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Sustainable Sub-Ballast Composed of Recycled Aggregates from Reclaimed Asphalt Road Pavements

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Abstract

The commonly employed granular sub-ballast layer in the construction of modern railway tracks consumes a substantial amount of natural aggregates, which may at times be unavailable due to specific requirements. Hence, there arises an opportunity to adopt recycled aggregates to promote sustainable development. The research, focused on the use of reclaimed asphalt pavement as granular sub-ballast, aligns with prior experiences indicating that the utilization of asphalt material can enhance the performance and durability of the layer. The study involves a laboratory investigation into the influence of various design factors on the mechanical performance of the layer, assessing the impact of reclaimed asphalt pavement characteristics and the compaction procedure. Laboratory results, simulating expected service conditions for these materials in railway tracks, have demonstrated the viability and suitability of using recycled asphalt materials to create more sustainable railway tracks. It is feasible to utilize up to 100% granular sub-ballast from reclaimed asphalt pavement aggregates, improving its mechanical behavior by re-compacting the layer at temperatures above 40°C.

Keywords: sub-ballast, railway infrastructure, sustainability, recycled aggregates, reclaimed asphalt pavement, laboratory tests.

1 Introduction

The emergence of high-speed rail in the 1960s, coupled with the demand for more durable infrastructure and higher quality standards, has led to the need to increase the load-bearing capacity of the railway track section [1]. Thus, modern railway tracks include a series of high-performance granular layers below the ballast, among which the sub-ballast plays a crucial role in providing vertical resistance while protecting the underlying layers from traffic loads and climatic actions.

Typically, the granular sub-ballast is composed of a granular layer with a thickness ranging from 20 to 30 cm, comprising fragmentation-resistant aggregates with a size smaller than 32-40 mm and providing a modulus of elasticity exceeding 120 MPa [2], [3]. Nonetheless, in the pursuit of achieving elevated mechanical performance and durability, the concept of bituminous sub-ballast emerged in the 1980s. This entails a layer approximately 12-15 cm thick, constructed from a dense asphalt mixture with an aggregate size less than 22 mm and a voids index less than 3-4% [4]. Numerous experiences and studies have illustrated the capacity of this bituminous sub-ballast to enhance the vertical resistance of the entire track, diminish the settlement tendency of the ballast, and enhance the protection of the underlying layers of the track section [5], [6], [7].

Moreover, the utilization of bituminous sub-ballast enables the use of aggregates with lower mechanical performance, as the bitumen coating protects them from fragmentation, impacts, and climatic actions. This proves advantageous, considering the potential challenge of sourcing high-performance aggregates in railway construction and/or rehabilitation [5], [8]. However, it is essential to consider the negative impacts associated with asphalt mixtures, encompassing energy consumption, non-renewable raw material usage during manufacturing, and various environmental and economic effects [9], [10]. In this sense, alternative approaches to enhance the sustainability of these materials involve substituting a portion of natural aggregates with those derived from reclaimed asphalt pavement (RAP), aiming to provide greater sustainability while retaining the advantages associated with the asphalt covering that protects the aggregates [11], [12]. Furthermore, the residual bitumen on aggregates could contribute to agglomerating the layer, providing additional mechanical performance and protection capacity. However, given the structural and functional significance of the sub-ballast in the railway track, it is imperative to investigate the feasibility of using RAP as a granular sub-ballast layer and define the essential characteristics required to yield the benefits.

In this context, the present study focuses on examining the feasibility of utilizing Reclaimed Asphalt Pavement (RAP) as high-performance granular sub-ballast. This approach seeks to provide sustainability by minimizing raw material consumption and reusing a plentiful waste material (RAP), predominantly sourced from deteriorated road pavements. More specifically, this investigation examines the attributes of different RAP types for their suitability as a sub-ballast layer. Furthermore, it explores into various design factors related to sustainable granular layers to define optimal conditions for application, with the goal of providing a high-performance solution in terms of load-bearing capacity, substructure protection, and longevity.

2 Methodology

In this section, the materials, test plan, and methods employed in conducting the research.

2.1 Materials

For the study, three different types of Recycled Asphalt Pavement (RAP) were used, denoted as RAP 1, RAP 2, and RAP 3, each possessing different characteristics and origins. Three recycled materials with different asphalt contents were chosen. RAP 1 is a fine-grained material with particle fractions falling within the 0/10.0 mm range, whereas RAP 2 is coarser, featuring particle fractions between 2.0 and 16.0 mm. Lastly, RAP 3 is categorized as an intermediate material, with particle fractions ranging from 1.0 to 12.5 mm.

The research also employed two reference materials. The first one, referred to as Sub-ballast Ref.1, constitutes a limestone-based sub-ballast with particle fractions in the 0/22.4 mm range, chosen for a direct comparison with Recycled Asphalt Pavement (RAP) since it predominantly consists of limestone aggregates with adhered bitumen. The second reference material, Sub-ballast Ref.2, is an ophitic sub-ballast (0/25 mm), commonly used in high-speed railway tracks in Spain due to its high resistance.

2.2 Testing Plan

The testing plan conducted in this research is presented in Table 1, consisting of three main stages: (1) the characterization of different types of Recycled Asphalt Pavement (RAP) compared to reference materials; (2) the study of the mechanical behavior and parametric analysis of designing variables for the RAP sub-ballast layer; and (3) the advanced characterization of mechanical properties based on the functionality of the RAP layer for its use as sub-ballast in railway tracks.

Stage	Properties	Materials	Test
Aggregates Characterization	•Physical Characterization •Mechanical Characterization •Compaction conditions	• Sub. Ref.1 • Sub. Ref.2 • RAP 1 • RAP 2 • RAP 3	• Granulometry • Particle Shape/Flakiness Index • Faces of fracture • Resistance to fragmentation (LA) • Sand Equivalent • Density • Proctor Compaction test.
Parametric Analysis: RAP as granular Sub-ballast Layer Design	•Influence of RAP Type •Influence of RAP compaction temperature	• Sub. Ref.1 • Sub. Ref.2 • RAP 1 • RAP 2 • RAP 3	• Indirect Tensile Strength • Compressive Strength

Stage	Properties	Materials	Test
Advanced Characterization of Mechanical Properties	•Elastic Modulus – Bearing Capacity •Material Strength Against Ballast Pressure •Vertical permeability (K)	• Sub. Ref.1 • Sub. Ref.2 • Opt. RAP	• Static Plate Bearing Test • Dynamic Punching Test • Permeameter

Table 1: Testing plan.

The first stage, focused on materials physical and mechanical characterization, begins with determining the particle size distribution of aggregates to compare them with the limits established in the Spanish Standard for sub-ballast, such as PF-7 (General Technical Specifications for Railway Materials) [3], defining nominal maximum and minimum sizes and assessing particle size continuity. In addition, two additional tests were conducted to obtain information regarding the shape of the aggregates, including the measurement of the percentage of fractured faces and the flakiness index, crucial aspects in understanding the mechanical behavior. Furthermore, a study of material resistance to fragmentation was conducted using the Los Angeles machine, and the quality of the fine material was assessed through the sand equivalent test. Finally, an aggregate density test was performed, and material compatibility was determined using the modified Proctor test, providing essential information for the fabrication of specimens in the subsequent stages of the study.

In the second stage, the influence of some design variables of the sub-ballast layer made from RAP was evaluated, analyzing their impact on essential mechanical properties such as indirect tensile strength and compression resistance of specimens compacted with the optimal moisture content determined in the previous phase. However, the design was varied based on the following variables:

- Influence of RAP type: Cylindrical specimens were produced and compacted for each type of RAP and reference materials without any additional material treatment, under optimal conditions determined by Proctor testing. Subsequent comparisons of indirect tensile and simple compression test results were made with the reference materials.
- Influence of RAP compaction temperature: Considering the bitumen content in recycled materials (RAP) and its potential binding effect on aggregates, the study assessed the impact of compacting RAP specimens at different temperatures to enhance this bonding effect. Initial specimens with RAP were manufactured and compacted at optimal moisture and room temperature. Additionally, these specimens were compacted at different temperatures (20°C, 40°C, and 60°C) after 24 hours, simulating normal construction conditions. The objective was to evaluate the effect of re-compaction temperature on indirect tensile strength and simple compression resistance.

The third stage of the research focused on conducting an advanced characterization of the sub-ballast layer with RAP (selecting the optimal type and design conditions based on the studies in the previous phases) concerning the requirements and expected functionality for this material during its service life as a granular layer in railway tracks. This involved evaluating the load-bearing capacity of the layer through the plate load test (resulting in the material's elastic modulus), its settlement resistance, and degradation against the punching actions of the ballast aggregates placed above the sub-ballast. Additionally, the resistance to water penetration (permeability) was assessed to evaluate its ability to protect the lower sub-layers. To determine the influence of using RAP as an alternative to virgin aggregates, the results were compared with those presented by the reference materials (limestone sub-ballast – Ref. 1, and ophitic - Ref. 2).

2.3 Test Methods

The test methods used in the characterization of aggregates followed the guidelines outlined in the European Standards: (i) Particle size distribution determination (UNE-EN 933-1:2012) [13], (ii) Fracture index determination (UNE-EN 933-3:2012) [14], (iii) The percentage of crushed particles (UNE-EN 933-5:2023) [15], (iv) Resistance to fragmentation test using Los Angeles machine (UNE-EN 1097-2:2021) [16], (v) Sand equivalent test (UNE-EN 933-8:2012) [17], (vi) Particle density and water absorption determination (UNE-EN 1097-6:2014) [18], and (vii) Compaction test – Modified Proctor (UNE 103501:1994) [19].

For mechanical characterization, the indirect tensile strength test was conducted in accordance with the standard UNE-EN 12697-23:2018 [20], using cylindrical specimens with a diameter of 100 mm and an approximate height of 60 mm. Similarly, the simple compression test was carried out according to the standard EN 103-400-93 [21], using cylindrical specimens with a diameter of 100 mm and a height of 200 mm, thus maintaining a 1:2 ratio between the diameter and height of the specimen.

In the advanced characterization phase of the materials, vertical soil load tests were conducted using a static plate (UNE 103808:2006) [22] to determine the vertical deformation modulus (E_v) by applying 2 loading cycles, each with six steps with approximately equal increments (85 kPa, 200 kPa, 300 kPa, 400 kPa, 500 kPa, 600 kPa).

Subsequently, in this phase, a dynamic punching test was conducted to assess the resistance of each material to the pressure applied by ballast particles in the case of railway tracks. In this case, the test involved applying 100,000 loading cycles at a frequency of 5 Hz (simulating an average speed close to 120 km/h of train bogies) with a pressure of approximately 470 kPa (considered an unfavorable condition according to expectations for the sub-ballast layer in railway tracks).

Finally, a constant head permeability test (adapted from UNE-EN 103403:1999) [23] was conducted using a box-shaped permeameter with dimensions of 300 mm x 300 mm and 500 mm in height, suitable for testing samples with heights around 150 mm. At the base of the box, a geotextile and a geomembrane were implemented to prevent the loss of fine particles from the samples without restricting water flow. The water flow was measured at the bottom of the device, recording the amount of water drained within a specified time.

3 Results

In this section, the results of materials characterization, the influence of RAP, the impact of compaction temperature, and the advanced characterization presented in previous phases are presented.

3.1 Materials Characterization

The results of the particle size distribution analysis, presented in Figure 1, are compared with the specifications defined by Spanish standard PF-7 [3] for aggregates projected for sub-ballast layer in railway tracks. The results indicate that the analysed RAP types exhibit a smaller maximum aggregate size and a less consistent granulometric distribution compared to the specified requirements. However, the compositions of RAP 1 and RAP 3 largely align with the established limits for the explored applications, closely resembling the characteristics of the reference materials. On the other hand, RAP 2 displays a slightly coarser granulometry and greater homogeneity in particle sizes, predominantly falling within the range of 6 to 12 mm.

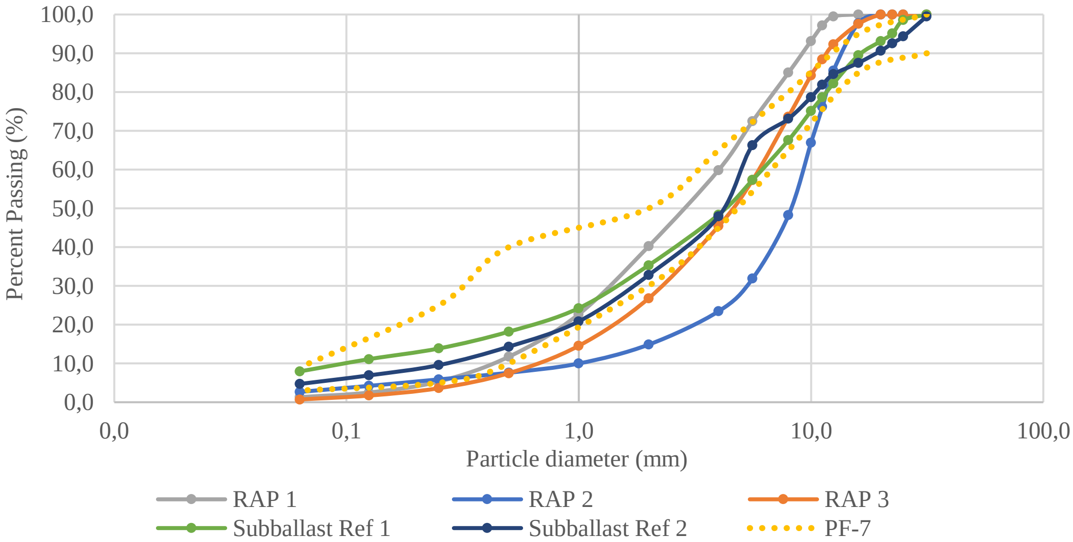


Figure 1 Particle size distribution.

Table 2 presents the characterization results for the different RAP and reference materials in comparison to the Spanish Standard PF-7 [3]. Confirming the agreement of these values with the established physical-mechanical properties in the mentioned specification, except for the coefficients of uniformity and granulometric curvature (in some fractions) for use as sub-ballast in railway tracks. However, these differences in granulometric requirements will be analysed to assess the influence of this RAP characteristic on the material's mechanical response in subsequent phases.

In comparison to the reference materials, it can be observed that the RAP exhibited fragmentation coefficients approximately 15-40% lower (indicating higher resistance) than those obtained for the reference sub-ballast type 1 - limestone (of similar nature and density to the predominant ones in the studied RAP cases). This might suggest that the bitumen film covering the aggregates contributes to protecting the particles from fragmentation, in certain RAP types studied, this even resulted in Los Angeles coefficient values comparable to those of sub-ballast type 2 (of an ophitic nature and higher density).

Properties	**RAP 1**	**RAP 2**	**RAP 3**	**Sub. Ref. 1**	**Sub. Ref. 2**	**Spanish Standard**
Determination of particle shape – flakiness index (%)	13	6	11	18	15	**-**
Faces of fracture (%)	100	100	100	100	100	**100**
Sand equivalent (%)	78	81	69	55	61	**>45**
Resistance to fragmentation (L.A.) (4/8mm) (%)	20.7	15.3	20.8	23.9	14.0	**<28**
Resistance to fragmentation (L.A.) (8/11.2mm) (%)	17.1	12.8	18.7	20.8	12.3	**<28**
Density (Mg/m3)	2.57	2.57	2.56	2.81	3.24	**-**
Coefficient of uniformity (Cu)	8	10	11	45	23	**>14**
Curvature coefficient (Cc)	3.1	3.1	1.4	3.1	2.9	**1-3**
Residual binder content (% Total weight)	3.9	3.0	4.0	-	-	**-**
Modified Proctor Opt. Moisture content (%) / Max Dry Density. (g/cm^3)	5.5 / 2.25	5.5 / 2.32	5.5 / 2.33	5.0 / 2.31	4.5 / 2.97	**-**

Table 2: Materials Characterization.

3.2 Influence of RAP

Figure 2 shows the results of indirect tensile strength and simple compression tests on RAP and reference specimens. The results indicate that, across all scenarios, the compression strength values were consistently higher than tensile strength values, with the most notable disparities between RAP and references observed under compression loads. Specifically, the RAP materials exhibited a reduction of up to 86% in compression strength compared to sub-ballast type 2 (ophitic) and 76% compared to sub-ballast type 1 (limestone origin).

Nonetheless, regarding indirect tensile strength, the behavior of RAP aligns with that of reference materials, indicating the ability of the residual asphalt in RAP to provide cohesion and resistance to the granular material. This underscores the potential application of RAP as a granular layer, still requiring further investigation into its design for optimization. This is further supported by the tensile results, where variations in values were observed depending on the RAP type, showing slight deviations higher or lower than the references.

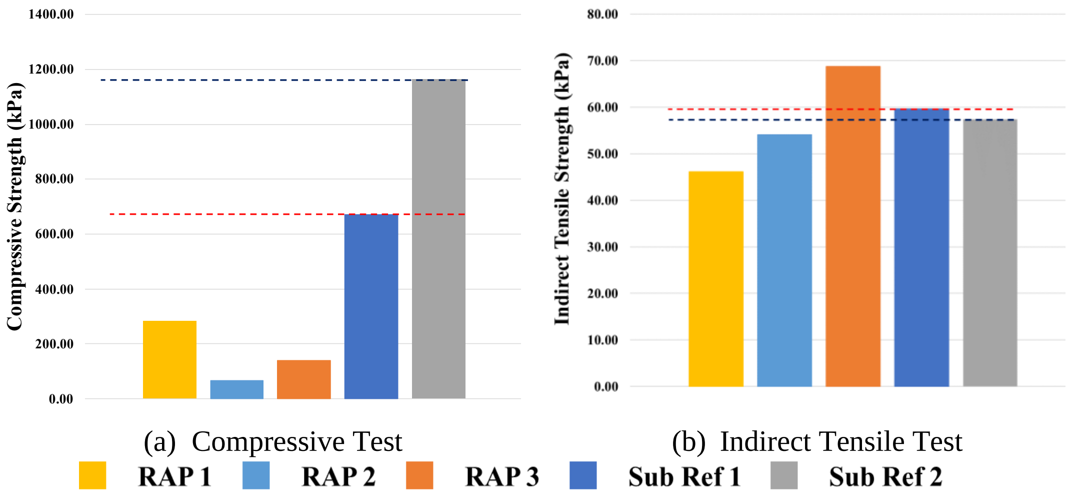


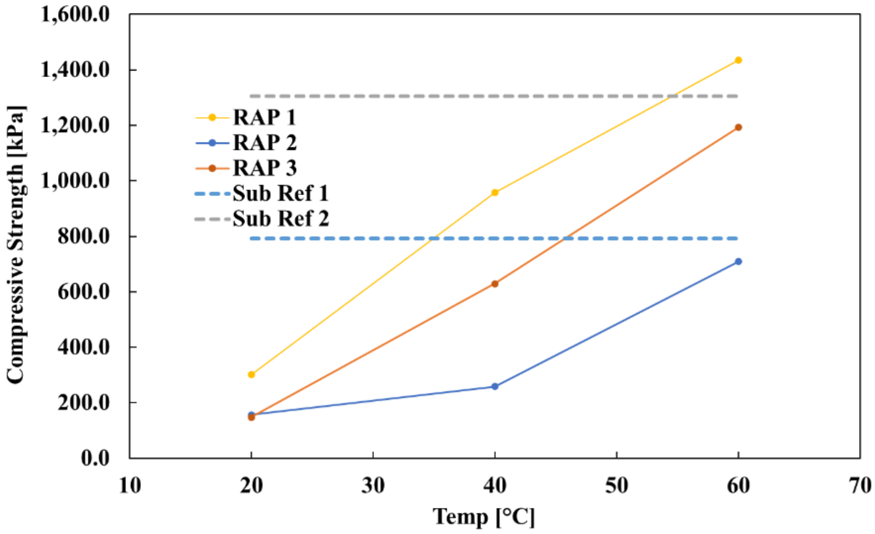
Figure 2 Results of the indirect tensile strength and compression tests.

3.3. Influence of RAP compaction temperature

Based on RAP ability to bind granular material, but being dependent on RAP characteristics, Figure 3 explores the improvement, in bonding advantages while reducing the impact of RAP characteristics by increasing the compaction temperature, aiming to improve compression strength as well. Specifically, Figure 3 presents the results of simple compression and indirect tension tests for different re-compaction temperatures (20°C, 40°C, and 60°C), compared to reference cases. It is observed that both compression and indirect tensile strengths of RAP samples increase with higher re-compaction temperatures.

Improvements in the behavior of RAP are observed when re-compacting at temperatures around 40°C and 60°C, showing an average increase of approximately 73% and 135%, respectively, in the value of indirect tensile strength. This leads to values higher than those measured for the reference sub-ballasts, regardless of the type of RAP studied.

Concerning the result of the simple compression tests, a similar trend is observed, indicating an increase in resistance with the rise in re-compaction temperature. The most favourable performances are consistently identified when re-compacting at 40°C, with notable improvements observed at 60°C. Notably, RAP 2, characterized by more discontinuous granulometry, demonstrates compression performance comparable to that of sub-ballast type 1. On the other hand, both RAP 1 and RAP 3 exhibit values surpassing this reference by approximately 50-90%. Intriguingly, when re-compacted at 60°C, these RAP types with more continuous granulometry attain compression values akin to sub-ballast type 2—recognized for its high performance and widespread use in high-speed rail tracks in Spain. This underscores the potential utilization of RAP as a viable alternative to virgin aggregate sub-ballast, particularly for RAP samples with more continuous granulometry, which appear to manifest superior mechanical behavior under the examined stresses. However, for a more comprehensive exploration of this design variable, further analysis is conducted to examine the impact of granulometry on material behavior.



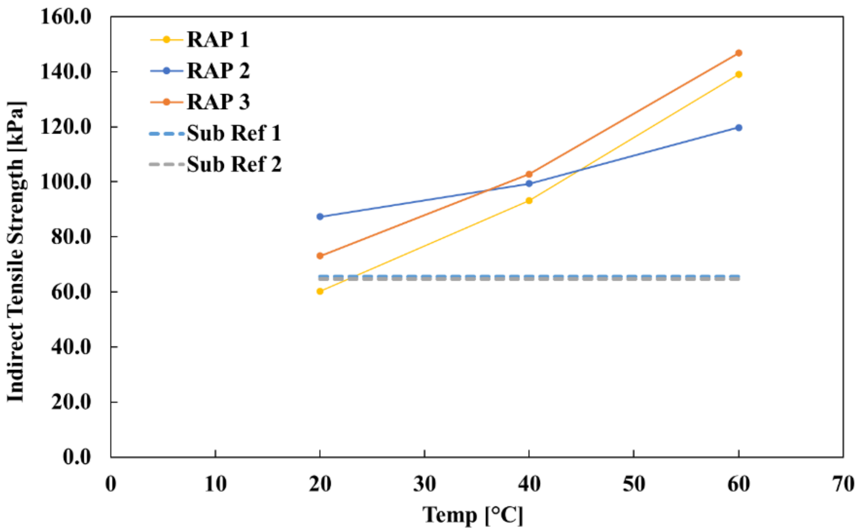


Figure 3 Effect of compaction temperature on mechanical behavior.

3.4. Bearing Capacity

Considering the previous outcomes, the subsequent analysis explores into the mechanical behavior to its application as a sub-ballast layer in railway tracks, with a particular emphasis on RAP 3. This type demonstrated intermediate physical-mechanical characteristics and exhibited suitable tensile and compressive strength under the 60ºC re-compaction condition. The ensuing results are juxtaposed with those of the reference sub-ballasts (Sub. Ref. 1; Sub. Ref. 2).

Table 3 summarize the results of the static plate load test, showing the values of the modulus for the first and second load cycles, respectively. The results reflects that the load-bearing capacity of the RAP-type material is comparable to that of the reference materials (Sub. Ref.1; Sub. Ref.2), even obtaining modulus of elasticity values higher than those presented by the reference sub-ballasts. Furthermore, it is confirmed that the susceptibility to settlement of the RAP is close to that of the high-performance sub-ballast (reference 2), while notably lower compared to sub-ballast type 1.

	RAP	Sub. Ref. 1	Sub. Ref. 2
Ev1 (Mpa)	90.9	66.0	107.6
Ev2 (Mpa)	176.2	183.8	168.2
Ev2/Ev1	1,4	2,8	1,5

Table 3: Static plate load test results.

3.5. Resistance To Ballast Punching.

The Figure 4 provides a summary of the 100,000 cycles punching test (470kPa) at a frequency of 5Hz; in this case, the final permanent deformation, the slope of the first 1,000 cycles and of the last 10,000 cycles are summarized. The RAP-type material demonstrates an intermediate structural behavior compared to the reference materials. Its mechanical response closely aligns with that of sub-ballast type 2 (ophitic nature), representing a notable improvement compared to sub-ballast type 1.

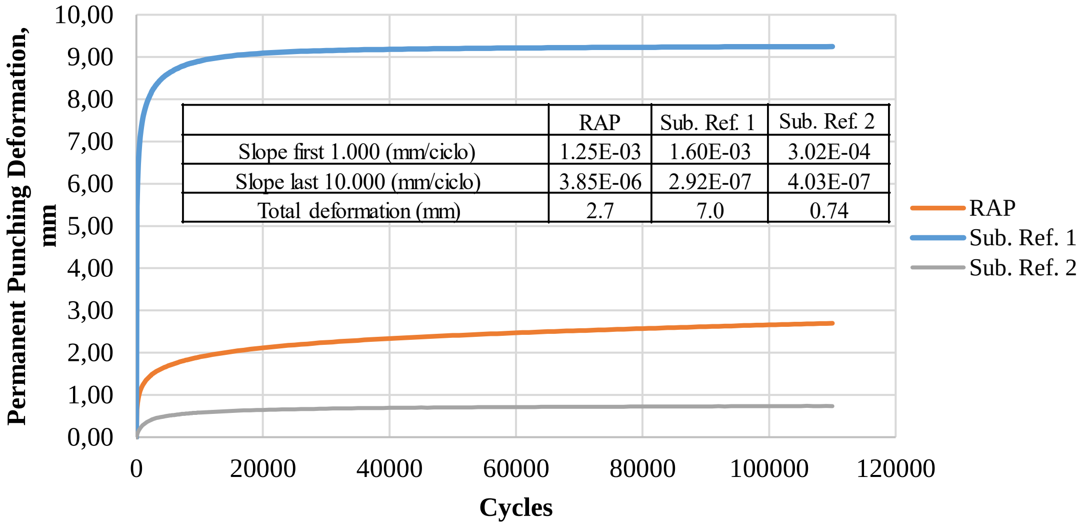


Figure 4 Punching test results (100.000 cycles – 470 kPa – 5Hz).

3.6. Permeability

Flow rate (m³/s) and vertical permeability coefficient (K) data were collected over a specific period to identify the evolution of these parameters. The permeability coefficient is reported when the flow stabilizes, typically around 4,000 seconds into the test. It can be observed that the lower permeability values were exhibited by the reference materials, sub-ballast type 1 and 2, with values close to 8.2 x 10^{-6} m/s and

9.0 x 10^{-6} m/s, respectively. However, the results demonstrate that RAP led to values on the order of those presented by the reference materials, stabilizing around 9.76 x 10^{-6} m/s.

4 Conclusions and Contributions

The main objective of this investigation focuses on analysing the feasibility of using RAP as recycled aggregates as an alternative to natural aggregates, intended for use in the sub-ballast layer in railway infrastructures. Based on the results obtained in laboratory tests characterizing different types of RAP and analysing the influence of various design variables, the following conclusions can be drawn:

- The recycled materials (RAP) used in the research exhibited appropriate physical and mechanical characteristics for use as granular sub-ballast, comparable to those commonly employed reference materials for such purposes.
- The presence of bitumen enveloping the recycled aggregates contributed to an enhanced resistance against fragmentation, resulting in performance that exceeded that of the reference sub-ballast with similar aggregate nature to RAP. Additionally, it approached the performance levels observed in the high-performance reference sub-ballast.
- Nevertheless, the diverse RAP samples exhibit lower coefficients of uniformity and higher granulometric curvature, indicating a notable impact on the material tensile and compressive strength. This emphasizes the significance of considering and analyzing the granulometry of the chosen RAP for the support layer.
- Under conventional compaction procedure, the recycled materials displayed lower compression strength compared to reference materials, resulting in strength reductions of approximately 60-80%, while also showing a slight decrease in tensile strength.
- However, as the re-compaction temperature increased, the performance of RAP improved due to the agglomeration potential of the bitumen film on recycled aggregates. This improvement was particularly noteworthy at temperatures around 60°C, with average enhancements of 135% in indirect tensile strength and 711% in compressive strength.
- Implementing RAP as sub-ballast yielded a layer with comparable load-bearing capacity and water permeability protection to that of reference materials.
- Additionally, the use of RAP enhanced the resistance to punching from ballast aggregates, in comparison to the reference with similar nature to RAP while approaching the levels of the high-performance reference sub-ballast.

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