A new proposal to assess shear fatigue resistance of asphalt pavement interfaces

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A new proposal to assess shear fatigue resistance of asphalt pavement interfaces

Abstract: the degree of adherence between two bituminous layers can be assessed from shear tests carried out at constant displacement speed, which allow the shear strength and stiffness of the interface to be obtained, being usual to specify a minimum strength. But stronger bonds will be more stressed, which could negatively affect their fatigue behaviour. In this work, the shear fatigue behaviour of two interfaces of different stiffness has been analysed, based on a cyclic compression test, performed at controlled stress, using the test device B described in the NLT-382 standard, included in the draft of the European pre-norm prEN 12697-48. From these tests, fatigue laws for each type of interface have been obtained. These laws, combined with a calculation method developed by the authors, have made it possible to obtain the number of cycles that each interface would withstand, under certain load hypotheses.

Keywords: tack coat; bituminous interface; shear fatigue; shear stress; horizontal reaction modulus; displacement speed

1. Introduction

Except for very light traffic, it is usual for flexible and semi-rigid pavement sections currently being designed to have considerable thicknesses of bituminous mix, which cannot be laid on-site in a single layer due to the impossibility of compacting it satisfactorily. For this reason, during the construction of the pavement, different bituminous layers are laid (base, binder and wearing courses) of limited thickness so they can be satisfactorily compacted and that add up to the total mix thickness required.

But, from a structural point of view, for this sum of thicknesses to be equivalent to the total design thickness, the layers must be well bonded to each other (and, if applicable, to the underlying layer, if this is a cement treated material), and work as a cohesive whole. For this, during construction, a tack coat is applied between the bituminous layers, so that the behaviour of the whole is as close as possible to that of a single layer.

If this bond is not achieved, premature deterioration will appear in the pavement that will compromise its durability, thus it is important to control not only the process and conditions of the tack coat application, but also the bond actually achieved between the layers.

To assess the degree of adherence between two bituminous mix layers, there are various types of test (tensile, torsion, shear) [1, 2], although the most used type are probably the shear tests [3]. Applied at a certain displacement speed and temperature, they allow the shear strength of an interface to be obtained. Minimum strengths to attain are specified, which, in general, vary depending on the interface being considered [4, 5, 6, 7, 8].

Thus, in Spain, a minimum shear strength value is specified of 0.6 MPa under the wearing course and 0.4 MPa in the lower layers, at a displacement speed of 2.5 mm/min and a temperature of 20ºC [4]. These values were established (as in some other countries) based on the results obtained after the first applications of the shear test during the quality control of the tack coats at a considerable number of works.

This has generated a certain amount of discussion on whether these values are adequate or not. The best way to check if they are correct, excessive or insufficient would be to compare the shear strength obtained in laboratory tests with the stress in service that can occur in the interface in the pavement under certain load conditions.

However, it is clear that this could involve certain difficulties due to the high number of factors that affect the stress distribution in a bituminous interface, and the interdependence between them in many cases. Before making this comparison, the effects of the various conditions that may exist must be assessed *in situ* and in the laboratory, namely temperature, displacement speed or the presence of normal stresses. Furthermore, the actions of the traffic must be correctly modelled and the combination of load assumptions and the most unfavourable environmental conditions carefully selected.

In this regard, Ortiz-Ripoll et al. (2020) [9] proposed a semi-empirical calculation method for estimating the true load level to which the bituminous interfaces are subjected under the action of traffic, based on direct shear tests without normal stress, as set out in standard NTL-382 (devices A and B) [10] or in the draft of the European pre-standard prEN 12697-48 (*Shear Bond Test and Alternative Shear Bond Test*) [11], carried out in the laboratory on cores extracted from the pavement.

Thanks to the use of the nomogram designed for this purpose, this method makes it possible to consider the contribution of the normal stress present at the most unfavourable point of the interface from the point of view of its shear load, since the normal stress affects both its stiffness and its shear strength. The method also provides an estimation of the displacement speed between the boundaries of the interface as a function of the load speed, and makes it possible to calculate its effect on the strength and on the shear stiffness modulus of the bond.

Thus, this stiffness modulus, which can be significantly different from that obtained in the laboratory, should be used to characterise the interface when attempting to obtain the stress distribution within the pavement layers in real conditions.

When consistently comparing the design shear stresses with the admissible shear stresses in a bituminous interface, it was observed that the maximum shear loads of the bond between bituminous layers occur at interfaces under thin layers with flexible mixtures, with high temperatures and low traffic speeds. In these conditions, the in-service shear stresses can reach values of 0.23 to 0.27 MPa, equivalent to 0.52 – 0.55 MPa in laboratory conditions (in accordance with standard NLT-382, at 2.5 mm/min and 20ºC). And taking into account some simple statistical considerations, it is possible to qualify as adequate the current lower limit of 0.6 MPa established in article 531 of the PG-3, when one of the layers is the wearing course [12].

In any case, as has been frequently proven, it is usually stated that the stiffest bonds will also be the strongest and will contribute to reducing the overall stresses of the pavement, particularly in bituminous layers, thus increasing their durability [2]. Therefore, specifying the shear strength of the bond between bituminous layers relates to specifying its stiffness, which justifies the importance of these types of requirements, irrespective of the shear load level to which the interface itself is subjected.

However, the shear fatigue life of the bituminous interfaces has not been considered at all in this approach. If the strongest (and stiffest) interfaces are going to be more stressed, will they maintain a fatigue life comparable to that of the less stiff interfaces?

With the aim of determining the shear fatigue life of a bituminous interface and verifying if this can be correlated with its maximum shear strength, this article contains the results obtained from a shear fatigue test applied to different types of interfaces. From these results, the corresponding fatigue laws of the interfaces were obtained which, combined with calculation method previously developed by the authors, make it possible to determine up to what point the response of the interface is critical in the design life of the pavement.

2. State of the art

From among all the equipment initially developed for testing the interface of bituminous mixes in static mode, some have been adapted for testing in dynamic mode, despite the complexity that this test mode entails. Added to this difficulty is the time required for carrying out the dynamic tests when the applied load levels are very low.

The first work to measure interlayer adherence dates back to 1978 when Uzan et al. designed a shear device which allowed the magnitude of the normal stress to be varied, using a displacement speed of 2.5 mm/min [13].

However, it was not until 1997 that Crispino et al. carried out the first dynamic shear tests [14]. They designed a device called Interlayer Reaction Testing Equipment (IRTE). This equipment applied a sinusoidal shear stress at a frequency of 10 Hz.

Another precursor test is that developed by Romanoschi and Metcalf in 1999, the Shear Fatigue Test (SFT), [15, 16], which subjects a specimen to a load applied with an inclination of 25.5 degrees with respect to the longitudinal axis of the specimen, so that it receives a shear load whose magnitude is half the normal load (this ratio of 0.5 is considered typical by Salam and Shahin [17, 18] in the areas where the vehicles brake and accelerate). This load is applied in haversine mode at a frequency of 5 Hz.

In 2000, Donovan et al. conducted a study at Virginia Tech to optimise the application rate of tack coats when using geocomposite membranes on bridge deck surfaces between the Portland cement concrete and the bituminous wearing course [19]. For this purpose, the Virginia Shear Fatigue Test was designed, which allows the application of half-sine cyclic loads to a cylindrical specimen until breaking~~.~~

Later, based on Uzan's work, Brown and Brodrick developed other similar equipment at the University of Nottingham for studying prismatic specimens subjected to repeated shear loads and normal load [20].

At Kansas State University, Wheat developed the KSU Bond Strength Test in 2007, which evaluates the shear strength and dynamic modulus of cylindrical specimens placed at an angle with respect to the applied force axis, in a similar way to that proposed by Romanoschi [21].

In the same year, Diakhaté et al. designed a device at the University of Limoges for testing a prismatic specimen comprising three bituminous mix layers bonded together by the tack coat [22]. The sample is located on the press in such a way that the layer between the end layers is subjected to a symmetrical pure shear force that can be monotonic or cyclic (at a frequency of 1 Hz). Later on they assessed the effect of the tack coat on bituminous layers at different temperatures, by applying a controlled force amplitude at 10 Hz [23].

Wellner and Ascher, also in 2007, adapted an equipment which had been previously developed by Leutner for statically testing cylindrical specimens or cores ([24]) so that cyclic loads could be applied and a normal load added [25]. Isailovic et al.

used this device to confirm the applicability of the test and define the most recommendable parameters to use one decade later [26]. They confirmed the high dependence that these fatigue tests had on normal stress. To take into consideration the effect of the normal stress, the researchers recommended conducting the test at low temperatures (10ºC).

In 2011, Collop et al. developed a torque test that can assess the effect of load repetition on the interface, the Automatic Torque Bond Test, which can be conducted either at a controlled torque rate or at a controlled rotation rate [27, 28].

The direct shear machine developed at the University of La Sapienza (SDSTM) by Tozzo et al in 2014 uses double layer cylindrical specimens with a diameter of 100 mm and acts as a guillotine [29]. The device allows a dynamic load to be applied on one of the two moulds with a frequency of 5 Hz and it is also possible to include a normal load. The researchers demonstrated the significant influence of the normal pressure on the fatigue strength of the interface. [30].

In 2015, Zofka et al. presented their Advanced Shear Test (AST) for cylindrical specimens, which allows static and cyclic loads to be applied, in controlled displacement or load mode, on a collar which holds one of the two parts of the specimen and a normal confinement [31] can also be applied to it.

Also in 2015, Kim et al. designed the Modified Advanced Shear Tester (MAST) test, based on the AST, which allows prismatic and cylindrical specimens to be tested in static and fatigue mode under controlled load or displacement [32]. The researchers verified the time-temperature superposition principle (t-TS) for the shear strength and the stiffness of the interface with different tack coats. [33].

In 2019 Ragni et al. designed an adaptation for applying cyclic loads with the ASTRA (Ancona Shear Testing Research and Analysis) developed by Canestrari et al. at the Università Politecnica delle Marche [34]. This test allowed prismatic specimens which are placed in boxes that separate the interface to be assessed. The new test was called C-ASTRA [35].

As can be seen, there are some proposals for dynamically assessing the bituminous interfaces. And as mentioned at the start of this section, the difficulty of applying them is evident given the different configurations of the test devices and, above all, the different variables that can affect the response of the interface, especially as regards the presence of normal stresses during the test that enormously complicate the test procedure.

For this reason, in this work, it was decided to propose a dynamic test procedure based on standardised equipment, and instead of considering normal loads during the test, it is proposed to combine the results obtained of the dynamic test with a new calculation procedure. This method will allow the stresses present at the interface to be obtained under service conditions and, therefore, considering both the effect of the normal stresses and that of the other variables and the displacement speed between its sides.

3. Experimental study

3.1. Materials

Within the framework of the SUPERBIT research project (Treatments for obtaining SUPERior properties and efficiencies of BITuminous tack coats to improve the durability of pavements) [36], an experimental section was constructed made up of two asphalt layers between which different tack coats were applied.

The 12-year-old bottom layer was formed by an asphalt concrete AC22 S 50/70 semi-dense mix of 7 cm thickness. On top of this was spread a new 4 cm thick layer of an asphalt concrete AC16 S 50/70 mix. Before this layer was laid, and after pressure washing the existing surface with water, different tack coats were applied using different rates of a C60B3 TER heat-adhesive emulsion (between 150 and 450 g/m^2), and then a treatment of calcium hydroxide slurry was applied in some cases, also with different rates (between 0 and 90 g/m^2), figure 1.

Figure 1. Application of tack coats in the experimental section, (a) with emulsion and (b) with emulsion and lime slurry.

The application of a diluted hydrated lime slurry has proved as an effective treatment for tack coats protection, because it avoids the *tire pickup* (tires from construction traffic removing the tack), blackening of road markings and other contamination caused by the vehicles and machinery used in placement of asphalt mixtures. It is an advantageous solution compared to the spray pavers, because it does not require such specific machinery, nor does it affect the daily output of laydown operation. The distribution of calcium hydroxide, at the rates commonly used, does not damage the bituminous interface strength, as has been repeatedly verified by direct shear and direct tensile tests, [37, 38, 39, 40].

Essentially, this treatment consists in entrusting the tack coat protection to a small application rate of calcium hydroxide, placed in the form of a highly diluted and stabilized lime slurry, distributed over the binder film. This slurry may be extended immediately after bituminous emulsion breaks and, preferably, when its water has completely evaporated. It is not necessary to wait after this moment to have a completely effective protection of the binder film that must provide adhesion between asphalt layers.

From this experimental section, a large number of specimens (572) were extracted that were used to analyse the effectiveness of the application of the lime slurries in the tack coats [41]. Of all the combinations with different rates of emulsion and lime slurry, only some were used to assess the shear fatigue life of the interface.

Among the set of cores for which the fatigue laws were obtained of the interfaces that are presented in this work, there were two types of tack coats: one emulsion only, with a rate of 450 g/m^2, and the other, with the same emulsion and rate over which a lime slurry was spread at a rate of 30 g/m^2.

3.2. *Test methodology*

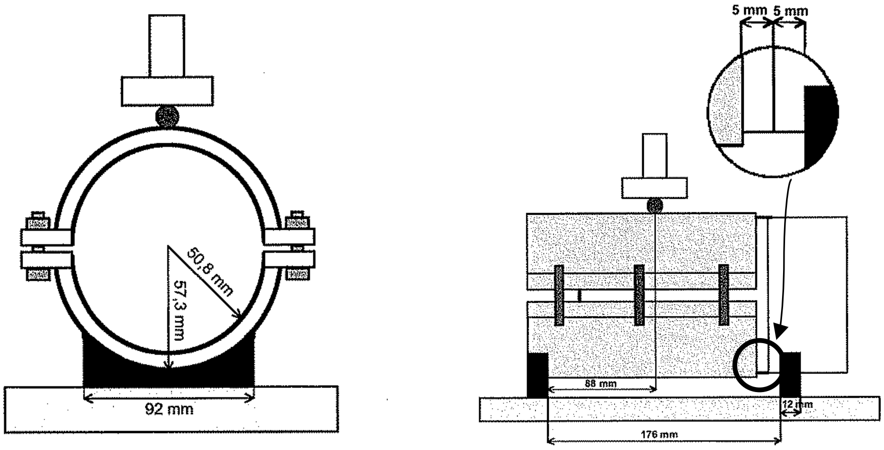
3.2.1. *Equipment*

The test developed for the fatigue characterisation of the bituminous interfaces is a compression cyclic test at controlled stress, using the B test device described in standard NLT-382 (included in the draft of the European pre-norm prEN 12697-48).

The equipment basically consists of a cylindrical clamp with an internal diameter of 101.6 mm, which keeps the bottom layer of the bi-layer specimen secure and leaves the interface with the top layer projecting 5 mm above the end of the clamp, figure 2.

The clamp is placed in a horizontal position on a base with two support points separated 176 mm between inner edges, so that one end of the clamp rests on one of them, while the other support point is positioned away from the clamp, and the top layer of the specimen rests directly on it, leaving the interface at 5 mm from the support.

With this configuration, the system acts as a beam on two supports. On applying a vertical load on the interface at a position equidistant from the support points, it will only be subjected to a shear force as it is very close to the support point.



(a) Front view (b) Lateral view

Figure 2. B test device, NLT-382 Spanish Standard (included in the draft of the European pre-norm prEN 12697-48). (a) Front view and (b) Lateral view.

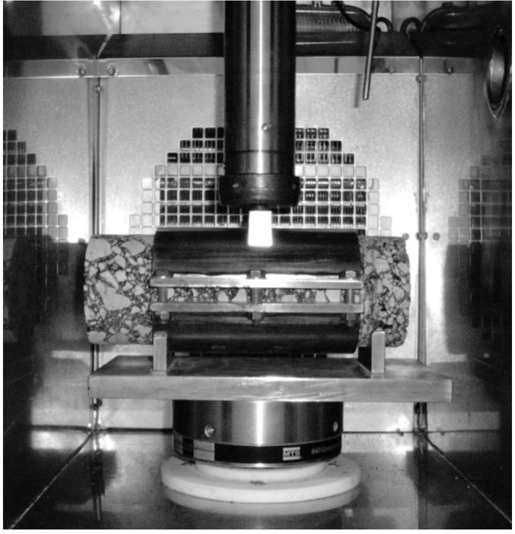


Figure 3. Clamp and position of the core in the press during the test.

3.2.2. Monotonic test

If the load is applied at a constant displacement speed until breakage, as set out in the standard (2.5 mm/min), a load-displacement curve is obtained from which the parameters that govern the response of the interface to a shear force can be obtained, in this case, without the presence of normal stresses:

- Resistance to the shear force:

$$R = \left({F_{max}}/{2}\right)/_{S} \qquad (1)$$

where
R the shear strength in MPa
F_{max} is the maximum breaking load in N
S is the area of the cross-section or area of the interface in mm^2

- Horizontal reaction modulus:

$$K = {\Delta\tau}/_{\Delta u} \qquad (2)$$

where
K is the horizontal reaction modulus, in MPa/mm
τ the shear stress, in MPa
u is the displacement, in mm

In figure 4 it can be seen that K can be defined in different ways, depending on where the slope of the stress-displacement curve is determined. In the first section, the slope of this curve varies gradually until it reaches a maximum value (K_{max}), corresponding to the displacement necessary for the specimen or core to adapt to the exact shape of the clamp and the shear strength of its complete section can be mobilised. Before reaching the maximum stress (τ_{max}), the slope of the curve depends on the load level and allows the determination of different values of the horizontal reaction modulus K. The figure shows the tangents to the stress-displacement curve at 150 kPa (K_{150}), 250 kPa (K_{250}) and secant (K_{sec}).

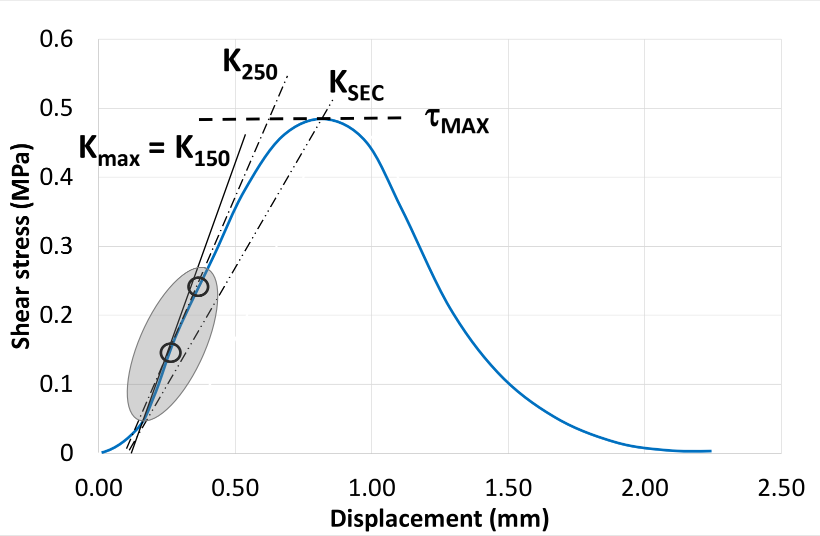


Figure 4. Determination of horizontal reaction modulus (K) on the stress-displacement curve obtained from the monotonic test.

Thus, the adherence of the interface can be characterised by what is called the *shear spring compliance* (AK), defined as the ratio between the relative horizontal displacement between the layers and the stress acting on the surface [42]. AK is, therefore, the reciprocal of the modulus of horizontal reaction:

$$AK = {1}/_{K} \qquad (3)$$

It is possible to ascertain that the threshold values that define the three possible adherence conditions of an interface (complete, partial or none) are, approximately, those indicated in Table 1.

Table 1. Approximate threshold values of K and AK to define three possible bonding interface conditions [14, 48].

CONDITION	K (MPa/mm)	AK (m^3/N)
Full bonding	> 1000	$< 10^{-12}$
Partial bonding	0.1 – 1000	$10^{-8} – 10^{-12}$
Debonded layers	< 0.1	$>10^{-8}$

3.2.3. *Cyclic test*

To assess the fatigue strength of the interface, the load will not be applied monotonically, as stipulated in the standard, but a cyclic compression load will be applied. Specifically, a semi-sinusoidal signal of constant load amplitude will be applied (test at controlled load) at a certain test frequency. The applied load in each cycle will oscillate between a minimum of 100 N, so that there is always a residual load and the press piston does not loose contact with the clamp, and a maximum that will depend on the selected amplitude for carrying out each test, figure 5.

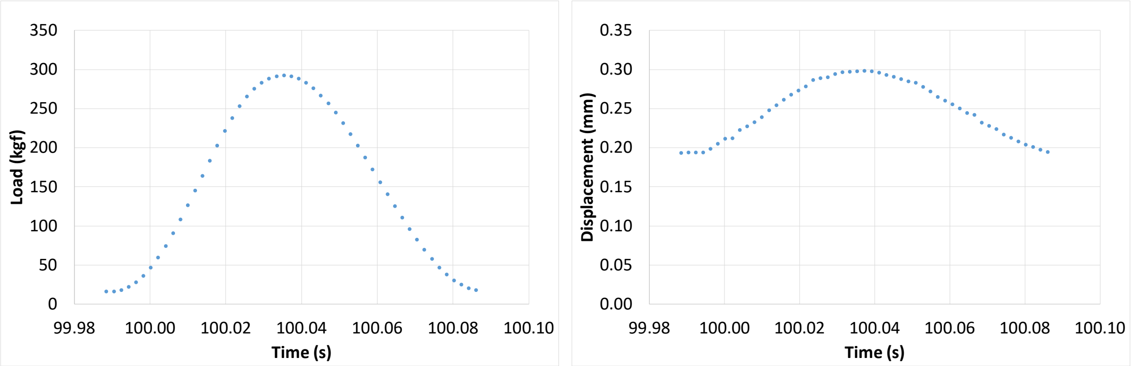


Figure 5. (a) Applied load, and (b) Displacement produced in one cycle at 10 Hz (cycle 1000).

Figure 6 shows the load-displacement loops produced during a test carried out at a frequency of 10 Hz, for the cycles 100, 1000, 10000, 100000, 200000 and failure. The figure shows that the loops practically do not change as the number of cycles increases. In the zoom of figure 6 (b), it can be seen that the area inside the loop is relatively small, so the energy dissipated in each load cycle is also relatively small.

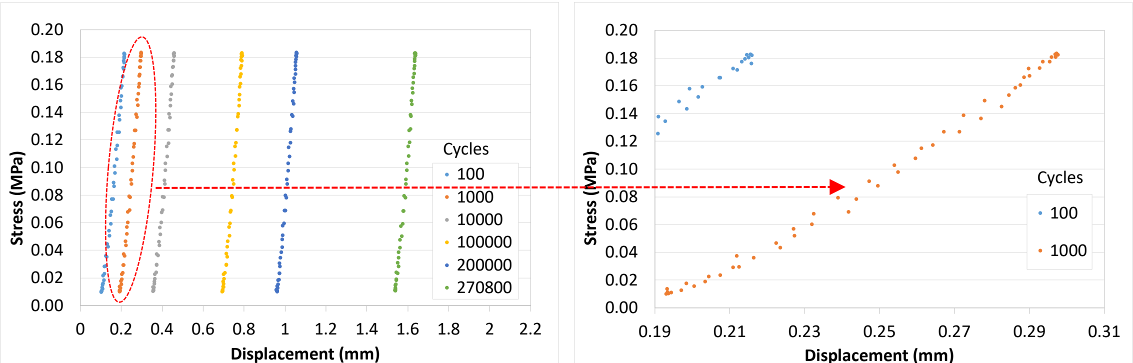


Figure 6. (a) Stress-displacement loops for cycles 100, 1000, 10000, 100000, 200000 and failure (10 Hz), and (b) Detail of a stress-displacement loop for cycle 1000.

The displacement speed at the interface will be different depending on the applied load amplitude and test frequency. In order to obtain results over a wide range of displacement speeds, tests at different frequencies were carried out. The frequencies used were 1, 10 and 20 Hz. In all cases, the tests were carried out at the same temperature of 20°C.

Previously, for each considered interface, a monotonic test will have been carried out (applying the load at a constant displacement speed) in order to obtain the maximum breaking load, so that the maximum applied load in the dynamic test does not, in any case, exceed a certain percentage of this value, usually 10%.

During the test, records are taken of the applied stress amplitude in the interface (obtained by dividing the half of the load amplitude applied in the piston by the cross-sectional area of the core), the produced displacement amplitude and the maximum displacement per cycle in the interface (obtained by multiplying by two the piston displacement, assuming that there are no deformations of the mixture in the vicinity of the support), which progressively increases with the number of cycles.

From these parameters, a dynamic modulus of reaction can be obtained, expressed in MPa/mm, by dividing the stress amplitude by the displacement amplitude in the interface, as well as the displacement speed to which the interface is subjected, which will be approximately twice the speed of the piston (again assuming that there are no other deformations).

From the cumulative maximum displacement, a displacement-number of cycles curve is obtained, as shown in figure 7, from which the number of cycles undergone by the interface can be estimated.

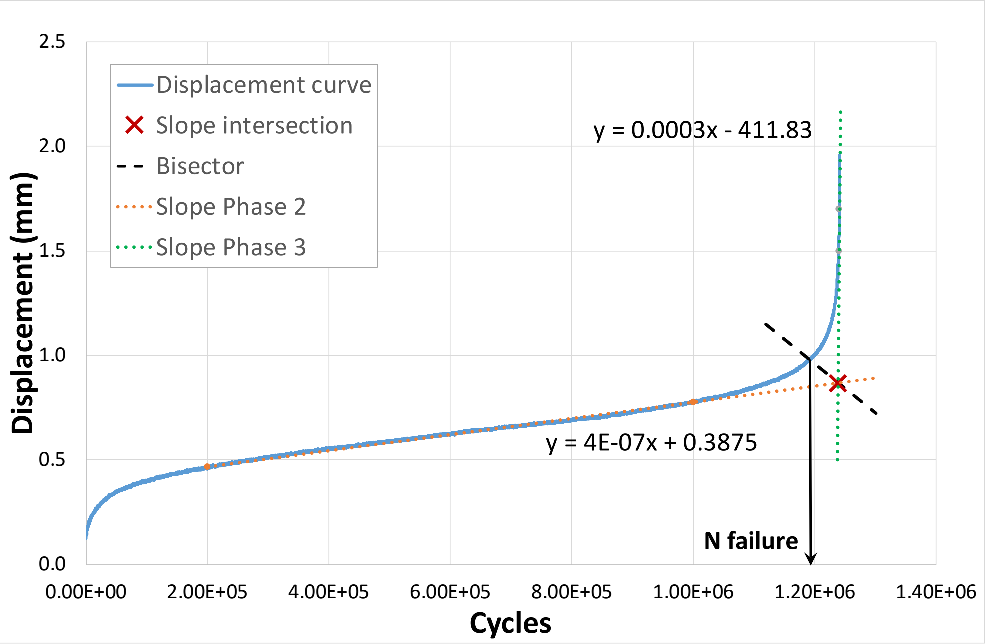


Figure 7. Cumulative maximum displacement per cycle in the interface.

Three clearly differentiated phases can be seen on the curve. In the first, there is a sharp increase of the displacement with the number of cycles; in the second, the increase of the displacement with the number of cycles is linear, a certain slope being maintained, until a number of cycles is reached from which the curve changes rapidly and, in this third phase, the cumulative displacement increases rapidly until the failure of the interface and the separation of the layers.

The failure criterion was established from the intersection with the curve of the bisector of the angle formed by the two straight lines indicated in the figure, corresponding to the tangents in the linear area and in the final part of the curve after the marked change of slope.

4. Results

The results presented in this section were obtained from testing the bi-layer specimens extracted from the experimental section, which contains two types of tack coats: one with C60B3 TER heat-adhesive emulsion only, at a rate of 450 g/m^2, and the other, with the same emulsion and rate, over which a lime slurry is spread, at a rate of 30 g/m^2.

4.1. Monotonic tests

Firstly, monotonic tests were carried out using device A included in standard NLT-382, equivalent to the classic Leutner equipment [10], with a displacement speed of 50 mm/min. The tests were carried out after 18 and 132 days after the application of the tack coat and the laying of the wearing course.

Figure 8 shows, by way of example, the stress-displacement curve obtained for one of the specimens (tack coat with emulsion only at 132 days), on which the obtaining of R and K_{max} has been indicated. The average results are shown in table 2, corresponding to the testing of 3 specimens, for the two types of tack coat and for each one of the considered ages.

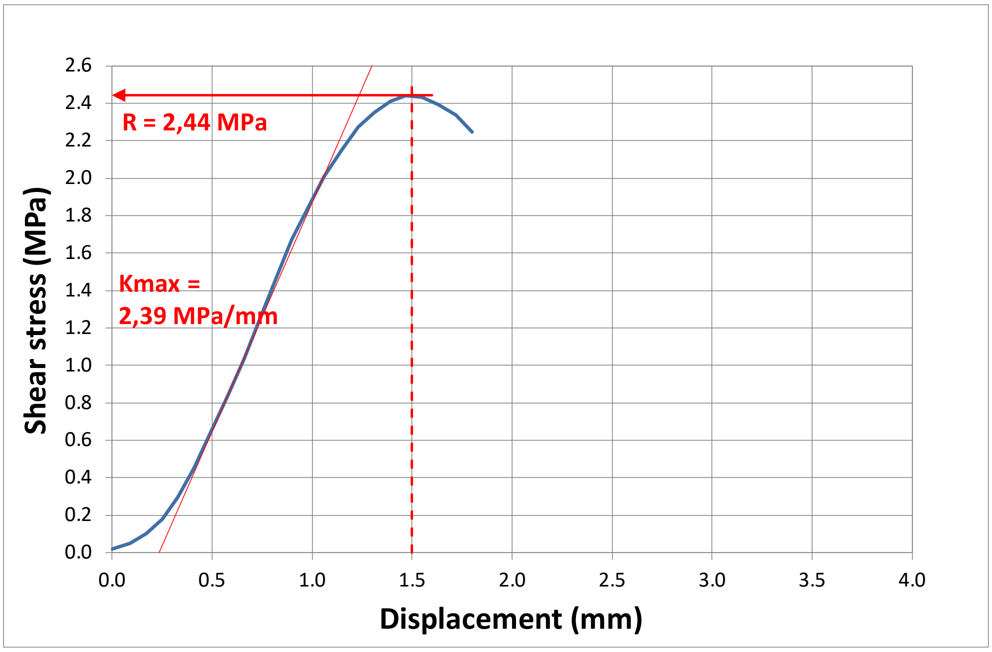


Figure 8. Stress-displacement curve obtained from monotonic test with device A, at 50 mm/min (tack coat with emulsion only, at 132 days).

Table 2. Average values of strength (R) and reaction modulus (K_{max}) obtained from monotonic test with device A, at 50 mm/min, for each type of tack coat, at 18 and 132 days.

Tack coat	18 days		132 days	
	R (MPa)	K_{max} (MPa/mm)	R (MPa)	K_{max} (MPa/mm)
Emulsion	1.37	1.42	2.44	2.32
Emulsion + lime slurry	2.33	2.22	2.59	2.54

The results show that the use of lime slurry in the tack coats allows higher short-term strengths to be achieved and provides higher stiffness to the interface. However, after a certain time, although the tack coats with lime slurry continue to show higher strength and stiffness with respect to the tack coat with emulsion only, the differences between both are much smaller than those observed short-term.

The question that arises is the following: could the higher stiffness of the interfaces with lime slurry have a negative influence on its fatigue life? This is what the cyclic tests described below intend to find out.

4.2. Cyclic tests

As indicated in section 3.2.3 for the fatigue characterisation of the bituminous interfaces, compression cyclic test at controlled stress were carried out, using the B test device described in standard NLT-382.

For each one of the considered tack coats (emulsion only or emulsion and lime slurry), tests were conducted considering a minimum three load amplitude ranges, applied at a certain frequency.

From the cyclic tests are obtained the evolution of the reaction modulus and the evolution of the total displacement with the number of cycles. Figures 9 and 10 show the results obtained from a representative core for three load amplitudes (190, 240 and 330 kgf in this case), at a frequency of 10 Hz and for one of the tack coat types (tack coat with emulsion and lime slurry). The results from just one core are shown for clarity.

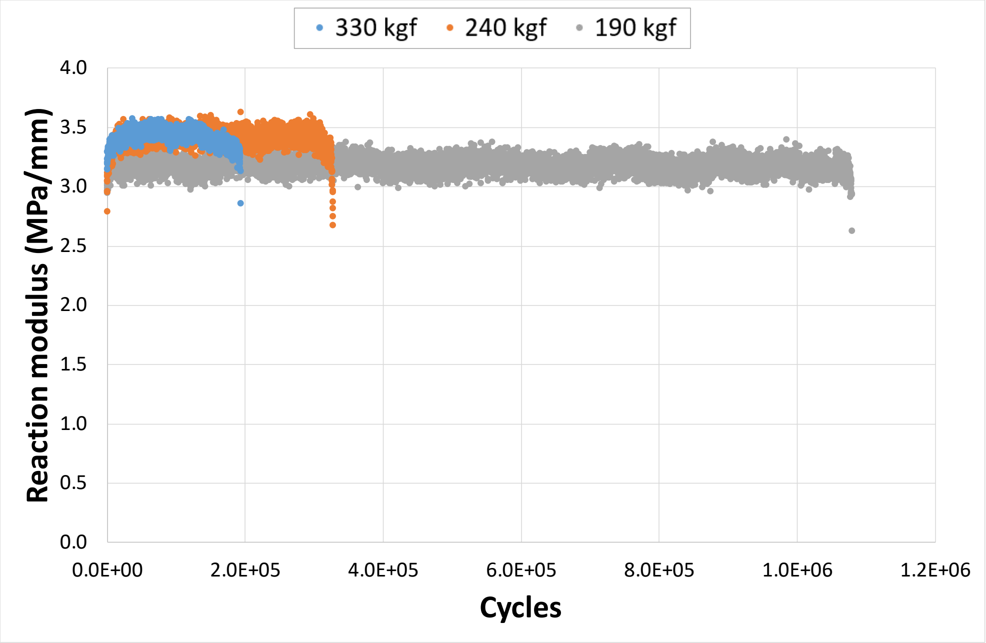


Figure 9. Evolution of reaction modulus with number of cycles for a core tested at 10 Hz, for three load amplitudes (190, 240 and 330 kgf).

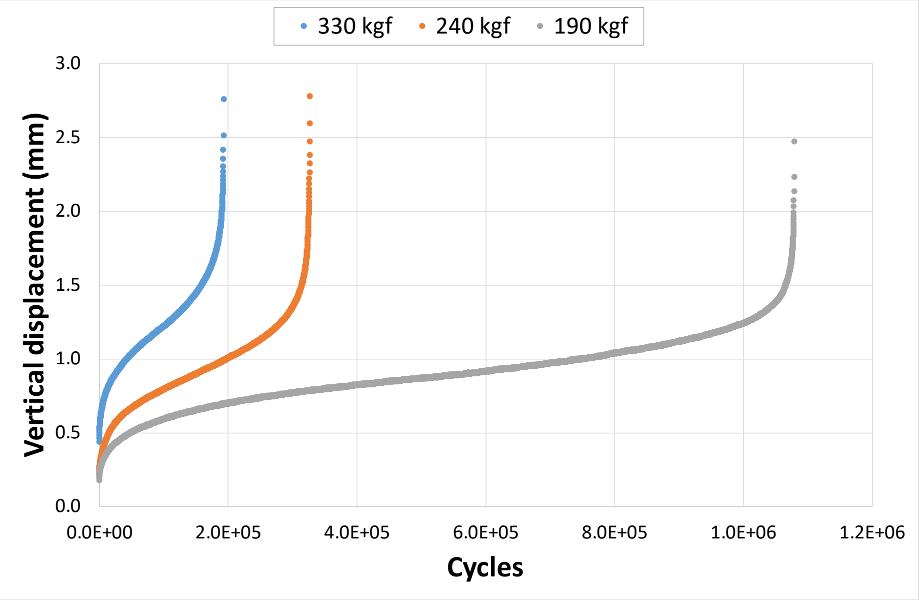


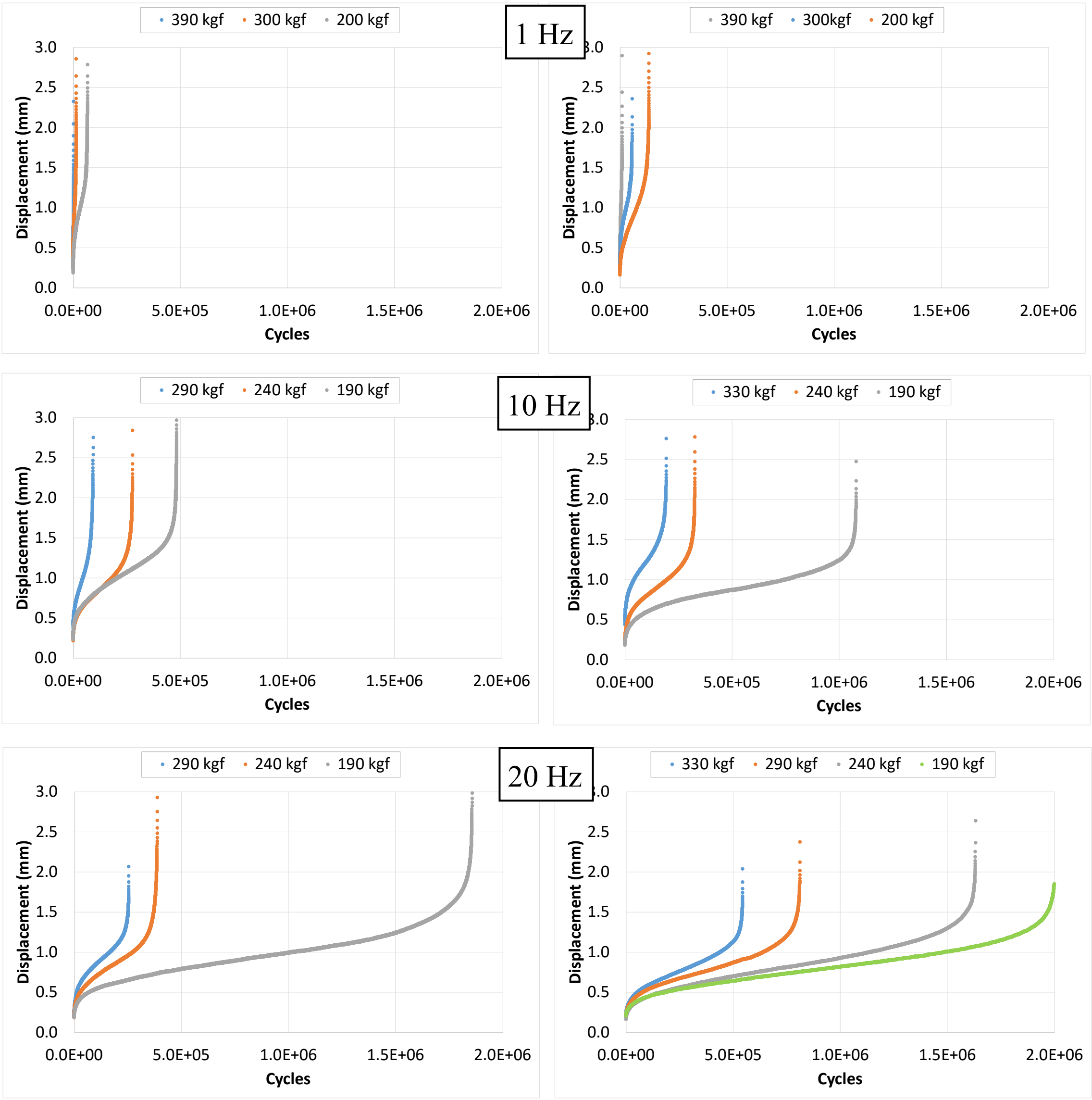
Figure 10. Evolution of cumulative maximum displacement in the interface with the number of cycles for a core tested at 10 Hz, for three load amplitudes (190, 240 and 330 kgf).

From the displacement and the test frequency, it is possible to determine the displacement speed to which the interface is subjected during the test.

This speed is obtained by dividing the displacement that occurs in each cycle by half of the period. As the speed varies with each cycle, the speed considered has been obtained by averaging the speed applied in all cycles.

If the test is carried out at a single frequency, it is possible that the displacement speeds in the interface, for the load amplitudes used, are very different from the displacement speeds that occur under service conditions in the pavement when subjected to a certain load that is moving over it at a certain speed.

In order to have results over a wide range of displacement speeds in the interface, the test was carried out at different frequencies. Figure 11 shows the evolution of the total displacement with the number of cycles (for the representative core), for the frequencies of 1, 10 and 20 Hz and for each one of the tested tack coat types.

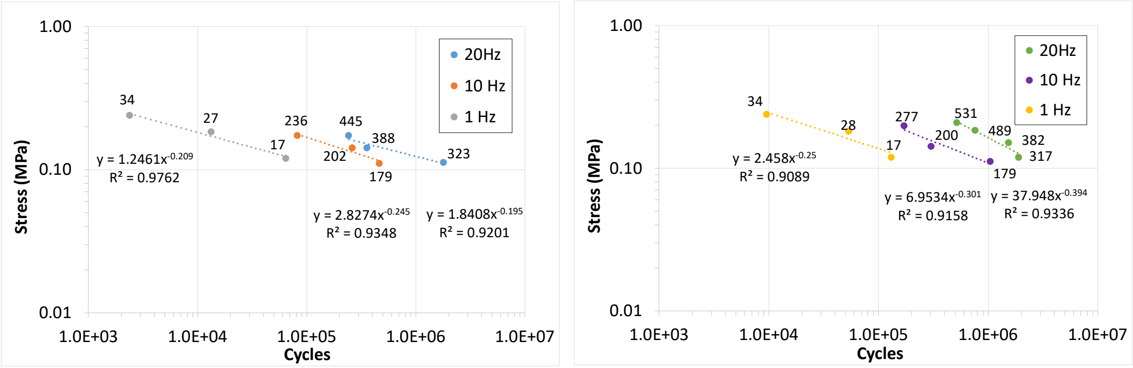


(a) (b)

Figure 11. Cumulative maximum displacement in the interface for the frequencies 1, 10 and 20 Hz, for (a) tack coat with emulsion and (b) tack coat with emulsion and lime slurry.

Applying the considered failure criterion (bisector of the angle of the tangents in phases 2 and 3), it is possible to determine the number of cycles to failure from which the shear fatigue laws of the interface will be obtained, figure 12.

The average speed of displacement at the interface of each representative point has been indicated in the corresponding fatigue laws.



(a) (b)

Figure 12. Fatigue laws for frequencies 1, 10 and 20 Hz, for (a) tack coat with emulsion and (b) tack coat with emulsion and lime slurry.

4.3. Application of the fatigue laws obtained when calculating the critical life of the pavement

Once the shear fatigue laws of an interface are obtained, it is relatively easy to determine the number of load applications that it will withstand, provided that the shear stress level and the displacement speed to which it will be subjected under service conditions are known, bearing in mind the structure of the pavement and the load conditions.

But as mentioned previously, the stress distribution that occurs in a bituminous interface within the pavement structure depends on many factors that have a certain interdependence between them. Thus, the load conditions (magnitude and speed of application) and environmental conditions (temperature, essentially), must be taken into consideration in addition to the characteristics of the interface itself (strength and stiffness).

These latter can be obtained from monotonic shear tests, like those conducted using devices A and B included in standard NLT-382. But these tests are carried out at a certain displacement speed and in the absence of normal stresses, that is, in conditions that are somewhat different to the true conditions in the pavement interface.

In order to be able to consider the contribution of the normal stress present at the most unfavourable point of the interface, which will affect both its stiffness and strength, as well as the effect of the displacement speed between its edges, which will depend on the load speeds, Ortiz et al. (2020) [9] developed a semi-empirical calculation method that allowed an estimation to be made of the true level of the shear stresses to which the interface will be subjected, from the strength and stiffness obtained in a direct shear test without normal stress carried out in the laboratory.

Figure 13 shows the nomogram proposed by Ortiz et al. for certain load assumptions: single 10 t axle with a quasi-rectangular load footprint (of 285x205 mm^2), travelling at 60 km/h that starts braking with the wheel partially locked. This load acts on a flexible pavement, formed by a granular layer of 25 cm and bituminous mix layers of 30 cm (section 121 of standard 6.1-IC), over which is spread a new surface layer, of variable thickness (2.5 and 5 cm were considered in this case), thus configuring the interface that is to be analysed. The bituminous mixes have been characterised from their modulus of elasticity and Poisson coefficient at a temperature of 20°C, figure 14.

Specifically, the nomogram consists of 5 steps:

1) Graph (a) allows obtaining the value of $K\sigma_n$ from $K\sigma_0$ and the thickness of the layer, that is to say, it takes into account the effect of normal stress at the critical point. This is obtained using the Canestrari equation of $K\sigma_n$ as a function of $K\sigma_0$, σ_n and τ, and the results from BISAR software that allows calculating the most critical σ_n/τ ratios.
2) Graph (b) takes into account the influence of the displacement speed between the edges of the interface, v_x, which is calculated from the results of BISAR software. This step also considers a relationship derived from Diakharé formula for K as a function of the load speed.
3) Graph (c) allows the shear stress under service conditions, σ_{xz}, to be calculated from the K value and the layer thickness using BISAR software.
4) Graph (d) is used to obtain the shear strength of the interface, $R\sigma_0(v_x)$, taking into account the displacement speed v_x. The curves have been drawn from the Canestrari equation that relates the shear stress τ_{vx} with displacement speed v_x.
5) Graph (e) has been developed to obtain the shear strength R taking into account the effect of normal stress, using the Canestrari formula that estimates the contribution of the normal stress σ_n to the shear strength of the interface $R\sigma_n$.

The different Canestrari and Diakhaté equations, as well as a more detailed explanation of the calculation method, are collected in [9].

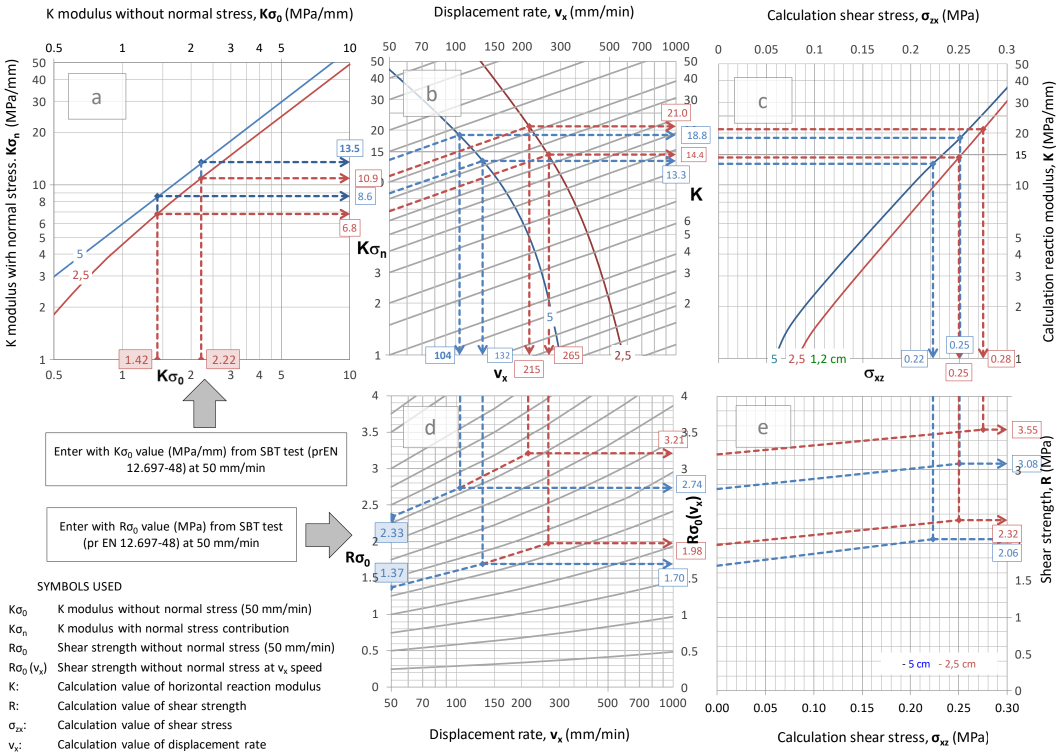


Figure 13. Application of the nomogram to obtain speed and shear stress in the interface under service conditions, from reaction modulus (K) and strength obtained from laboratory tests (at 50 mm/min) on cores at 18 days, considering two different thicknesses (2.5 and 5 cm).

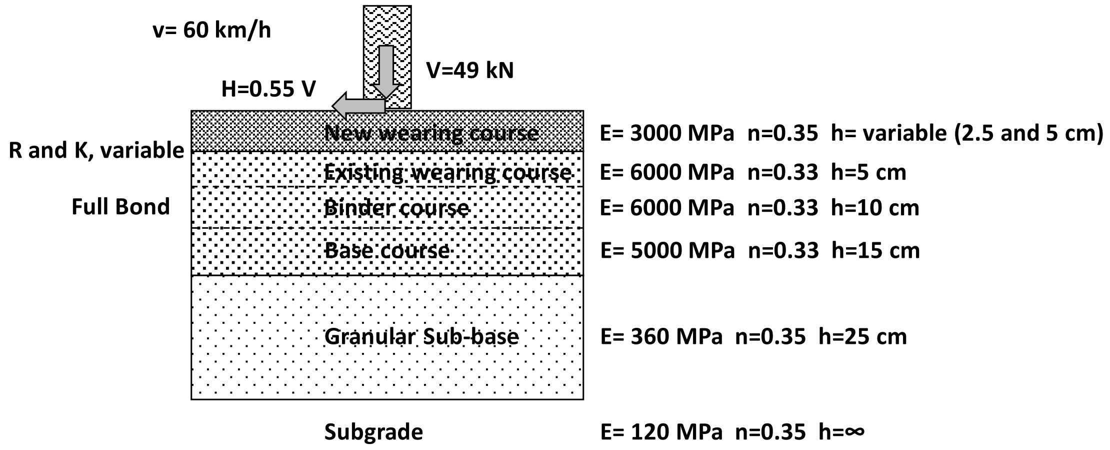


Figure 14. Loading hypothesis and pavement structural section considered in the obtainment of the nomogram.

Inputting the horizontal reaction modulus (K) and shear strength (R) measured in the shear test at 50 mm/min (device A) into the nomogram, it is possible to obtain the displacement speed and the shear stress of the interface, as well as the calculation shear strength. Table 3 includes those values obtained from each one of the input values of each one of the interfaces (emulsion only, or emulsion and lime slurry).

Table 3. Speed and shear stress in the interface under service conditions, for all the studied variables (tack coat type, age and layer thickness).

Thickness	**18 days**		**Nomogram**		**132 days**		**Nomogram**	
2.5 cm	R (MPa)	K_{max} (MPa/mm)	Speed (mm/min)	Shear Stress (MPa)	R (MPa)	K_{max} (MPa/mm)	Speed (mm/min)	Shear Stress (MPa)
Emulsion	1.37	1.42	265	0.25	2.44	2.32	214	0.276
Emulsion + lime slurry	2.33	2.22	215	0.275	2.59	2.54	204	0.282
Thickness	**18 days**		**Nomogram**		**132 days**		**Nomogram**	
5 cm	R (MPa)	K_{max} (MPa/mm)	Speed (mm/min)	Shear Stress (MPa)	R (MPa)	K_{max} (MPa/mm)	Speed (mm/min)	Shear Stress (MPa)
Emulsion	1.37	1.42	132	0.223	2.44	2.32	101	0.253
Emulsion + lime slurry	2.33	2.22	104	0.251	2.59	2.54	97	0.258

With the aim of obtaining the number of load cycles that each of the coats considered could bear, in the above-mentioned hypotheses, it will be sufficient to enter the graph of the fatigue laws corresponding to each coat with the shear stress that will be produced at the interface (table 3) until finding the law that for that stress, has the displacement speed obtained. Figure 15 shows how to do it in the case of coat with emulsion only, from the characteristics of the cores tested at 18 days. In doing so, it is being accepted that the displacement speed obtained in both monotonic and dynamic tests can be considered equivalent, although conceptually they are not exactly the same.

However, it is difficult to estimate the number of cycles with some precision directly on the graph. In order to do this correctly, iso-speed curves have been used, which join points of equal speed of the fatigue laws obtained at different frequencies. Figure 15 shows the iso-speed curve 265 mm/min (speed corresponding to the tack coat considered).

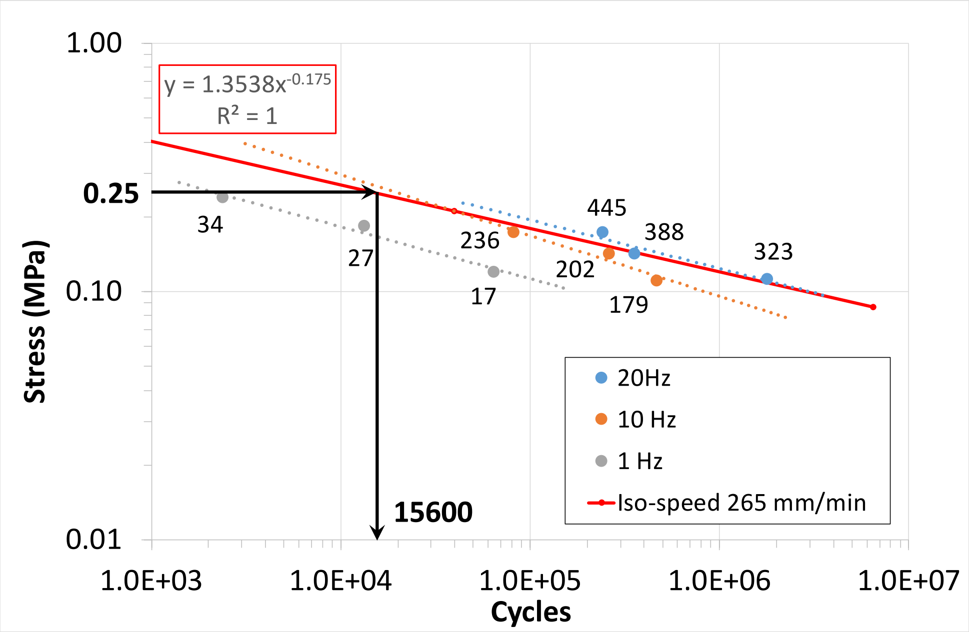


Figure 15. Iso-speed curve (265 mm/min) for tack coat with emulsion from cores extracted at 18 days.

The iso-speed curves are determined from the speed-cycle curves. Figure 16 shows the iso-speed lines of 100, 200 and 300 mm/min. These three speeds cover the range in which the speeds obtained (shown in table 3), fall.

Transferring the points of intersection of these horizontal lines with the speed-cycle curves corresponding to each test frequency, to the stress-cycle fatigue laws, the iso-speed curves will be obtained, figure 17.

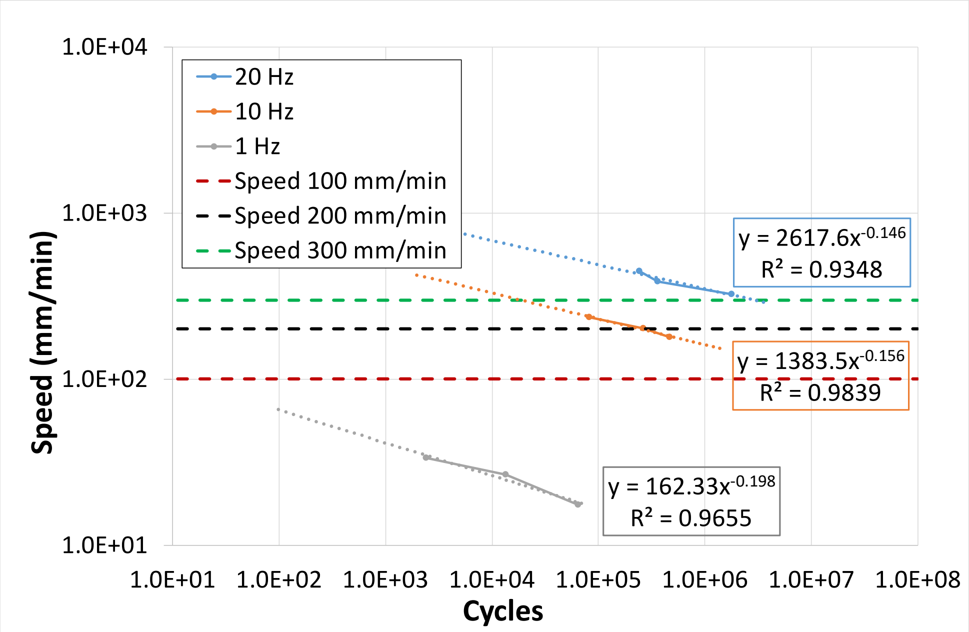


Figure 16. Speed-cycles curves for the tack coat with emulsion and straight lines of iso-speed (100, 200 and 300 mm/min).

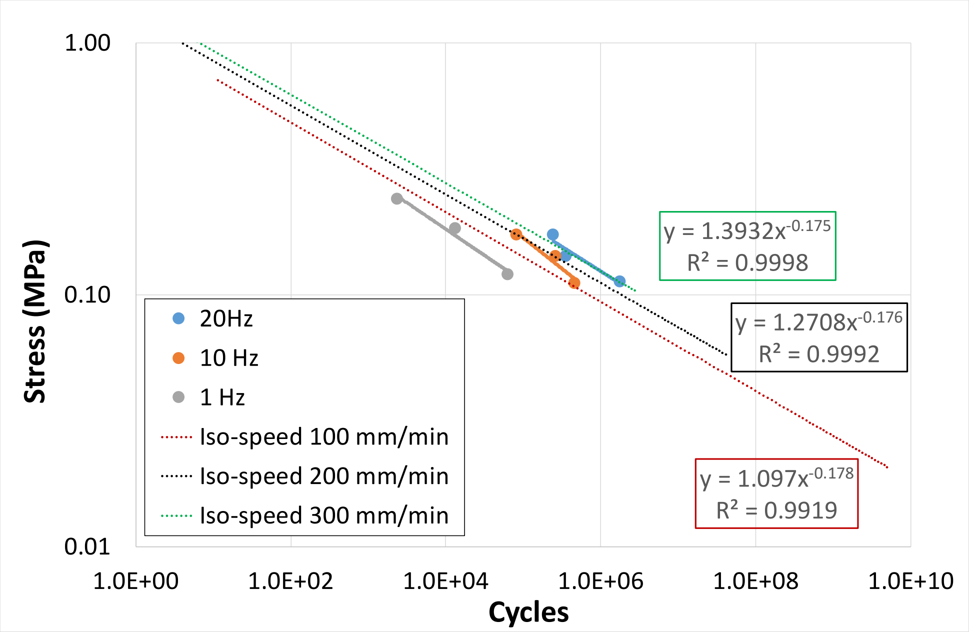


Figure 17. Iso-speed curves (100, 200 and 300 mm/min) in a stress-cycles plot, for the tack coat with emulsion.

Table 4 shows the number of cycles obtained for the type of coat and age considered, based on the corresponding values of shear stress and displacement speed that will occur at the interface, for the two layer thicknesses considered.

Table 4. Cycles obtained at the interface under service conditions, for all the studied variables (tack coat type, age and layer thickness).

	Cycles	
Thickness 2.5 cm	**18 days**	**132 days**
Emulsion	15600	6400
Emulsion + lime slurry	19800	16500
Thickness 5 cm		
Emulsion	11200	4000
Emulsion + lime slurry	13600	11300

These results show that the greater stiffness of the interfaces provided by the tack coat with emulsion and lime slurry compared to those with emulsion only, observed from the monotonic tests carried out on the cores, does not negatively affect the fatigue life of the interfaces. At early ages and as the thickness of the top layer increases, the differences between the two types of coats are relatively small, but in the longer term, when the emulsion has fully cured, the emulsion-lime slurry interfaces withstand a greater number of cycles than the emulsion-only interfaces.

Although it may seem that the number of cycles to failure at the interface is relatively small, in reality it is not, since the load considered for this calculation (a vertical load of 49 kN corresponding to a single 10-tonne axle, travelling at 60 km/h, and initiating braking with the wheel partially locked producing a horizontal force of H=0.55V) will only correspond to a relatively small percentage of the trucks travelling on the road. Without knowing the number of loads occurring in these conditions, it is very difficult to compare whether the interface is more or less critical than the most stressed layer to flexural-tensile loading under the same vertical load without the braking effect (being this last condition much more frequent over the service life of the pavement).

However, if we assume that the pavement considered in the calculations has been designed to withstand 10^7 cycles of the vertical type load, and that according to the results obtained an interface could withstand in the order of 10000 cycles in the load conditions equivalent to the calculation hypotheses considered, these conditions would have to occur in 0.1% of the trucks circulating on the pavement so that the life of the mix layer and that of the interface were similar. Therefore, in braking areas or in small radius curves, for example, where this percentage of trucks could be higher than 0.1% of the total, the interface would be more critical than the asphalt layer.

Furthermore, it should be taken into account that if the loads move on the pavement at other speeds than those considered, the stresses generated will also be different: at higher speeds, lower stresses, and vice versa.

A final consideration should be made in this analysis of lives. The fatigue laws have been obtained from a test in which no normal stresses have been applied. If these had been applied, the fatigue laws obtained would probably be different: under the same load amplitude, the displacements that would be obtained in a cyclic test applying normal stress would be smaller than without normal stress, the displacement speeds would also be smaller, and the number of cycles endured would be greater.

Therefore, by considering on the one hand the real service stresses that take into account the contribution of normal stress, obtained from the nomogram, and on the other hand the fatigue laws obtained with tests without normal stress, the most critical combination that would lead to obtaining results on the safety side is being considered.

Obviously, from the nomogram, the service stresses could also be obtained without the contribution of normal stresses, which will be somewhat lower than those taking into consideration the normal stresses, and which combined with the laws obtained without normal stresses, would give longer lives, but this would be a clearly unrealistic situation.

5. Conclusions

The degree of adherence between two layers of bituminous mix forming part of a pavement structure can be evaluated with the shear strength and the horizontal reaction modulus obtained from shear tests carried out at a given displacement speed and temperature.

The stiffest bonds will also be the strongest, will absorb more stresses and will contribute to reducing overall pavement stresses, particularly in the overlapping bituminous layers, increasing their durability.

But if the stronger and stiffer interfaces are going to be more stressed, the question raised in this study is whether this can negatively affect the fatigue behaviour. For this purpose, the shear fatigue behaviour of two interfaces with different stiffness has been analysed, based on a cyclic compression test, carried out at controlled stress, using test device B described in the NLT-382 standard (included in the draft of the European pre-norm prEN 12697-48). The tests have been carried out at three load amplitude ranges, applied at different frequencies.

From these tests it has been possible to obtain the fatigue laws for each type of coat. But since different load amplitudes have been used for each frequency, the displacement speed generated in the interface is not constant and so, the iso-speed curves are obtained and used to compare the results under constant speed.

When fatigue life of two interfaces with different strength and stiffness have to be compared, it should be taken into account that the stress to which the interfaces will be subjected and the displacement speed at the interface, will be different. These interdependencies make the response to which interface has better shear fatigue behavior far from evident.

This is the reason why these iso-speed curves have been combined with the calculation method previously developed by the authors to obtain the number of cycles that each of the interfaces considered would withstand, under certain load hypotheses. This calculation method allows to obtain the stresses present at the interface under service conditions and, therefore, to consider both the effect of normal stress and that of other variables such as the displacement speed between the edges of the interface.

The results of the monotonic tests reveal that with the use of the lime slurry in the coats, greater resistance and stiffness are reached in the short term with respect to the coat that has only emulsion, although after a certain time, the differences between both coats become smaller.

The dynamic tests have shown the importance of considering the speed of displacement between the edges of the interface, in addition to the level of shear stresses. The shear fatigue life of each interface is analyzed as a function of the characteristics that affect its in-service response rather than at arbitrary and equal stress and displacement speed in all cases. As shown, the crucial characteristic is stiffness, because each interface will be subjected to different stresses and different displacement speed in service, depending on its stiffness (measured under certain test conditions, i.e. at a determined loading speed).

It has been observed that the greater stiffness of the interfaces provided by coat with emulsion and lime slurry compared to those with emulsion only does not negatively affect the fatigue life. On the contrary, emulsion-lime slurry interfaces withstand a higher number of cycles than emulsion-only interfaces, especially when the tack properties are considered once the emulsion has completely cured.

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