# Evaluation of Dry Asphalt Rubber Concrete in Railway Sub-Ballast using the Four Point Bending Test

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# Paper 1

# Evaluation of Dry Asphalt Rubber Concrete in Railway Sub-Ballast using the Four Point Bending Test

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The study of bituminous mixes can be related to tyre rubber material recycling. Encouraging scrap tyre disposal and cutting down on pit employment are the environmental aims. In the field of railways, technological processes involved in the use of crumb rubber are the wet-dry processes. In the mechanical characterisation of the asphalt concrete in terms of both the fatigue resistance and the stiffness modulus it is necessary to use a design method for the sub-ballast railway material, even more so if the asphalt concrete investigated is an innovative material such as a dry asphalt rubber concrete (DARC) (*i.e.* a bituminous mixture with crumb rubber formed by a dry process). Such material is less known and investigated than the wet process, even if its application implies peculiar economic and environmental advantages such as no specialized equipment or significant plant modifications and a large quantity of recycled waste tires compared to the wet process. Different kinds of test are usually used in the experimental work such as bending tests or uni-axial tests, but they do not give the same answer.

In the work, described in this paper, mechanical characterization was carried out by means of fatigue tests for asphalt material: a two point bending (2PB) test and four point bending (4PB) test, focused on the mechanical behaviour of DARCs with different rubber content by weight of the aggregates. Different strain controlled tests were undertaken for the same material under the same loading conditions, frequency and temperature (15Hz, 20 degrees centigrade), in particular an experimental survey was carried out in order to determine the stiffness modulus by means of the four point bending test on prismatic specimens (UNI EN 12697-26, 2004). This paper reports the experimental results for rubberized asphalt mechanical properties for a sub-ballast layer performed in a laboratory using the dry process.

# 1 Introduction

Flexural fatigue is one of the main failure modes in asphalt mixtures and flexible layers. This means good prediction of fatigue life will help to develop and improve design procedures.

Fatigue resistance and stiffness are two required parameters necessary to dimension the sub-ballast structure in railways (layer thickness).

European standards (EN 12697-24/26) [1] specifies the methods for characterizing fatigue and stiffness of bituminous mixtures by different bending tests (2PB - 4PB) and direct/indirect tensile tests. Usually tests are performed applying a sinusoidal loading (stress or strain) to a different kind of specimen (trapezoidal or prismatic), depending on the mode of loading.

In Italy, in light of the environmental issues is established that the use of the recycled rubber from the waste tires has to be increased both in the road infrastructures and in the railways.

In the field of railways nevertheless the applications of the rubber asphalt via dry process are very few even because both its complex stiffness modulus and fatigue behaviour are not investigated enough. The potential benefits of adding rubber to asphalt cement have been discussed for many years however its use was delayed due to lack of technology and equipment to economically mix the rubber in asphalt cement [2].

In this paper through an experimental survey carried out in the Laboratory of the Road Materials of Department of Civil Engineering at the University of Palermo, the authors have focused on the mechanical properties of the Dry Asphalt Rubber Concrete (DARC) as material for base layer within the sub-ballast layer.

With this aim four materials were analysed and compared: the first was a bituminous mixture without rubber, the others were Dry Asphalt Rubber Concrete (DARC) with respectively a rubber content equal to 1.0, 2.0 and 3.0 by weight of the aggregates.

The objective of the experimental survey was to determine the influence of the rubber content, of the load frequency and of the temperature on the mechanical and dissipative properties of the materials for the railway sub-ballast layer.

The test procedures were conducted by means of the four bending points (4PB-PR) apparatus according to EN 12697-26. The recycled crumb rubber comes from the waste tires of truck and so it can be considered as natural rubber which is more suitable to the mixing with the asphalt concrete.

## 1.1. Background

The complex stiffness modulus is a complex number that relates stress to strain for linear visco-elastic material subjected to continuously apply sinusoidal loading in the frequency domain. A hot mix asphalt (HMA) mixture can be considered as linear viscoelastic material under small strain levels (≤100με).

In order to resist fatigue cracking, an asphalt binder should be elastic, able to dissipate energy by rebounding and not cracking. Therefore, the complex shear modulus viscous portion should be minimum. When fatigue cracking is worrying, a maximum value for the viscous component of the shear modulus is specified.

Thus, the HMA stress-strain relationship under continuous sinusoidal loading in the linear viscoelastic region can be defined by the complex dynamic modulus (±T[a]) as the ratio of the amplitude of the sinusoidal stress (±time and load-frequency) and sinusoidal strain (at the same time-frequency) that results in a steady state response.

$$E^* = \frac{\sigma(t)}{\varepsilon(t)} = \frac{\sigma_0 sin(\omega t)}{\varepsilon_0 sin(\omega t - \phi)} = \frac{\sigma_0}{\varepsilon_0} \cdot e^{i\phi} = |E^*| \cdot e^{i\phi} \tag{1}$$

$$|E^*| \cdot e^{i\cdot\phi} = |E^*| \cdot (\cos\phi + i \cdot sin\phi) = E_1 + iE_2 \tag{2}$$

Being:

$$E_1 = |E^*| \cdot \cos\phi = |E^*| \cdot \cos(arctg(E_2 / E_1)) \tag{3}$$

$$E_2 = |E^*| \cdot sin\phi = |E^*| \cdot sin(arctg(E_2 / E_1)) \tag{4}$$

Where:

- *$|E^*|$ = complex modulus; $\sigma_{0v}$= peak (maximum) stress; $\varepsilon_0$ = peak (maximum) stress;*
- *$\omega$ = angular velocity; $f$ = load frequency; t = time; $i$ = imaginary unit*
- *$\emptyset$= phase angle that represents the lag time between stress and strain;*

The real component $E_1$ represents the elastic property of the material while the imaginary component $E_2$ describes the viscous behaviour. The absolute value of the complex modulus is called stiffness modulus and it can be calculated as:

$$|E^*| = \sqrt{(E_1^2 + E_2^2)} \tag{5}$$

EN12697-26 European Standard "*Determination of the stiffness of bituminous mixture*" Annex B, describes the procedure for evaluating the real component $E_1$ and the imaginary component $E_2$ of the complex modulus, the stiffness modulus and the phase angle by means of four point bending test on prismatic specimens.

To the aim of this work the accurate evaluation of the phase angle is major because it plays a decisive role for the attenuation of the borne vibrations by traffic.

Generally the interpretation of a bending test is based on the solution of the motion equation of an elastic beam subjected to a force F, in which the Young's modulus is replaced by the stiffness modulus. The solution, in terms of vertical displacement *v* of a point at *x* position and any given time *t*, is:

$$v_{(x,t)} = \frac{q_n}{m(\omega_n^2 - \omega^2)} \cdot sin\frac{n\pi x}{L}\left[sin(\omega t) - sin(\omega_n t)\right] \tag{6}$$

Where:

- $\omega_n = \omega_n^* = \frac{n^2 \cdot \pi^2}{L^2}\sqrt{\frac{E^* I}{m}}$*, frequency of the n-armonic wave;*
- *I, moment of inertia of the beam's cross section (Fig. 1) ;*
- $q_n = 2P/L \cdot \left[(sin\, n\pi/3) + (sin\, 2n\pi/3)\right]$*;*

• *P, applied load (Fig. 1); $\omega$, angular velocity for unit of length;*
• *m, mass for unit of length; L, length of the beam [m];*

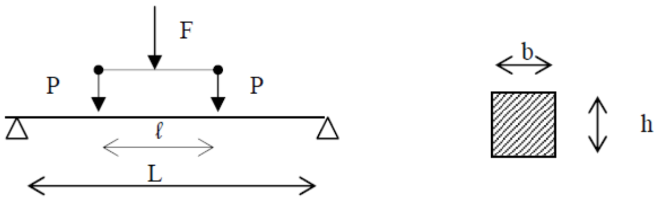



Figure 1: Loading scheme and cross section

The complex mechanical impedance is defined as:

$$Z^* = \frac{2P}{v_{\max}} e^{i\phi} = \frac{E^* I \pi^4}{L^3 \left[ \sum_i \frac{1}{i^4 \left(1-\omega^2/\omega_1^2\right)} \right]} \left( sin\frac{i\pi}{3} + sin\frac{2i\pi}{3} \right) \cdot sin\frac{i\pi}{2} \tag{7}$$

$$v_{\max} = 2PL^3 \big/ E^* I \pi^4 \cdot \left[ \sum_i \frac{1}{i^4 \left(1-\omega^2/\omega_1^2\right)} \cdot \left( sin\, i\pi/3 + sin\, 2i\pi/3 \right) \cdot sin\, i\pi/2 \right] \tag{8}$$

The maximum vertical displacement, $v_{max}$ that occurs at $x=L/2$. The complex modulus can be rewritten as:

$$E^* = E_1 + iE_1\theta \tag{9}$$

Where $\theta = \tan\varphi$ is the damping factor. We have:

$$Z^* = \frac{\frac{\pi^4 E_1 I}{L^3} + iE_1 \frac{\pi^4 I}{L^3}\theta - \omega^2 Lm}{\left( sin\, \pi/3 + sin\, 2\pi/3 \right) \cdot sin\, \pi/2} = \frac{\pi^4 E_1 I}{\sqrt{3}L^3} + iE_1 \frac{\pi^4 I\theta}{\sqrt{3}L^3} - \frac{\omega^2 Lm}{\sqrt{3}} \tag{10}$$

By imposing the equality of the real parts, respectively, present at the first and at the second member of (4.5) we have:

$$\frac{2P}{v_{\max}}\cos\phi = \frac{\pi^4 E_1 I}{\sqrt{3}L^3} - \frac{\omega^2 Lm}{\sqrt{3}} \rightarrow E_1 = \left( \frac{2P}{v_{\max}}\cos\phi + \frac{mL}{\sqrt{3}}(2\pi f)^2 \right) \frac{\sqrt{3}L^3}{\pi^4 I} \tag{11}$$

Known $E_1$ is possible obtain $E_2$ through the equation:

$$E_2 = E_1\theta = E_1 \tan\theta = \left( \frac{2P}{v_{\max}}\cos\phi + \frac{mL}{\sqrt{3}}(2\pi f)^2 \right) \frac{\sqrt{3}L^3}{\pi^4 I} \tan\theta \tag{12}$$

The relations to calculate the components of the complex modulus suggested by the regulation:

$$E_1 = \gamma \left( \frac{F}{D}\cos(\phi) + \frac{\mu}{10^3}(2\pi f)^2 \right); E_2 = \gamma \left( \frac{F}{D} sin(\phi) \right) \tag{13}$$

Where:

• *F = 2P is load amplitude (peak-peak);*
• *D is the vertical displacement measured;*
• *γ is a form factor that depends by the type of sample and its geometry;*

$$\gamma = \frac{L^2 \cdot A}{b \cdot h^3}\left(\frac{3}{4} - \frac{A^2}{L^2}\right); A = \frac{L-l}{2} \tag{14}$$

• *L, space between outside clamps;*
• *l, distance between the points of load application;*
• *b, width; h, height of the prismatic specimen;*
• *μ, mass factor related to the sample mass M and to the moving parts masses;*

$$\mu = R(X)\left(\frac{M}{\pi^4} + \frac{m}{R(A)}\right); R(X) = \frac{12 \cdot L}{A}\left[\frac{1}{\left(3X/L - 3X^2/L^2 - A^2/L^2\right)}\right] \tag{15}$$

• *X is the coordinate on which the displacement is measured;*

(13) appears to be identical to the expressions (11) and (12) obtained through the impedance method, without the inertial term in the expression of $E_2$. Apart from this difference, the formulas of the regulation and those just obtained are equivalent.
How easy it is to check the expression (13) provided by the European standard for the evaluation of the real part, $E_1$, of the complex modulus coincides perfectly with (11) obtained with the impedance method (considering only the first term of development), while the expression for the evaluation of the imaginary part, $E_2$, is devoid of the inertial term present in (12).

$$\frac{M \cdot L^3}{\pi^4 \cdot I}\omega^2 tg\varphi \tag{16}$$

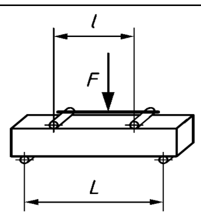
| Load type | Form factor, γ $mm^{-1}$ | Mass factor, μ (g) |
|---|---|---|
|   | $\frac{AL^2}{bh^3}\left(\frac{3}{4} - \frac{A^2}{L^2}\right)$ | $R \cdot \left(\frac{M}{\pi^4} + \frac{m}{R_A}\right)$ |

Table 1: Mass & form factors to 4PBT (EN12697-26)

## 1.2. Visco-elasticity

Asphalt is a viscoelastic material, thus it dissipates energy under mechanical work (loading and relaxation). Usually, in an elastic material the energy is stored in the system when the load is applied, all the energy is recovered when the load is removed; in this case the unloading and the loading curves coincide.

Viscoelastic materials are characterised by a hysteresis loop because the unloaded material traces a different path to that when loaded (phase lag is recorded between the applied stress and the measured strain); in this case the energy is dissipated in the form of mechanical work, heat generation, or damage [3].
The area of the hysteresis loop represents the dissipated energy in a load cycle, the equation (17) can be used to calculate its value in a linear viscoelastic material [4]:

$$W_i = \pi \sigma_i \varepsilon_i \sin \varphi_i \tag{17}$$

Where:
• $W_i$ = *Dissipated energy in cycle I;*
• $\sigma_i$ = *stress level in cycle I;*
• $\varepsilon_i$ = *strain level in cycle I;*
• $\varphi_i$ = *phase angle in cycle I;*

During a fatigue test, the stiffness reduces, the fatigue process starts and microcracks are induced in the material; therefore the dissipated energy, $W_i$, varies per loading cycle and it increases for controlled stress and decreases for controlled strain tests.

## 1.3. Fatigue

Flexural fatigue due to repeated traffic loading is a process of cumulative damage.
From a mechanical point of view, the mechanism of fatigue can be divided into two parts: a repetitive tensile stress/strain in the base layer (it causes the accumulation of micro damage in the bottom layer); the second one is the repetitive occurrence of such tensile stress/strain under load repetitions (it breaks causing deep cracks between the aggregate and the binder) [5].

Since the asphalt layer has viscoelastic behaviour, it recovers when the load is removed. At the end of this first cycle there is part of the strain that is recovered and a small part that is permanent. Under the next load the sub-layer undergoes the same cycle.

Physically speaking, micro cracking originate at the bottom of an asphalt concrete layer caused by horizontal tensile strain; this compromises the contact between the aggregate skeleton and the binder (particle-to-particle contacts). Furthermore the water trapped in the cracks and the repeated loading leads to a decrease in the strength of the mixtures and micro cracking starting to propagate towards the layers above and leading to pavement collapse. This phenomenon is called Bottom-Up Cracking [6].

Pasquini [7] used the indirect tensile fatigue test to evaluate the fatigue resistance at 20˚C. Fatigue resistance can be correlated to indirect tensile strength [8].

According to European standards, fatigue can be evaluated by means of direct and indirect tests. This paper focuses on bending tests, in particular on 4 Point bending (4PB) tests, which are widely used for measuring fatigue resistance and stiffness for asphaltic material. A sinusoidal loading is applied to the specimen, but geometry of the specimen and loading mode are different in the two tests. In the 4PB, instead, the specimen is not glued and the fracture happens in the middle part of the beam characterized by a constant maximum value of bending moment. (Figure 2).

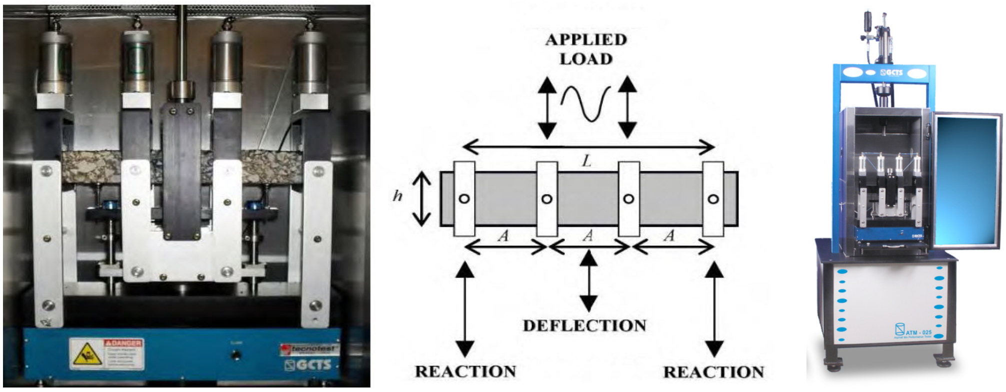



Figure 2: Load and strain amplitude for 4PB

### 1.3.1. Four Point Bending test

The 4 Point Bending test is the most used fatigue test, which was performed for the experimental work with servo-hydraulic actuator connected to a 2.5kN load cell mounted, a testing system at University of Palermo (Figure 3). Prismatic beams were manufactured with dimensions of 380mm in length, 50mm in height and 63mm in width. The specimen is restrained at four points by means of four clamps: the two outside remains static, the centrals deflect according to the strain applied. The deformation of the specimen is measured at the bottom between the two central clumps.

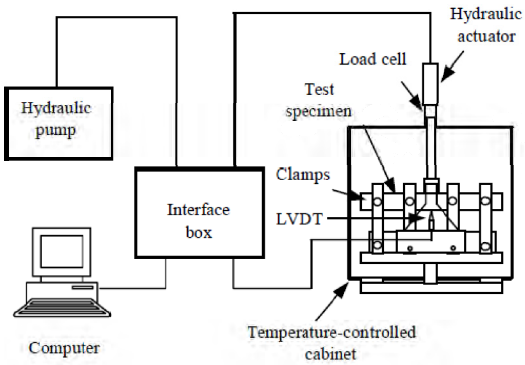



Figure 3: Configuration of 4PBT. Beam Fatigue testing machine

The vertical deflection and the applied load are used to calculate the strains and stresses. Furthermore, phase angle, dissipated energy and cumulative dissipated energy are also computed during the test.

A cyclic sine wave displacement is applied at the central H-frame third points of a beam specimen, while the outer third points are held in an articulating fixed position. The frequency rate ranges from 5-10Hz [9].

This test simulates very well a pavement fatigue failure under traffic loading because repeated loading causes tension in the bottom zone of the specimen, cracking will initiate and propagates to the top zone until failure; failure usually occurs in the area of uniform bending moment between the two inner clamps.

In this type of test free lateral translation are permitted in order to prevent internal stresses developing in the specimen.

In the 4 point bending test, initial stiffness is usually chosen between the $50^{th}$ and the $100^{th}$ load application. Conventionally, fatigue failure is the moment when the stiffness has decreased to half of its initial value [10].

### 1.3.2. Two Point Bending test

The 2-Point Bending test is more used in Europe. The methodology consists of applying a sinusoidal continuous waveform at the top of the specimen. Usually four specimen for each tests were used, in which each one were mounted as vertical cantilever. Sinusoidal constant displacement is applied at the top of the specimen, while the bottom base is fixed. As mentioned before, fracture usually occurs at 1/3 height from the bottom because that area is the most stressed in the specimen [11].

## 1.4. Fatigue in railway Infrastructure

Since many years in many countries the possibility of using rubber products, resulting from the treatment of end-of-life tyres in HMA production is investigated to improve asphalt performance through the elastic properties of the rubber. Constructing a sub-ballast of asphalt material involves a reduction of the acceleration peak values, leading to a reduction of tensions and thus a reduction of fatigue phenomena that characterises sub-ballast during its life. This implies a reduction of damage and of ground borne vibrations in rail track can be achieved.
It is widely known that placing a bituminous sub-ballast layer under a ballast layer improves the mechanical behaviour of rail track; some advantages such as the reduction of the ballast tension stresses and thus the reduction of fatigue phenomena are usually observed in this case [12].

The rail ballast absorbs the train weight and distributes it from the rails to the subgrade, thereby avoiding any deformation. The railroad can thus keep its geometrical features. The rapid decay of the railroad level which occurs with traditional ballast construction is mainly due to the unsatisfactory "fatigue behaviour" of the ballast; this is mostly due to embankment settling.

By interposing a special semi-rigid layer (sub-ballast) in the area between the ballast and the embankment, the behaviour of the overall structure is greatly improved. The adoption of a bituminous sub-ballast layer might allow important reductions in seasonal vertical displacements [13].

Recent studies have demonstrated that a track design analysis showed that structural performance was good when a 12-14cm conventional bituminous sub-ballast layer was used in lieu of the usual granular layers, and were discussed ways that a bituminous sub-ballast can reduce track maintenance needs [14].

Therefore, a bituminous sub-ballast layer could be a good option to improve railways in order to cope with future bigger traffic volume, heavier loads and higher speed velocity rail. Rubberized sub-ballast undoubtedly provides a number of advantages, such as low production costs (maintenance and management) and high quality physic-mechanical characteristics.

# 2 Laboratory testing

The developed research was used to analyse a dry asphalt rubber concrete (DARC) mixture for a sub-ballast layer in a rail track, comparing the mechanical behaviour of a rail track in different sub-ballast mixing cases:

- An asphalt sub-ballast layer (±12 cm) made of a conventional asphalt mixture according to the Italian standards (called by HMA-RFI).
- Two dry asphalt rubber mixture characterized by 1%-2% of rubber content obtained by means of the substitution of limestone aggregates with crumbed rubber in volumetric proportion (DARC1_2).
- A dense-open graded rubber-modified asphalt concrete (RUMAC-DRY) mixture produced by adjusting the grading curve to incorporate different percentages of crumb rubber (3-5% of CRM by mass of the total aggregate) in the experimental work (DARC3).

## 2.1. Material

### 2.1.1. Aggregates and mixtures

The mineral aggregate fractions used in this investigation consisted of limestone commonly adopted in Sicily. The physical attributes of the aggregates are summarized in Table 2. It should be underlined that the mineral skeletons of both mixes were the same and these mixes only differed in the type and content of binder.

| Test | Value | Standard |
|---|---|---|
| Los Angeles abrasion loss (%) | 4,5 | *EN 1097-2:2010* |
| Shape coefficient $C_f$ | 1.25 | *EN 933-4:2008* |
| Flakiness index $C_a$ | 1.54 | *EN 933-1:2012* |
| Micro-Deval wet abr. Loss (%) | 20.7 | *EN 1097-1:2011* |
| Sand equivalent (%) | 89 | *EN 933:8:2012* |
| Voids dry comp. filler (%) | 31.3 | *EN 1097-4:2008* |
| Polished stone value | 0.39 | *EN 1097-8:2009* |

Table 2: Aggregate physical properties

The dry process CRM mixtures were produced by adjusting the grading curve to incorporate different percentages of crumb rubber. The recycled crumb rubber comes from the waste tires of trucks. In table 3 the main volumetric parameters of the asphalt mixes are shown.

| Identification | Binder (%) | Rubber (%) | Air voids (%) | Specific Gravity (kg/m$^3$) |
|---|---|---|---|---|
| HMA(RFI) | 3.70 | 0.0 | 5-7 | 2534 |
| DARC1 | 4.00 | 1.0 | 7 | 2250 |
| DARC2 | 4.30 | 2.0 | 8-9 | 2375 |
| DARC3 | 4.80 | 3.5 | 11 | 2860 |

Table 3: Volumetric parameters of the asphalt sub-ballast

The specific gravity for the aggregates and bitumen fractions of the mixtures, were made available by the producers. The specifications are listed in Table 4.

| Component | Type | Specifications | Bulk Gravity (g/cm$^3$) |
|---|---|---|---|
| Coarse aggregate | Limestone | 2.36mm<Ø<20mm | 2.60 |
| Fine aggregate | “ | 0.075mm<Ø<2.36mm | 2.85 |
| Filler | “ | Ø<0.075mm | 2.70 |
| Bitumen | 50-70 Pen | >70ºC Soft. point | 1.03 |
| Crumb rubber | Truck tyres | 2-8mm | 1.15 |

Table 4: Aggregate, rubber and bitumen specification

It was considered the gradation master band of the RFI standards and the average gradation was selected as showed in Table 5 and Figure 4.

| Grading curve sub-ballast RFI | | | |
|---|---|---|---|
| Sieve Size (mm) | % Passing limit | | |
| | Lower limit (%) | Upper limit (%) | Total mix (%) |
| 25.4 | 100 | 100 | 100 |
| 19.1 | 80 | 100 | 90 |
| 9.52 | 54 | 76 | 65 |
| 4 | 36 | 56 | 46 |
| 2 | 23 | 40 | 31.5 |
| 0.42 | 10 | 22 | 16 |
| 0.175 | 7 | 16 | 11.5 |
| 0.074 | 6 | 10 | 8 |

Table 5: Material gradation of control

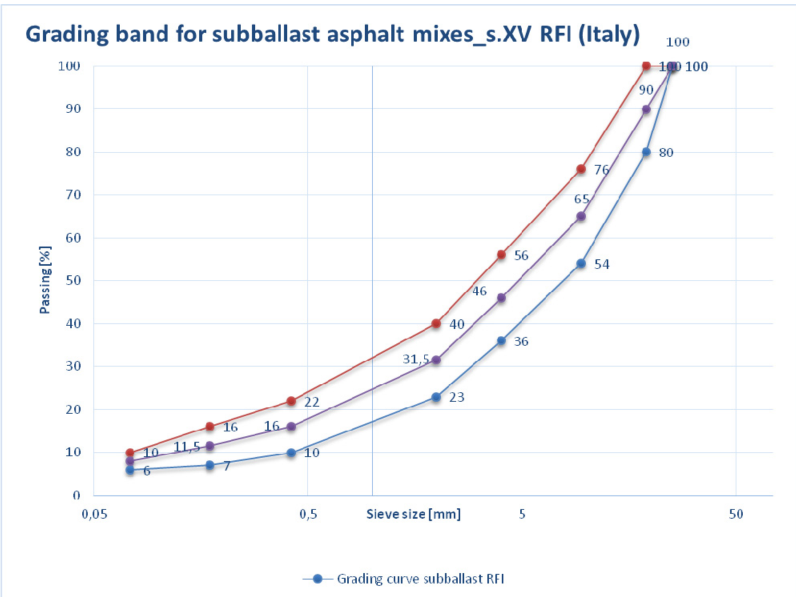



Figure 4: RFI master band gradation

Production methods normally used are two, in one case rubber powder (<1mm) is used to “modify” the bitumen (wet process), they are mixed together (≈8-15% of rubber by weight of bitumen) before the addition of the lithic aggregates.

In the other case (dry process) a part of the natural aggregates (≈2-6% by weigh of the aggregates) is substituted with rubber granulate (2-5mm) which is used and mixed nearly as any other aggregate (Table 6).

| Nominal sieve opening (mm) / Sieve Designation mesh (Nº) / Passing by Weight (%) |
|---|
| 6.3mm: 100%; 4.75mm: 76 – 100%; 2.0mm: 28 – 42%; 0.85mm: 16 – 24% |

Table 6: Requirements for rubberized mixes

The dry process involves larger amount of rubber and seems therefore much more promising than the wet one in vibration control applications because of its stronger influence on rheological characteristics of composite mixture.

Rubber used in the dry process is ground rubber that is generally produced in a granulator process. This process further reduces shredded tire rubber and generates cubical, uniformly shaped particles ranging in size from 9.5 mm (3/8”) down to a 0.42mm (N. 40 sieve).

As the grading curve was modified to replace 1.5% and 3.5% aggregate by mass with crumb rubber, the grading of rubber particles was also taken into consideration when designing the mixture.

Furthermore, the mixtures were produced in different short-term conditioning regimes to reflect the effect of the rubber-bitumen interaction during the production period (1-6 hours) and were also compacted to achieve the percentage of voids content proposed to each mixture.

### 2.1.2. Mixture design

The preliminary mix design was carried out according to the Marshall test [EN 12697-34 2013]. For each mixture with given percentage of binder, the number of specimens is at least two, in order to average the values of stability and flow measured. Moreover, it must be provided a further test for determining the percentage of voids. These parameters vary with the percentage of bitumen used and it is possible to define experimentally the correlation of these characteristics with the proportion of binder. The properties of the binder are reported in Table 7.

| Characteristics | | Standard | Required values | Observed values |
|---|---|---|---|---|
| Pen @ 25°C (mm) | | EN1426:2007 | 50-70 | 56 |
| Softening Point (°C) | | | ≥70 | 49 |
| Equi-viscosity temperatures (°C) | 0.28Pa·s | AASHTO T316-04 | - | 145 |
| | 0.17Pa·s | | - | 150 |
| Bulk gravity (g/cm$^3$) | | - | - | 1.03 |

Table 7: Physical and rheological properties of the binder

Of each mixture it was determined the stability and the percentage of the voids to vary the percentage of bitumen and rubber incorporated. In Table 8 there are reported the main volumetric parameters of the materials.

| Mixture | Stability (kN) | Flow (mm) | Stiffness (kN/mm) | Air voids (%) | Binder (%) |
|---|---|---|---|---|---|
| HMA-RFI | 17-19 | 3.9 | 4.65 | 5-7 | 3.7 |
| DARC1 | 13-15 | 4.2 | 3.30 | 7 | 4.0 |
| DARC2 | 9.5-11 | 4.8 | 2.10 | 8-9 | 4.3 |
| DARC3 | 7-8 | 5.5 | 1.45 | 11 | 4.8 |

Table 8: Marshall Test parameters of the asphalt sub-ballast

The stone aggregate prior to mixing is placed in an oven for 24h at a temperature of about 25ºC higher than the mixing, separating from the filler (0.074 mm).

Finally, the Marshall stiffness and control of voids content are not considered valid parameters for characterizing the mechanical strength of the mixture, also in view of the possible use of non-traditional conglomerates.

## 2.2. Experimental set-up

### 2.2.1. Test program

The four point bending test was carried out in order to evaluate the mechanical behaviour and the damping property of the bituminous mixtures on prismatic specimens (EN 12697-26:2004). This method is conducted on compacted beam specimens to evaluate the fatigue properties of an asphalt concrete mixture [15].

The four point bending tests were performed on a total of 8 beams related, respectively to each mixture. Then, the experimental points representative of the mechanical quantities were averaged over a number of two samples (Figure 5).

The test is generally carried out by keeping constant the frequency and the temperature. The tests were undertaken at the temperature of 10ºC, 17ºC e 25ºC and the loading frequencies were 0.1Hz, 0.5Hz, 1Hz, 2Hz, 5Hz, 10Hz and 15Hz.

The specimens were obtained through the cut of several slabs manufactured in laboratory under static compaction. The final required dimensions of the test specimen, are 380±6mm in length, 50±2mm in height, and 63±2mm in width.

Figure 5: Preparation of three specimens compacted with the requirements of standards

Are shown in Tables 9, 10, 11 and 12, the values of $E_1$, $E_2$, $\Phi$, $|E^*|$ and damping ratio related to the average of the values obtained in tests for each mixture.

| HMA_RFI | | | | | UNI EN 12697-26:2004 | |
|---|---|---|---|---|---|---|
| T=10 °C | | | | | | |
| *f* [Hz] | $E_1$ [MPa] | $E_2$ [MPa] | $\Phi$ [°] | $\lvert E^*\rvert$ [MPa] | Dissipated energy [kJ/m$^3$] | Damping Ratio |
| 0.1 | 10714 | 4720 | 24.25 | 11726 | 1.262E-05 | 0.226 |
| 0.5 | 15748 | 4547 | 16.18 | 16398 | 1.195E-05 | 0.145 |
| 1 | 16657 | 4109 | 13.91 | 17158 | 1.074E-05 | 0.124 |
| 2 | 19795 | 3032 | 8.71 | 20028 | 7.821E-06 | 0.077 |
| 5 | 19849 | 2257 | 6.59 | 20017 | 6.778E-06 | 0.058 |
| 10 | 21583 | 1022 | 2.66 | 21617 | 2.495E-06 | 0.023 |
| 15 | 17543 | 427 | 1.43 | 17551 | 1.454E-06 | 0.012 |
| T=17 °C | | | | | | |
| 0.1 | 4869 | 3670 | 37.19 | 6103 | 1.042E-05 | 0.381 |
| 0.5 | 8902 | 4686 | 27.77 | 10069 | 1.331E-05 | 0.264 |
| 1 | 10994 | 4848 | 23.75 | 12025 | 1.390E-05 | 0.220 |
| 2 | 15084 | 4300 | 15.91 | 15691 | 1.284E-05 | 0.143 |
| 5 | 16309 | 4051 | 13.92 | 16815 | 1.367E-05 | 0.124 |
| 10 | 17865 | 3494 | 11.18 | 18213 | 1.007E-05 | 0.098 |
| 15 | 16140 | 1728 | 6.27 | 16242 | 6.075E-06 | 0.054 |
| T=25 °C | | | | | | |
| 0.1 | 1346 | 1591 | 49.82 | 2085 | 4.513E-06 | 0.592 |
| 0.5 | 2802 | 2824 | 45.25 | 3978 | 8.029E-06 | 0.505 |
| 1 | 3952 | 3529 | 41.79 | 5299 | 1.028E-05 | 0.447 |
| 2 | 8009 | 5092 | 32.46 | 9503 | 1.584E-05 | 0.319 |
| 5 | 9785 | 5208 | 28.38 | 11144 | 1.539E-05 | 0.266 |
| 10 | 11191 | 5299 | 25.53 | 12401 | 1.489E-05 | 0.236 |
| 15 | 11693 | 3618 | 17.77 | 12245 | 1.219E-05 | 0.155 |

Table 9: Experimental data mixture HMA-RFI

| DARC 1% | | | | | UNI EN 12697-26:2004 | |
|---|---|---|---|---|---|---|
| T=10 °C | | | | | | |
| *f* [Hz] | $E_1$ [MPa] | $E_2$ [MPa] | $\Phi$ [°] | $\|E^*\|$ [MPa] | Dissipated energy [kJ/m$^3$] | Damping Ratio |
| 0.1 | 10093 | 4471 | 23.99 | 11040 | 1.190E-05 | 0.223 |
| 0.5 | 14166 | 4359 | 17.23 | 14824 | 1.188E-05 | 0.155 |
| 1 | 15308 | 4084 | 15.06 | 15846 | 1.118E-05 | 0.135 |
| 2 | 18164 | 3329 | 10.96 | 18487 | 9.608E-06 | 0.097 |
| 5 | 18139 | 2138 | 8.36 | 18351 | 8.129E-06 | 0.074 |
| 10 | 17211 | 490 | 2.38 | 17228 | 2.792E-06 | 0.021 |
| 15 | 14622 | 560 | 2.91 | 14640 | 2.588E-06 | 0.024 |
| T=17 °C | | | | | | |
| 0.1 | 4059 | 3290 | 39.13 | 5226 | 9.390E-06 | 0.407 |
| 0.5 | 7047 | 4333 | 31.58 | 8273 | 1.248E-05 | 0.307 |
| 1 | 9800 | 4913 | 26.72 | 10964 | 1.417E-05 | 0.252 |
| 2 | 14390 | 4681 | 18.15 | 15135 | 1.394E-05 | 0.164 |
| 5 | 14793 | 4164 | 16.18 | 15394 | 1.236E-05 | 0.145 |
| 10 | 14970 | 2488 | 9.62 | 15179 | 9.671E-06 | 0.084 |
| 15 | 14808 | 1893 | 7.68 | 14941 | 6.109E-06 | 0.066 |
| T=25 °C | | | | | | |
| 0.1 | 1223 | 1521 | 51.24 | 1955 | 4.325E-06 | 0.627 |
| 0.5 | 2307 | 2751 | 50.15 | 3594 | 7.983E-06 | 0.602 |
| 1 | 3252 | 3527 | 47.46 | 4801 | 1.039E-05 | 0.547 |
| 2 | 6848 | 4993 | 36.29 | 8483 | 1.504E-05 | 0.368 |
| 5 | 8724 | 4932 | 29.75 | 10029 | 1.282E-05 | 0.285 |
| 10 | 10573 | 5242 | 26.81 | 11828 | 1.548E-05 | 0.250 |
| 15 | 10600 | 4107 | 22.03 | 11377 | 1.491E-05 | 0.195 |

Table 10: Experimental data mixture DARC1 (1.0% CRM)

| DARC 2% | | | | | UNI EN 12697-26:2004 | |
|---|---|---|---|---|---|---|
| T=10 °C | | | | | | |
| $f$ [Hz] | $E_1$ [MPa] | $E_2$ [MPa] | $\Phi$ [°] | $\lvert E^*\rvert$ [MPa] | Dissipated energy [kJ/m$^3$] | Damping Ratio |
| 0.1 | 9160 | 3346 | 20.07 | 9753 | 9.112E-06 | 0.183 |
| 0.5 | 12407 | 3179 | 14.37 | 12808 | 8.324E-06 | 0.128 |
| 1 | 13644 | 2936 | 12.14 | 13957 | 7.874E-06 | 0.108 |
| 2 | 15561 | 2018 | 7.41 | 15693 | 5.386E-06 | 0.065 |
| 5 | 15385 | 951 | 3.44 | 15435 | 2.488E-06 | 0.030 |
| 10 | 15733 | 1586 | 5.71 | 15816 | 4.011E-06 | 0.049 |
| 15 | 14070 | 531 | 2.25 | 14082 | 1.692E-06 | 0.020 |
| T=17 °C | | | | | | |
| 0.1 | 3998 | 2760 | 34.61 | 4858 | 7.848E-06 | 0.345 |
| 0.5 | 7034 | 3516 | 26.56 | 7864 | 1.026E-05 | 0.250 |
| 1 | 8571 | 3663 | 23.14 | 9321 | 1.071E-05 | 0.214 |
| 2 | 11980 | 3273 | 15.33 | 12420 | 9.816E-06 | 0.137 |
| 5 | 12837 | 2617 | 11.60 | 13104 | 8.451E-06 | 0.102 |
| 10 | 14627 | 2666 | 10.45 | 14873 | 7.414E-06 | 0.091 |
| 15 | 12976 | 1545 | 6.98 | 13073 | 5.142E-06 | 0.059 |
| T=25 °C | | | | | | |
| 0.1 | 1352 | 1306 | 43.99 | 1880 | 3.782E-06 | 0.483 |
| 0.5 | 2606 | 2223 | 40.47 | 3426 | 6.575E-06 | 0.426 |
| 1 | 3495 | 2728 | 37.98 | 4433 | 8.070E-06 | 0.390 |
| 2 | 6585 | 3726 | 29.54 | 7566 | 1.153E-05 | 0.283 |
| 5 | 7964 | 3708 | 25.07 | 8786 | 1.114E-05 | 0.233 |
| 10 | 9582 | 4094 | 23.52 | 10424 | 1.296E-05 | 0.214 |
| 15 | 9901 | 3499 | 20.12 | 10504 | 1.370E-05 | 0.177 |

Table 11: Experimental data mixture DARC2 (2.0% CRM)

| DARC 3% | | | | | UNI EN 12697-26:2004 | |
|---|---|---|---|---|---|---|
| T=10 °C | | | | | | |
| $f$ [Hz] | $E_1$ [MPa] | $E_2$ [MPa] | $\Phi$ [°] | $\|E^*\|$ [MPa] | Dissipated energy [kJ/m$^3$] | Damping Ratio |
| 0.1 | 7811 | 2792 | 19.69 | 8298 | 7.604E-06 | 0.179 |
| 0.5 | 10558 | 2673 | 14.23 | 10898 | 7.431E-06 | 0.127 |
| 1 | 11700 | 2602 | 12.55 | 11994 | 7.153E-06 | 0.111 |
| 2 | 13521 | 2073 | 8.70 | 13685 | 5.675E-06 | 0.077 |
| 5 | 12401 | 845 | 3.88 | 12431 | 2.503E-06 | 0.034 |
| 10 | 11391 | 791 | 4.20 | 11422 | 2.388E-06 | 0.036 |
| 15 | 10354 | 988 | 5.75 | 10412 | 2.041E-06 | 0.048 |
| T=17 °C | | | | | | |
| 0.1 | 3328 | 2198 | 33.45 | 3989 | 6.472E-06 | 0.330 |
| 0.5 | 5696 | 2850 | 26.59 | 6370 | 8.257E-06 | 0.250 |
| 1 | 6971 | 3062 | 23.72 | 7614 | 8.707E-06 | 0.220 |
| 2 | 9614 | 2799 | 16.27 | 10013 | 7.760E-06 | 0.146 |
| 5 | 10525 | 2390 | 12.84 | 10793 | 6.651E-06 | 0.114 |
| 10 | 11292 | 1827 | 9.31 | 11440 | 5.298E-06 | 0.081 |
| 15 | 10796 | 1757 | 9.56 | 10940 | 5.755E-06 | 0.081 |
| T=25 °C | | | | | | |
| 0.1 | 1206 | 1071 | 41.60 | 1613 | 3.021E-06 | 0.444 |
| 0.5 | 2543 | 2302 | 41.55 | 3434 | 6.497E-06 | 0.445 |
| 1 | 2874 | 2142 | 36.70 | 3584 | 6.135E-06 | 0.373 |
| 2 | 5262 | 2975 | 29.54 | 6044 | 8.834E-06 | 0.283 |
| 5 | 6568 | 3211 | 26.21 | 7311 | 8.926E-06 | 0.245 |
| 10 | 7728 | 3145 | 22.57 | 8344 | 8.710E-06 | 0.203 |
| 15 | 8097 | 3200 | 22.48 | 8707 | 1.000E-05 | 0.198 |

Table 12: Experimental data mixture RUMAC (3.0% CRM)

After analysing the experimental data, stiffness was calculated considering a different range of initial cycles depending on the frequency (200-400 cycles).

Since fatigue cracking is more prevalent in thin layers, the strain-controlled parameter can be considered of most concern for fatigue resistance. With each load cycle, part of this work is recovered by the elastic rebound of the layer, while part is dissipated in the form of permanent deformation, heat, cracking and crack propagation (Carpenter & Shen, 2006). Therefore, in order to minimize fatigue cracking the amount of work dissipated per loading cycle should be minimized.

### 2.2.2. Results and discussion

In Figure 6 the isothermal curves are shown, plotting stiffness modulus versus frequency at different temperatures. The complex modulus results of experimental work could be summarized in master curve which is the representation of the variation of |E*| as a function of the reduced frequency.

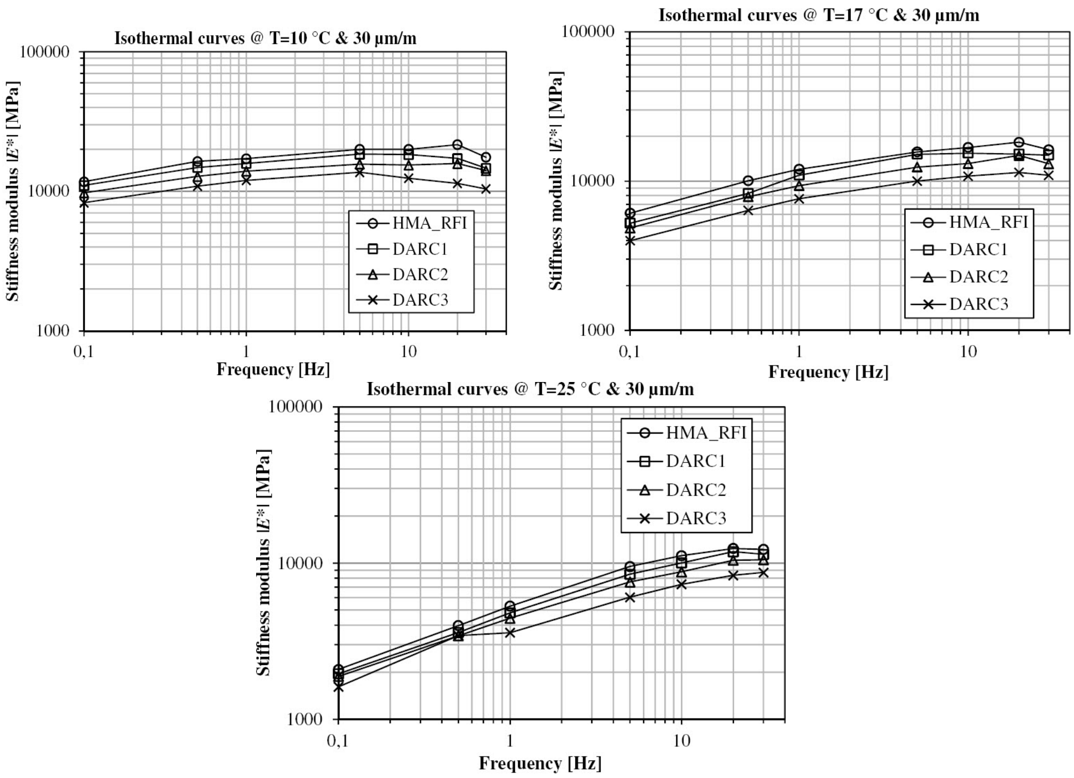



Figure 6: Isothermal curves at T$^a$ = 10°C, 17ºC, 25ºC; $\varepsilon_0$: 30μm/m

Regarding the flexural stiffness of the mixture, the experimental results showed that DARC stiffness modulus is lower than HMA-RFI for each T$^a$ and frequency. There was higher values with increasing test frequency and when the percentage of crumb rubber decrease. It depends on the rheological behaviour of the binder for which, the viscous properties are enhanced by an increase of the temperature and/or to a decrease of the frequency. This occurs for all the mixtures studied.

The analysis of the results allows an immediate understanding of the relationship between the complex modulus and frequency-temperature, at which the material is subjected.

# 3 Conclusion

The characterisation of the asphalt mixtures in terms of both the fatigue resistance and the stiffness modulus is necessary to use any design method of the flexible pavements, especially for innovative material such as dry asphalt rubber concrete.

This article analysed the mechanical behaviour of a hot mix asphalt traditional mixture in Italy, a rubber modified asphalt dry mixture and two dry asphalt rubber concrete mixtures with different rubber content that varies within 0 and 3.5% by weight of the aggregates.

Comparing the values at the test conditions, the stiffness modulus shows values ranging from 21.6GPa for HMA_RFI (f=20Hz, $T^a$=10ºC) and 16GPa for the RUMAC Dry mix (f=0.1Hz, $T^a$=25ºC).

Such experimental evidence explains, as the same material, in terms of grading curve, can have a mechanical response very different to change the amount of rubber, binder and stress conditions. So emerges the need for further analysis.

Note the anomalies related to experimental points in correspondence of the highest frequency (30Hz): the relevant forms of stiffness are lower than those found at the previous frequency (20Hz).

A possible cause of this phenomenon can be ascribed to the achievement of the resonance frequency of some elements compared to the higher stiffness of the specimen: in fact, this inconsistency is manifested at low test temperatures and the highest selected frequency. This explanation is accompanied by the fact that lower stiffness (T = 25ºC) this phenomenon seems quite slight.

The following conclusions can be made on the experimental work carried out by means of the four point bending test on prismatic specimen based on the conventional mix design:

- Only the mixture HMA-RFI without rubber for the limits imposed by Italian standard is permissible in terms of rigidity, in reference to almost all of the levels of binder tested;
- The value of the damping ratio depends on both the temperature and the frequency because the dissipative properties of the material increased in relation to an increase of the temperature and/or to a decrease of frequency;
- 4 point bending test was suitable to characterize the mechanical behaviour of several innovative materials;
- Complex modulus decreases when rubber content increases. In addition, complex modulus is bigger at higher frequency.

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## PROCEEDINGS OF THE THIRD INTERNATIONAL CONFERENCE ON RAILWAY TECHNOLOGY: RESEARCH, DEVELOPMENT AND MAINTENANCE

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**Paper 37**

### Evaluation of Dry Asphalt Rubber Concrete in Railway Sub-Ballast using the Four Point Bending Test

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**Keywords:** fatigue, stiffness modulus, dry asphalt rubber concrete, four point bending test, sub-ballast, railway.

**Summary**

The study of bituminous mixes can be related to tyre rubber material recycling. Encouraging scrap tyre disposal and cutting down on pit employment are the environmental aims. In the field of railways, technological processes involved in the use of crumb rubber are the wet-dry processes. In the mechanical characterisation of the asphalt concrete in terms of both the fatigue resistance and the stiffness modulus it is necessary to use a design method for the sub-ballast railway material, even more so if the asphalt concrete investigated is an innovative material such as a dry asphalt rubber concrete (DARC) (*i.e.* a bituminous mixture with crumb rubber formed by a dry process). Such material is less known and investigated than the wet process, even if its application implies peculiar economic and environmental advantages such as no specialized equipment or significant plant modifications and a large quantity of recycled waste tires compared to the wet process. Different kinds of test are usually used in the experimental work such as bending tests or uni-axial tests, but they do not give the same answer.

In the work, described in this paper, mechanical characterization was carried out by means of fatigue tests for asphalt material: a two point bending (2PB) test and four point bending (4PB) test, focused on the mechanical behaviour of DARCs with different rubber content by weight of the aggregates. Different strain controlled tests were undertaken for the same material under the same loading conditions, frequency and temperature (15Hz, 20 degrees centigrade), in particular an experimental survey was carried out in order to determine the stiffness modulus by means of the four point bending test on prismatic specimens (UNI EN 12697-26, 2004). This paper reports the experimental results for rubberized asphalt mechanical properties for a sub-ballast layer performed in a laboratory using the dry process.

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