Effect of aggregate type on the fatigue durability of asphalt mixtures

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Abstract: Effect of aggregate type on the fatigue behaviour of asphalt mixture is an important variable to ensure greater durability of the pavements over time. This study presents the main results about the evaluation of the physical properties of different aggregates on the fatigue behaviour of asphalt mixtures. Two fatigue tests were used for this study, one standardized and another, which was recently developed and evaluates dissipated energy during the cracking process of the asphalt mixtures (EBADE® test). Three types of aggregates were used and adjusted to a semi-dense aggregate gradation: two of fluvial type (AF1 and AF2) and one from quarry (AC). Two different shredding processes were used to obtain them. The results obtained show that there is a greater relationship between the shape and texture of the fine aggregates and the fatigue behaviour of the mixtures. It was also showed that the greater the thickness of the mixture in the pavement structure, the more influence these properties have. Likewise, the shape and texture properties of the fine aggregate influence the ability of asphalt mixtures to dissipate energy during the process of fatigue damage.

Keywords: aggregates, shape, texture, EBADE® test, stiffness, fatigue, durability

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1. INTRODUCTION

Most of the roads and highways are built with asphalt mixtures due to they provide good mechanical properties, smoothness and durability [1]. However, the performance of asphalt mixtures are conditioned to environmental conditions, traffic loads and mainly, the properties of their materials (mineral aggregates, asphalt binder and filler) [2]. In relation to the aggregates, their properties (physical and mineralogical) can affect the mechanical behavior of an asphalt mixture. In this context, one of the main damages that affect asphalt pavements is fatigue cracking [3, 4], which is the reason why the study of this phenomenon has become a fundamental aspect to consider in the durability of pavements [5]. A material becomes fatigued when it cracks as a result of the accumulation of individual repeated loads whose magnitudes are below the ultimate strength of the material [6]. Numerous efforts have been made to understand the phenomenon of fatigue in asphalt mixture. This phenomenon is evaluated in laboratories through different standardized methods which are based on reproducing the state of stress that occurs in the layer subjected to traffic [3, 7]. These methods involve a long implementation period and are characterized by subjecting different types of asphalt specimens to cyclic loading applications, in which the applied deformation or tension is maintained constant until the failure of the mixture takes place. The traditional criterion of fatigue failure of standardized trials is the 50% reduction in stiffness [8- 10]. However, other researchers consider that the dissipated energy in the fracture process is an indicator of a better fatigue performance of the mixture. When there is a higher quantity of energy dissipated in the fracture process, this is considered an indicator of a better fatigue performance of the asphalt mixture [11-14]. The EBADE® test developed in the laboratory of the Technical University of Catalonia, is a new test which incorporates dissipated energy in the fracture process as a measurable variable. By using this test method, research already carried out conclude that asphalt mixtures with more dissipated energy in the cracking process require more energy to break the mixture and therefore show a better fatigue behaviour [14].

On the other hand, asphalt mixtures correspond to a composite material whose matrix is usually composed approximately of 5% asphalt binder and 95% aggregates; consequently, the influence of aggregates on the performance of the asphalt mixture is very important [15]. Pan et al. [16] have shown that there is a good correlation between the properties of the aggregates specified by the SHRP and the mechanical behaviour of the asphalt mixtures. In this context, Aragão et al. [17] indicated that the characteristics of the coarse aggregates correlated better with the resistance to the damages evaluated. The authors also concluded that the superficial texture of the particles showed a strong correlation with the performance of the asphalt mixtures and recommended including this parameter in the specifications of asphalt mixture design. Hu et al. [15] demonstrated that particle size was related with the deformations that occurred in the asphalt mixture, indicating that if the size of the particles increases, the deformations in the mastic do as well. Other authors have pointed out that the properties of the asphalt mixture both during the compaction process and in service are influenced by the geometric characteristics of the aggregates, thereby indicating that the particle size, shape index and the angularity of the aggregates are factors to be considered in this order of importance [18]. On his behalf, Aragão et al. [17] showed that the modulus of stiffness, especially at intermediate and low frequencies, is affected by the morphological characteristics of the aggregates. In recent years, the study of the morphological properties of aggregates through image analysis techniques has gained relevance; a few examples of this are Computer Particle Analyzer, Video Imaging System (VIS), Camsizer, Wipshape, Aggregate Imaging System (AIMS) [17]. By using image analysis technologies, Sukhwani et al. [19] determined an angularity and texture gradient, whereby they predicted that granitic aggregates possess an elevated texture and consequently may show better adherence characteristics with asphalt binder, compared to limestone aggregates which showed lower angularity and texture gradients. Zhang et al. [20] defined an index that combines the effects of angularity and texture in coarse aggregates; this index would be beneficial as an aggregate selection parameter. Other studies have demonstrated that the physical parameters of the aggregates such as the Particle Index determined by the method proposed by the ASTM-D3398, as well as the shape parameters proposed by Zingg [21], showed interesting correlations in regard to the stiffness and resistance to cracking at low temperatures [22], and the adhesion and cohesion properties of aggregate-binder matrix [23]. As noted above, it has been revealed that getting to know how the physical and morphological characteristics of aggregates influence the fatigue performance of an asphalt mixture through simple procedures, would allow to design and select more efficient asphalt mixtures in fatigue performance. Through this design and selection, the hope is to contribute to the creation of more resistant asphalt mixtures.

This study shows the influence of aggregate type on the fatigue resistance of asphalt mixtures. Three types of aggregates have been studied which differ from each other by their physical, morphological and mineralogical characteristics. The fatigue performance of the asphalt mixtures have been evaluated through a standardized test method and a new test procedure (EBADE®), whereby the dissipated energy in the fracture process of the asphalt mixtures have been evaluated. Additionally, the results of the effect of aggregate shape and texture properties on pavement structure durability are presented, defined through a fatigue life analysis given by a mechanistic-empirical design methodology.

2. MATERIALS AND METHODS

2.1 Materials

The asphalt binder used in this study was a CA24 conventional binder whose characterization in accordance with Chilean standard is showed in Table 1.

Three types of aggregates were evaluated; two of fluvial origin, AF1, and AF2 and one of quarry origin AC. AF1 and AF2 differ in terms of their shapes, due to the production process. AF1 and AC, whose particles are more irregular, were obtained through a final cone crushing process, while AF2 was obtained through a final impact crushing process, Figure 1.

AF1 and AF2 were extracted from the same source and are mainly composed of the particles dolomite, basalt, dacites, andesites, rhyolites, sandstone, quartz, and quartzite. The quarry aggregate, AC, is primarily composed of quartz, biotite and iron oxides. A chemical analysis of the aggregates was performed using Scanning Electron Microscopy (SEM). It was observed that both the quarry aggregate and the fluvial aggregates are of quartz type and their average silica content corresponds to 59.9% for AF1, 59.1% for AF2 and 63.3% for AC.

The aggregates were characterized for their use in an asphalt mixture, Table 2. The average size measurement of the filler particles was performed through an image analysis by using the light scattering phenomenon. This methodology acts through the alteration of the direction and intensity of a beam of light that strikes an object due to the combination of reflection, refraction, and diffraction. The average values of the particles obtained were 708nm for AF1, 298nm for AF2 and 351nm for AC.

The morphology of the aggregates was determined by the Zingg method, which it corresponds to a procedure that classifies different particles of coarse aggregates according to their shape [21]. This method is based on the measurement of length, width and thickness of particles greater than 5 mm in order to obtain four parameters: shape factor, sphericity factor, elongation ratio and flatness ratio according to the equations described in the protocol [21]. With the elongation and flatness relationships, four aggregate shapes are defined: disk, rod, cubical, and blade. Table 3 shows values of the three types of aggregates according to Zingg method, classifying as laminar for the aggregate AC, disk-like for AF1, and cube-like for AF2.

Particle shape and texture characterization were obtained according to Particle Index (PI), determined by the ASTM-D3398 standard. PI is a parameter that represents a global measurement of the shape and texture characteristics of aggregates. PI values were calculated in accordance with this standard (Criterion I) as well as with two different criteria defined to this study (Criterion II and III) to explain the phenomenon observed in the mechanical performance of the mixtures. The criteria used for the calculation of the PI and its results are described in Table 4.

2.2 Mixtures design

A semi-dense asphalt mixture was selected according to Chilean Standards, with a maximum aggregate size of 12.5 mm (Table 5). An optimal asphalt binder content of 5.2% on weight of aggregates was obtained using the Marshall method. This optimal binder content was used in the three asphalt mixtures manufactured (AF1, AF2 and AC). The mixing and compaction temperatures were 155ºC and 145ºC, respectively.

2.3 Test methods

The fatigue laws of each asphalt mixture were determined by applying the procedure described in the standard UNE-EN 12697-24, Annex E. Cylindrical specimens were used to characterize the behaviour of the asphalt mixtures by subjecting them to repeated diametral compression loading. The deformations produced in the direction perpendicular to the load were registered. The test was performed at a temperature of 20°C with a loading frequency of 10 Hz and stress levels of 200, 250 and 300 kPa. The failure criteria selected was defined as the necessary loading cycle when the deformation reached twice its initial value, obtained in cycle 100. The deformation for each load application is calculated by applying Equation 1.

$$\varepsilon_0 = \left[\frac{2\Delta H}{\Omega}\right] x \left[\frac{1+3\nu}{4+\pi\nu-\pi}\right] \quad (1)$$

Where, ε_0 is the tensile strain in the center of the sample in (μℇ), ΔH the total horizontal deformation in (mm), Ω is the diameter of the sample in (mm) and ν is the Poisson ratio.

To obtain the fatigue law of the asphalt mixture, the value pairs were considered: initial deformation and failure cycle for each of the tested load amplitudes. Lastly, using a least-squares approach, the fatigue law is obtained using Equation 2.

$$\varepsilon = a \cdot \mathcal{N}^{-b} \tag{2}$$

Where ε is the tensile strain, N is the number of strain applications to failure; a, b are the fatigue growth rate coefficients.

For each fatigue law (AF1, AF2 and AC), 18 cylindrical fatigue samples were manufactured by gyratory compactor (diameter 100 mm) applying the same compaction energy (100 cycles at 600kPa and 0.82º). For each stress level evaluated, the average value of six samples was calculated.

The stiffness modulus has been determined by indirect tensile strength (ITS) test described in the standard UNE-EN 12697-26, Annex C. This methodology consists of applying a sinusoidal pulse loads and periods of rest to produce a controlled horizontal deformation in cylindrical specimens. The stiffness modulus is obtained by applying Equation 3.

$$S_M = \frac{F \cdot (v + 0.27)}{(z \cdot h)} \tag{3}$$

Where S_M is the stiffness modulus measured in (MPa), F is the maximum vertical load in (N), z is the amplitude of horizontal deformation in (mm), h is the average thickness of the specimen in (mm), and v is the Poisson ratio.

For each type of mixture, five cylindrical samples (diameter 100 mm) were manufactured by gyratory compactor applying the same compaction energy (100 cycles at 600kPa and 0.82º). The test was performed at 20°C.

The EBADE® test was used to determine the dissipated energy in the fracture process of the asphalt mixtures during the development of fatigue damage. This test consists of performing a scan for deformations in a cyclic tension-compression test over a prismatic specimen, where two notches were made in the central area to reduce the area of the specimen in the middle section in order for failure to take place, Figure 2a. To carry out the EBADE® test, five cylindrical samples were manufactured for each asphalt mixture (AF1, AF2 and AC), and compacted with the Marshall compactor applying 75 blows per face. The samples were cut to get the dimensions according to the test method proposed by laboratory of the Technical University of Catalonia [14]. The specimen dimensions were 6 cm of height and 5 cm in width and thickness. The specimens were subjected to an increasing series of 5000 tension-compression stress cycles at 10 Hz and a temperature of 20 °C. The first series of cycles were initiated with a deformation of $2.5 \cdot 10^{-5}$ and the amplitude deformations were increased in increments of the same value until the material broke, Figure 2b [14]. During the test, the load and deformation produced were registered. In this way, parameters such as stress (σ), strain (ε), norm of the complex modulus (|E*|), and the dissipated energy density (DED) can be obtained. Norm of the complex modulus was determined according to Equation 4.

$$|E^*| = \frac{\sigma_{max}}{\varepsilon_{max}} \tag{4}$$

Where σ_{max} is the stress amplitude in a cycle and ε_{max} is the strain amplitude during the same cyle.
DED was calculated by adding the areas by cycle of the ellipse, which is formed in the load/displacement graph, due to the delay between both signals by using the Gauss area formula according to Equation 5.

$$DED = \frac{g}{S} \cdot \frac{1}{2} |(\sigma_1\varepsilon_1 + \sigma_2\varepsilon_2 + \ldots + \sigma_{n-1}\varepsilon_{n-1} + \sigma_n\varepsilon_1) - (\sigma_2\varepsilon_1 + \sigma_3\varepsilon_2 + \ldots + \sigma_n\varepsilon_{n-1} + \sigma_1\varepsilon_n)| \tag{5}$$

Where g is gravity, S is the fracture area, $\sigma_i\varepsilon_i$ are the n values obtained from the load-displacement pairs for each cycle.

2.4 Evaluation of durability of asphalt mixtures

To model the behaviour of the pavement structures in the face of the traffic loads, a mechanistic-empirical pavement analysis was performed. The deformations were evaluated at critical points for different thicknesses of proposed pavements for each mixtures studied in the experimental phase. The input variables were the stiffness modulus of the asphalt layer obtained experimentally, the Poisson ratio and the thickness for each layer that make up the structure. The structures analyzed are composed of an asphalt mixture of variable thickness ranges from 10 to 30 cm, a granular base of 15 cm and a granular subbase of 15 cm supported over the subgrade. The modules used for the granular base layers, granular subbase and subgrade were 279, 146 and 77 MPa, respectively.
In the durability analysis, two load configurations were used: a standard axis of 8.16 Tn of weight equivalent to 80kN, used in mechanistic methods for the design of pavements; and a single axis double rotor of 11 Tn weight equivalent to 110kN, which is the maximum weight allowed in Chile for this type of axis. The failure criterion considered corresponds to fatigue cracks which are produced due to traction in the bottom of the asphalt layer.

3. ANALYSIS OF THE RESULTS

3.1 Evaluation of fatigue behaviour and durability of the mixtures

The values obtained for the stiffness modulus test for the aggregates AC, AF1, and AF2 were 3153, 3791 and 3464 MPa, respectively. The results obtained do not show a clear relationship between the stiffness modulus and the PI values of criteria I and II (Table 4). However, there is a correlation with the results of the weighted PI of fine aggregates (criterion III) and the filler size, since, at a greater PI value and size value, the stiffness modulus becomes greater. From this, it can be deduced that the shape and texture of the fine aggregates have an influence on the stiffness of the mixtures; in other words, the more texture and angularity of aggregate the more internal friction, giving greater modulus values.

In Figure 3 the fatigue laws of the evaluated mixtures are shown. The tested mixtures show similar laws of fatigue; however, the fluvial aggregates showed a lower slope in the fatigue line than the AC mixtures, which implies that these are less sensitive to deformation, as pointed out by Silva et al. [24]. This finding is related to the results obtained in the stiffness modulus, as the mixtures that possess a greater modulus are mixtures that are less susceptible to deformation for similar load values [25].

Taking into account the shape and texture of the aggregates using the PI value, a relationship with the criterion III is observed, which, similar to the stiffness, the greater value of this index, the lower the slope of the fatigue law is. In other words, the greater the texture and angularity of the fine aggregates are, the better the behaviour of the mastic is. This better behaviour allows the internal friction in the mixture to be improved, thus making it less susceptible to deformations.

In Figure 4 it can observe the results of the pavement structure durability with thicknesses from 10 to 30 cm for the different mixtures evaluated according to the type of aggregate used; and for axis with 80 kN and 110 kN. In accordance with the results obtained, the deformations produced for each kind of mixture by the axis 110 kN are superior to those of 80kN; for this reason, their durabilities are less for the evaluated thicknesses. However, the difference in durability between the different mixtures and the different thicknesses is lower in the case of the axis of 110kN than for 80kN, as it can be observed in Table 6.

For both axle loads, it was proven that for a thickness layer of 10 cm there are no major differences in terms of the durability of the mixtures among themselves. On the other hand, starting at 15 cm of thickness important variations begin to be seen. From here, in all of the cases, the AF1 are the asphalt mixtures that show the greatest durability, followed by AF2 and lastly, AC.

According to the ASTM-D3398 standard, the aggregates with a PI $\geq$ 15 are classified as crushed particles possessing high angularity. Due to the results obtained for the evaluated mixtures and the layer thicknesses greater than 10 cm, the mixtures with particles containing a greater PI of fine aggregate (AF1 and AF2) prove to be durable. This finding concurs with the study carried out by Kim et al. [26] who evaluated the mechanical behaviour of the asphalt mixtures by analyzing the influence of the type of aggregate and its gradation, changing the content, % voids and the temperatures; they also performed a statistical analysis to see the principal effects and interactions. They concluded that the type of aggregate has a significant impact on both properties evaluated; thereby allowing the mixtures with aggregates possessing a rough and angular texture, to obtain a better performance, especially in permanent deformations.

At the same time, the mixture with more significant content of flakiness particles (AC) (Table 1), shows a lower durability against the mixtures AF1 and AF2, due to the fact that when they possessed a greater amount of flakiness, these tend to break during production and compaction. As a result, the probability of cracks appearing increases and this results in fatigue failure in the pavement structure; this agrees on the studies performed by Kandhal and Park [27] and González and Velandia [28]. These results may also be correlated with aggregates' resistance to fragmentation since the aggregates which have demonstrated to be less resistant in the Los Ángeles test (Table 1), are those which have shown the worst results in durability. This fact coincides with Moreno et al. [29] pointed out, where the most resistant aggregates showed a better behaviour against cracking.

This behaviour could try to explain through the chemical composition of the aggregates, especially the silica content, which indicates how acid the aggregate is, and how affects the adhesiveness of the mixture [30]. The lowest amount of silica in the fluvial aggregates (AF1 and AF2≈59%), with regard to the quarry aggregate (AC≈63%), would influence a better adherence with the binder, showing a greater durability against fatigue failure. However, this explanation could not be applied in analyzing the results of the mixtures with the fluvial aggregates, since the AF2 aggregate shows a slightly lower acidity than AF1; therefore, they would have to show a greater durability, Figure 4. Thus, in this case, it can be deduced that the shape, texture, and angularity of the aggregates have more influence, correlated with the PI, than the chemical composition of the aggregates.

3.2 Dissipated Energy by EBADE® Test

The results obtained in the EBADE® test for the 3 mixtures evaluated are shown in Figure 5 and Figure 6. The evolution of the complex modulus ($|E^*|$) during the test is showed in Figure 5. These results indicate that the mixture manufactured with the AF1 aggregate obtained the highest initial modulus value ($|E^*_i|$), 5851 MPa. On the contrary, the value of $|E^*_i|$ of the mixture manufactured with AC obtained the lowest value, 2821 MPa; and the mixture manufactured with the AF2 obtained an intermediate value. These findings are similar to those reported for the ITS test, but the differences between them are greater. Also, all mixtures showed a continuous and progressive damage as the strain level increased, without a sudden failure. In relation to Fig. 6, the dissipated energy during each cycle was recorded as the area of the hysteresis loop formed in the stress-strain plane. In the initial stage, as the strain amplitude applied increased, so the stress amplitude did, and consequently the hysteresis loop area and dissipated energy. In the second phase, once the asphalt mixture reached its maximum stress amplitude, the dissipated energy gradually decreased, until the material failed. AF1 and AF2 mixtures showed a greater accumulated dissipated energy density values (DED_a) in relation to the AC mixture; 13,034,600 J/m^3, 11,763,171 J/m^3 and 4,769,555 J/m^3, respectively. The DED_a by the AC mixture was 63% lower than the DED_a by the AF1 mixture and 9.8% lower for the mixture AF2 against AF1. These dates implies that in order to induce the same deformations in each cycle, AF1 mixture require more work for each cycle, dissipating more energy throughout the whole fatigue process compared to the AF2 and AC mixtures, being their fatigue resistance higher. Similarly to the previous section, these results appear to be related with the PI of the fine aggregates, since the greater the PI of the fine aggregate, the more texture and angularity the aggregates possess. As a result, mastic with a greater internal friction is formed, making them more resistant to fatigue damage and giving them a greater capacity to support loads; this translates into a greater capacity to dissipate energy during the fatigue process. As the same of previous fatigue analysis, it is most important the shape, texture and angularity of the aggregates (PI value) than their chemical composition. This could be explained, due to the little difference of percentages of silica, between 63% and 59%, classified as intermediate acidic aggregate, according to Allen [30].

The EBADE® results obtained agrees on the results obtained in the study carried out by Valdés et al. [31], in which cracking behaviour at low and intermediate temperatures was evaluated using the Fénix® test for the same aggregates used in mixtures with four different binders. Those mixtures which showed a greater resistance to cracking and greater flexibility capacity for similar stiffness values, were those mixtures manufactured with the aggregates with greater values of texture and angularity of their fine aggregates, similar to the results obtained in this study.

4. CONCLUSIONS

This study analyzed the influence of aggregate properties' on the deterioration of asphalt mixtures using the standardized fatigue test, the EBADE® test and by studying the durability of pavement structures through the analysis of the results of the mechanistic-empirical design method. The main conclusions obtained are:

- The shape and texture of the fine aggregates affect the stiffness, fatigue behaviour and durability of the flexible pavement structures evaluated in this study.
- The asphalt mixtures with a greater PI value for the fine aggregates proved to be more rigid, less susceptible to deformation and their durability increased with the greater the pavement thickness for both types of axle loads evaluated, being lower in the case of 110kN for three types of aggregates studied.
- The aggregates with greater PI value in the fine aggregate showed a more resistant behaviour to fatigue cracking and a greater capacity to support loads, which translates into a greater capacity to dissipate energy during the cracking process.
- For aggregates of the same origin, the shape and texture of the aggregate are important properties to evaluate the fatigue behaviour.
- For aggregates of different origin, in addition to shape and texture, it is important to consider the chemical nature of aggregates.
- The asphalt mixtures with a greater dissipated energy in the EBADE® test showed a better fatigue behaviour.
- The EBADE® test allows evaluate the fatigue behaviour of the asphalt mixtures in a shorter time than classical fatigue test; it also makes possible to see the effect of the properties of the aggregates on the durability of the mixtures.

5. ACKNOWLEDGMENTS

The present paper is the result of the research supported by Universidad de la Frontera program, conducted within the framework of the Project DI18-0053.

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7. FIGURES

Fig. 1. Morphology of the aggregate used in this study.

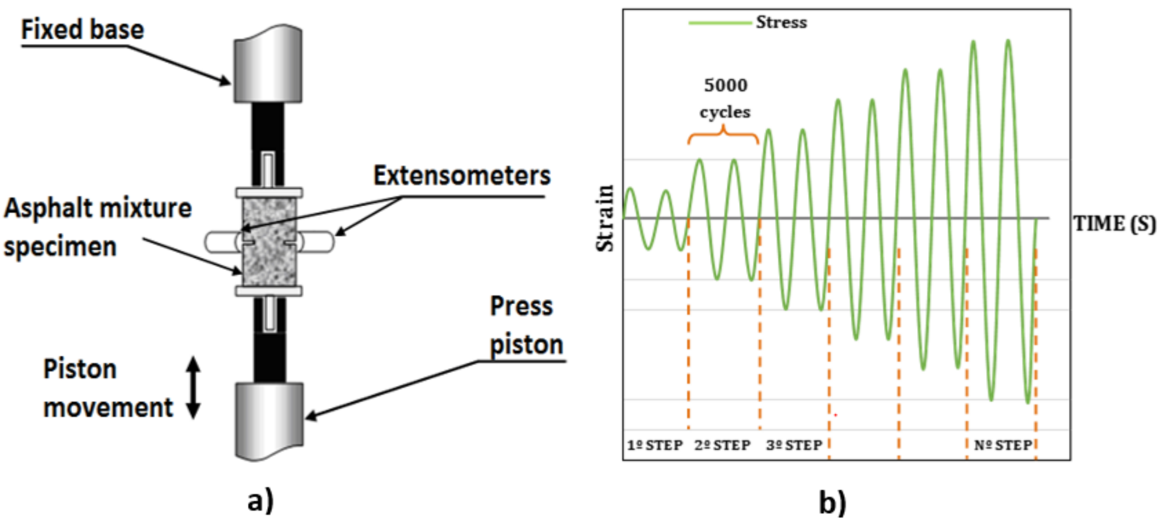

Fig. 2. a) EBADE Test device, b) sinusoidal strains tension-compression applied to the specimen.

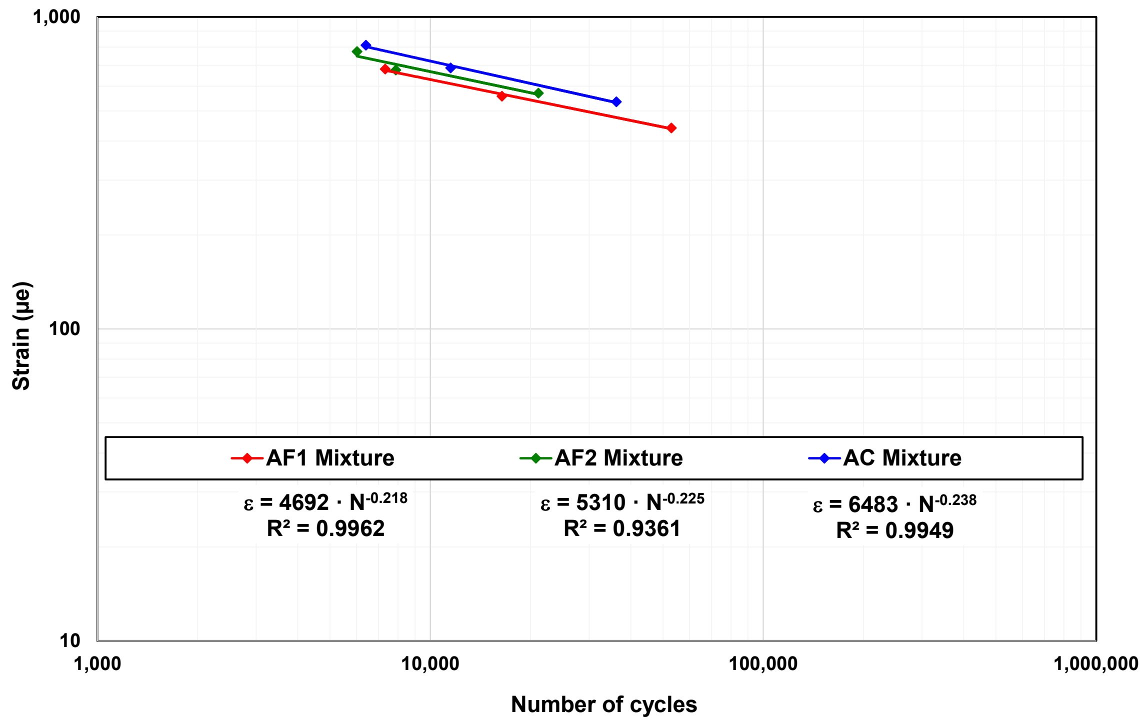

Fig. 3. Fatigue laws obtained through the fatigue indirect tensile test at 20ºC.

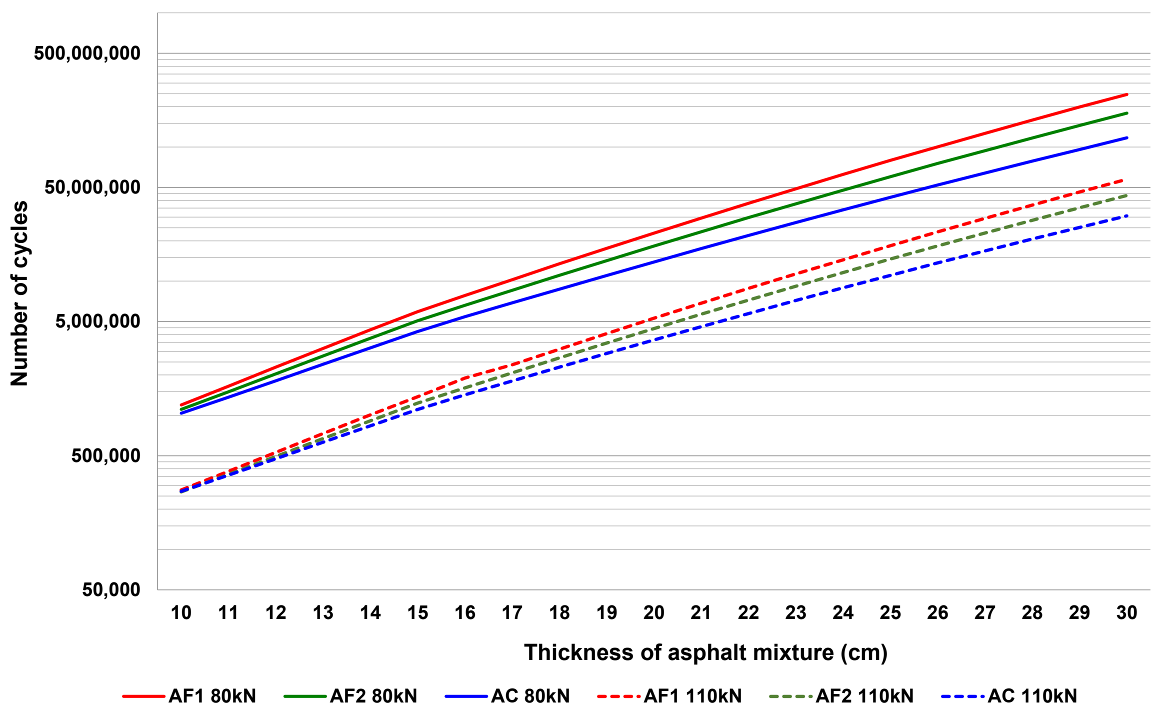

Fig. 4. Durability of the pavement structure for different thicknesses and traffic loads.

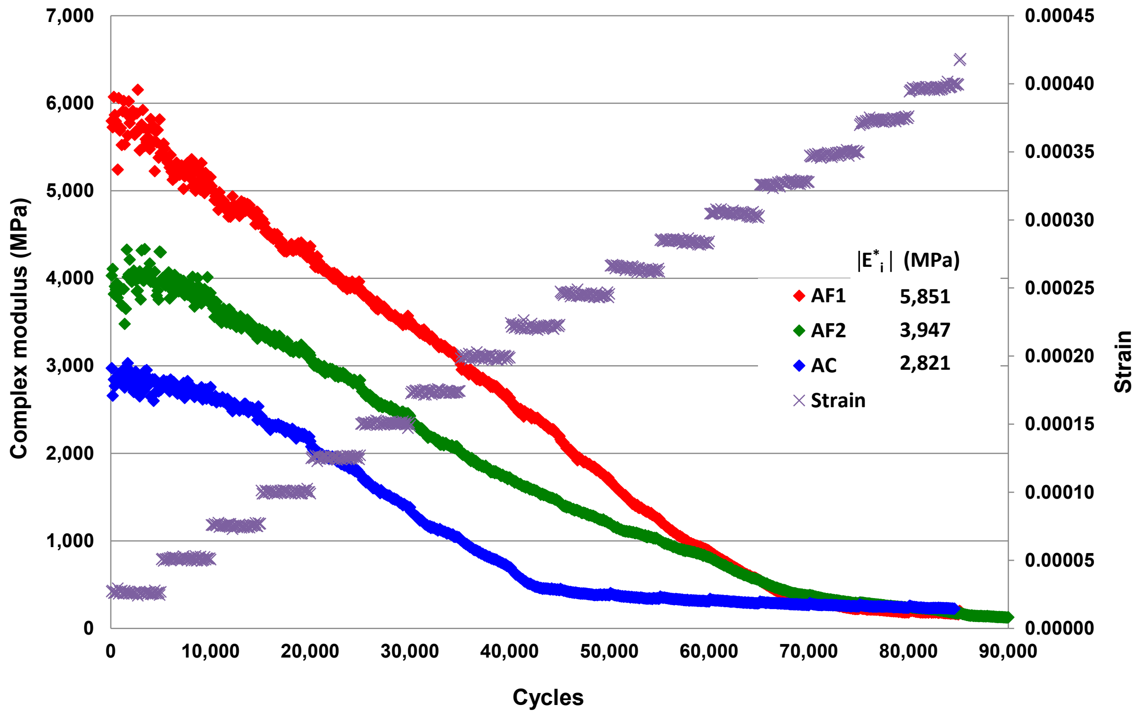

Fig. 5. Evolution of complex modulus in asphalt mixtures with different type of aggregates at 20ºC.

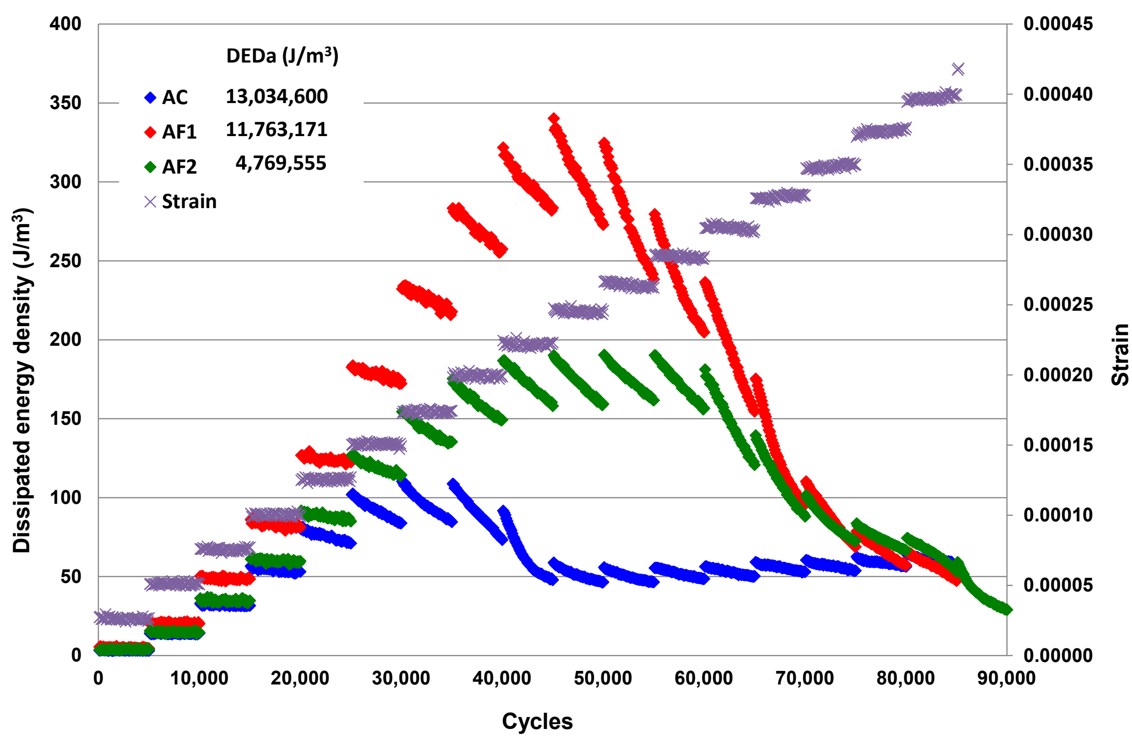

Fig. 6. Evolution of dissipated energy density in asphalt mixtures for different type of aggregates at 20ºC.

8. TABLES

Table 1. Physical properties of binder.

Test	Standard method	Criteria	Test results
Absolute viscosity at 60ºC, 300mmHg (P)	AASHTO – T202-80	Min 2400	3077
Penetration (dmm)	ASTM D36	Min 40	56
Ductility at 25ºC (cm)	AASHTO T51	Min 100	>150
Softening point (ºC)	ASTM D36-76	-	51
Flash point (ºC)	AASHTO T48	Min 232	332
Trichloroethylene solubility (%)	AASHTO T44-78	-	99.9
Penetration index	-	-1.5 a +1.0	-0.7
RTFOT			
Mass loss (%)	AASHTO T240-13	Max 0.8	0
Absolute viscosity at 60ºC, 300mmHg (P)	AASHTO – T202-80	-	7475
Ductility at 25ºC (cm)	AASHTO T51	Min 100	150
Durability index	-	Max 3.5	2.4

Table 2. Physical properties of aggregates.

Tests	Specifications	AC	AF1	AF2
LA abrasion (%)	Máx.25%(*)-35%	25	16	15
Flakiness index (%)	Máx. 10%(*)-15%	8	2.5	0
Crushed aggregates (%)	Mín. 90(*)%-70%	100	92	90
Specific surface (m^2/kg)	-	36.34	31.15	31.24
Specific gravity (kg/m^3)	-	2360	2630	2640

(*) Wearing course

Table 3. Shape characterization parameters according to Zingg method.

Aggregate	Elongation Ratio*	Flatness Ratio *	Shape Factor *	Sphericity Factor *	Particle Shape
AF1	0.70	0.62	0.52	0.66	Disk
AF2	0.76	0.73	0.60	0.72	Cubical
AC	0.61	0.54	0.41	0.56	Blade

* Weighted according to the size proportion in the mixture.

Table 4. Particle index (PI) of aggregates used in the study.

Criterion type	Description	AC	AF1	AF2
Criterion I	All sizes are considered, according to their amount in the designed asphalt mixture.	14.3	16.8	14.1
Criterion II	Only coarse aggregate is considered (>2.5 mm), according to its amount in the designed asphalt mixture.	14.4	14.5	12.6
Criterion III	Only fine aggregate is considered (<2.5 mm), according to its amount in the designed asphalt mixture.	14.1	23.0	17.8

Table 5. IV-A-12 aggregate gradation.

Particle size, D (mm)		20	12.5	10	5	2.5	0.63	0.315	0.16	0.08
Percent passing (%)	Max.	100	95	85	58	42	24	17	12	8
	Min.	100	80	70	43	28	13	8	6	4
	Selected gradation	100	92	81	55	30	15	10	7	5

Table 6. Average of durability in asphalt mixtures.

Thickness (cm)	ESALs of 80kN		ESALs of 110kN	
	Average AF1 vs AC (%)	Average AF1 vs AF2 (%)	Average AF1 vs AC (%)	Average AF1 vs AF2 (%)
10	13	7	2	3
15	29	14	20	11
20	39	20	31	16
25	47	24	40	21
30	53	28	47	24