast-sleeper interface friction (tan δ).
- The main numerical results are presented in Tables 3 & 4.
- The ratio between the ballast/sleeper interface friction angle and the ballast friction angle is in all cases below 0,5.
- The sleepers that show a more resistant interface with ballast are those made of timber and synthetic materials, while the less resistant is the one made of plastic.

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