MINERAL FILLER INFLUENCE ON MASTIC FRACTURE ENERGY

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ABSTRACT

The mechanical properties of asphalt mastic influence significantly the overall performance of hot mix asphalt. The behavior of the asphalt mastic influence almost every aspect of the design, construction, and performance of hot mix asphalt. The fatigue damage and fracture in the hot mix asphalt are strongly related to binder characteristics, filler properties, interaction between the binder and filler, and is a phenomenon affected by the development and growth of microcracks in the mastic. The mixture performance can be improved if the mastic is design to resist fracture and fatigue. Fracture energy is an important property related to fatigue resistance of binders and have a strong influence on the cracking performance of flexible pavement. A new binder fracture energy test was developed by Roque et al (2012) based on nonlinear 3-D Finite Element Analysis (FEA) to determination of stress and strain on the fracture plane, which in turn assures accurate determination of fracture energy. The study of the mastic behavior is important to evaluate the effects of the mineral filler amount and the asphalt binder properties, as well as the different filler types and nature effects, and evaluate its influence on the asphalt binder stiffness and elasticity, provided by the filler addition at different ratio filler/binder. The overall objective of this study was to determine the fatigue damage characteristics of asphalt binders and mastics by measuring the fracture energy. The addition of filler to the asphalt binder decrease the fracture energy value, compared to the pure asphalt binder, and as the filler amount increases, the fracture energy value decrease even more, including the Portland cement filler.

Keywords: Asphalt, Fatigue Cracking, Fracture-toughness, Mastic Asphalt, Mineral filler

1. INTRODUCTION

The importance of mineral filler to the behavior of asphalt mixtures has been recognized for a long time. The mineral filler fills the voids between the larger aggregate particles of the hot mix asphalt, and modify the asphalt binder properties, because it acts like an active portion in the mastic (combination of asphalt binder, mineral filler and air).

The mastic quality influences overall mechanical responses of the asphaltic mixtures, as well as its workability. The fatigue performance, affected by the microcracks development and growth in the mastic, is highly related to the asphalt binder characteristics, to the mineral filler properties, and the physical-chemical interaction between both, which is affected, mainly, by the mineral filler surface characteristics and fineness.

The asphalt mastic stiffness affects the development of stresses and the fatigue strength at intermediate temperatures, the rutting susceptibility of asphalt mixtures at high temperatures and the development of stresses and the cracking strength at low temperatures.

Fatigue damage and fracture, one of main distresses in asphalt mixtures, initiates with cohesive and/or adhesive microcracking and propagates as the microcracks grow and coalesce. Since crack phenomena (cohesive and adhesive fracture) are governed substantially by properties of the mastic, mixture performance can be improved if the mastic is engineered to resist fracture and fatigue.

Several researchers including Bahia et al. [1] and Smith and Hesp [2] have performed fatigue studies on binders and mastics. The general findings from these studies are that fatigue damage is strongly related to binder characteristics, filler properties, interaction between the bitumen and filler, and phenomena that affect microcrack development and growth in the mastic such as crack pinning [3].

Most of researches perform traditional testing methods, such as Dynamic Shear Rheometer (DSR), Bending Beam Rheometer (BBR), Elastic Recovery, Ductility etc., with traditional parameters such as complex shear modulus G*, phase angle δ etc. or some parameters derived from these tests such as yield energy and strain at maximum stress [4].

Fracture energy is an important property related to fatigue resistance of binders. However, a recently completed study for FDOT [5] showed that existing binder testing methods in current specifications do not accurately predict cracking performance at intermediate temperatures.

According to previous research, fracture energy analysis based on Direct Tension testing can predict cracking performance at intermediate temperatures better compared to other binder tests. However, according with Roque et al. [6], the traditional Direct Tension test has some crucial deficiencies in terms of obtaining fracture energy accurately.

A new binder fracture energy test was developed by Roque et al [6] based on nonlinear 3-D Finite Element Analysis (FEA) to determination of stress and strain on the fracture plane, which in turn assures accurate determination of fracture energy.

The use of mechanics is necessary to account fundamentally and accurately for the different factors that affect the development and propagation of cracks in asphalt pavements. Fracture energy, defined as the energy required to initiate fracture in a mixture, is known to have a strong influence on the cracking performance of flexible pavement. Accurate determination of fracture energy of laboratory specimens requires accurate determination of strain through fracture, at the instant of fracture, on the plane where fracture occurs.

Fracture energy is believed to be one of the most important failure limits for describing and modeling the fracture behavior of asphalt mixtures. Previous studies have determined that fracture energy is a reliable indicator of the crack resistance of a mixture when other conditions such as pavement structure and traffic are similar [7].

The fracture energy determination from the properties of its components (that is, aggregate and asphalt binder properties) can be used in pavement design. Based on the binder fracture energy it must be possible the asphalt mixture fracture resistance prediction. The determination of the accumulated energy until the fracture in binder tests can improve the ability of prediction the cracking performance in intermediate temperatures. Thus, a test able to determine the binder fracture energy can provide better parameters related to the binder fatigue resistance. Also, there is a need for a system to determine mixture fracture energy from constituent properties for purposes of pavement structural design.

2. MATERIALS AND TESTING PROCEDURE

Two asphalt binders, with penetration of 5.0 - 7.0 mm (50/70 PEN) and penetration of 8.5 - 10.0 mm (85/100 PEN), and three fillers, Portland cement, limestone and hydrated lime were selected for this study. The characteristics of the binders and the fillers are presented in Table 1 and 2, respectively.

Table 1: Physical Properties of the Asphalt Binder

Test	50/70 PEN	85/100 PEN	Unit
Penetration	50	102	0,1 mm
Softening Point	48.6	43.5	degree C
Brookfield Viscosity135GC	377	252.5	cP
Brookfield Viscosity 150GC	187	130	cP
Brookfield Viscosity177GC	69	52.5	cP

Table 2: Mineral Fillers Properties

Mineral Filler	Specific gravity (g/cm^3)	Specific Surface (cm^2/g)
limestone	2,749	2800 – 3500
hydrated lime	2,350	5000 - 15000
Portland cement	3,030	2200 – 2750

The fracture energy was determinate on asphalt binder and mastics samples, unaged and aged in laboratory. Due to the lack of information and researches about which is the more suitable aging method for mastics, the aging was performed by two ways: (1) the standard procedure, applying 100 °C for 20 hours and; (2) a modified procedure, applying 60°C for 100 hours, stirring the sample every 20 hours.

The mastics samples were subjected to the dog bone direct tension test, unaged and aged, were used with fillers of Portland cement and limestone, at the ratio f/a of 0,6 and 1,2; and with the filler of hydrated lime, at the ration f/a of 0,3 and 0,6. The specimens preparation is made according to "Standard Method of Test for Determining the Fracture Properties of Asphalt Binder in Direct Tension (DT), AASHTO Designation: T 314-02".

The procedure consists in heating the asphalt binder, or the mastic; the molds must be heated about the same temperature of the asphalt binder, for approximately 3 minutes. The molds should be placed above a nonstick base molding, and on the internal section of the metal mold a release agent, like glycerin, so the specimen ejecting is performed without deformation. The mold shall be overfilled with the sample; then allow the specimen to cool for, at least, 30 minutes, and trim the sample with a heated spatula.

Following, the specimens, still inside the molds, must be placed in the temperature controlled chamber surrounding the servo-hydraulic testing machine (MTS). This group should remain on the test temperature for, at least, 4 hours, for temperature stabilization. The specimens should be taken out of the chamber and carefully de-mold. If the binder specimen is deformed, even a little bit during de-molding, or if de-molding is not smooth due to the lack of release agent somewhere on the mold, discard the specimen. The final geometry configuration of the specimen is shown in the Figure 1.

Figure 1: Specimen final geometry configuration.

The specimen must be vertically and loosely suspended to insert the loading head into the slot of upper loading head of the load frame. Any tiny deviation from this will deform the specimen and make it unsuitable for testing. Insert the small steel bar through the holes of loading heads. Lower down the loading head the load frame slowly, and carefully make the lower loading head of specimen smoothly enter into the slot of the lower loading head of the load frame. Insert the small steel bar through the holes of loading heads.

After the specimen reaches the test temperature, the loading rate should be chosen. This selection depends on the type of material to be tested. Roque et al. [6] (2012) performed the test in pure and modified binder, with polymer and SBS, and the test initial loading rate was 500 mm/min. The test with asphalt mastics showed that the most appropriate initial loading rate was 100 mm/min. The final configuration after the fracture test is shown in the Figure 2 a.

Figure 2 (a) and (b) show examples of appropriate fracture and premature fracture of the fracture energy test, wherein this type of fracture is not suitable for calculating the property.

(a) (b)

Figure 2: Specimen Fracture in the Dog Bone Direct Tension: (a) appropriate fracture; (b) premature fracture

If the test results is a complete stress-strain curve, so the results are acceptable and the test procedure should be repeated in different specimen with higher loading rates. For each loading rate, the test must be performed in two specimens, and the difference in fracture energy density between two replicates must be, at most, 15%, and the average value should be taken as the fracture energy density at this loading rate level.

Whenever premature fracture occurs (i.e., incomplete stress-strain curve), the sample should be test at lower loading rates, until the loading rate levels result in fracture that is not premature, if possible. If premature fracture still occurs, then the temperature must be changed.

The identification of premature fracture is based on the true stress-true strain curve, as an incomplete true stress-true strain curve. The Roque et al. [6] (2012) research indicates the stress-strain curve characteristics for each kind of asphalt binder tested.

A new procedure of analysis of the test data was developed by Roque et al. [6] (2012) to adjust the lower deformation of the finite element solution, considering the necking which occurs in large deformations. Further details of the calculation steps of the fracture energy using this procedure can be found at Bardini [8].

As shown in Figure 3, after the application of this method of calculation the starting point of cracking can be observed. The energy after the initial fracture point should not be considered in the calculation of fracture energy as it is the energy required to separate the specimen in half, and not the energy to start cracking in the asphalt binder. The fracture energy should be calculated from the beginning of the stress-strain curve up to the last peak, which is the point of fracture.

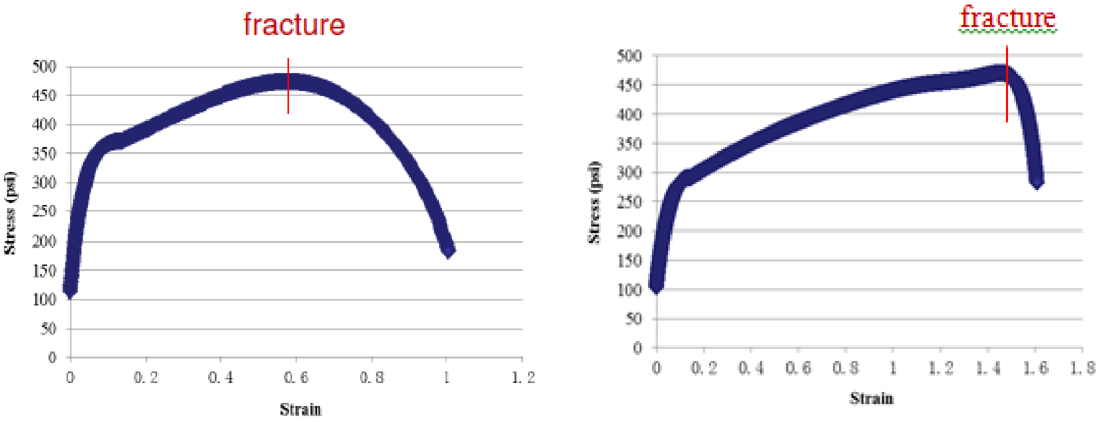

Figure 3. Stress-Strain Curve by New Calculation Procedure Porposed by Roque et al. [6]

3. FRACTURE ENERGY RESULTS

Initially, the determination of the fracture energy was performed to the pure asphalt binder, the 50/70 PEN and 85/100 PEN. As has already been proven by Roque et al. [6] (2012), the fracture energy is loading rate and temperature independent, and the initial recommended temperature is 15 °C, however, to the binder in this research the specimen rupture at this temperature was ductile, that is, a large elongation in the middle cross section, leading to an improper determination of the fracture energy. For this reason, the tests were performed at 10 °C. After, the test was performed in pure asphalt binders samples aged in the PAV by the standard procedure, that is, at 100 °C for 20 hours; the tests results, performed at different loading rates and temperature of 15 °C. Finally, the pure asphalt binders samples, aged in the modified PAV procedure (60 °C for 100 hours), were tested in different loading rates and temperature of 15 °C.

The available data for this test (ROQUE et al., 2012) were based only in pure and modified binder, but to asphalt mastic its necessary validate that the fracture energy is temperature and loading rate independent.

First, the testes were performed in asphalt mastics composed by Portland cement, at the ratio f/a=0.6 and 1.2 (in mass) and two temperatures were tested (15 e 20 °C), and different loading rate. Following, the test was performed in mastic samples, composed by Portland cement, and aged in the conventional and modified PAV procedure.

The DT Dog Bone test was performed in mastics composed by limestone, at the ratio f/a=0.6 and 1.2 (in mass) and two temperatures were tested (15 e 20 °C), and different loading rate. Then, the test was performed in aged mastic samples (conventional PAV procedure), composed by the limestone. Lastly, the test was performed in aged mastics (modified PAV procedure), composed by the limestone.

Following, the testes were performed in asphalt mastics composed by hydrated lime, at the ratio f/a=0.3 and 0.6 (in mass). Two temperatures were tested (15 e 20 °C), and different loading rate. Ultimately, the test was performed in aged mastics (modified PAV procedure), composed by the hydrated lime.

Figure 4 presents the summary of the fracture energy average to mastics composed by 50/70 PEN and Portland cement, limestone and hydrated lime fillers. It can be notice that adding filler to the asphalt binder decrease the energy fracture value, compared to the pure asphalt binder, as the filler amount increases, the fracture energy value decrease even more, except for the Portland cement filler.

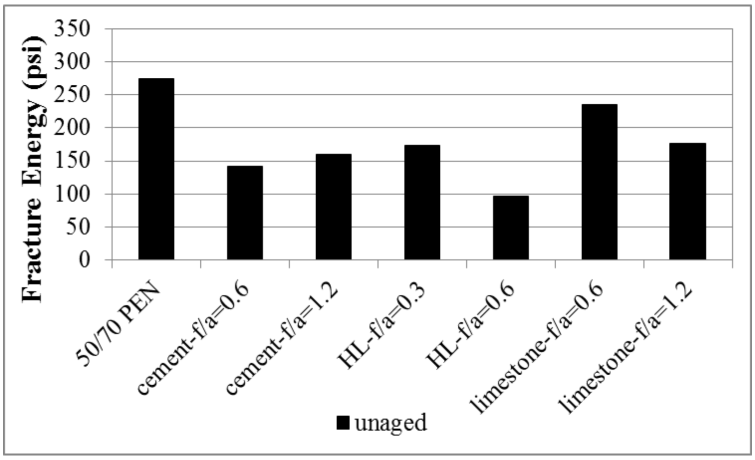

Figure 4: Fracture Energy of mastics composed 50/70 PEN (unaged)

Figure 5 presents the summary of the fracture energy average to mastics composed by 50/70 PEN and Portland cement, limestone and hydrated lime fillers, unaged and aged in the standard PAV procedure (20hours at 100°C). It can be notice that the aging decrease the fracture energy of pure asphalt binder, however, increase the fracture energy of the mastics, except for the one composed by the limestone filler at the ratio f/a of 1.2; it can also be noted that for the mastics composed by the Portland cement and hydrated lime, the fracture energy increasing is greater to the mastic with low filler concentration.

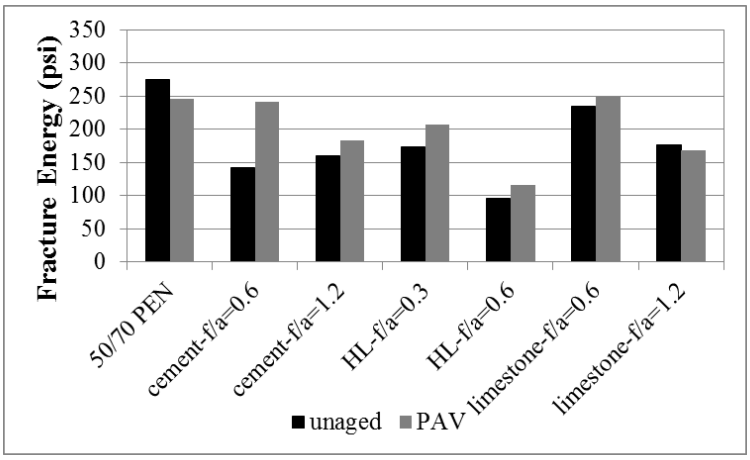

Figure 5: Fracture Energy of mastics composed 50/70 PEN, unaged and aged in the standard PAV procedure.

Figure 6 presents the summary of the fracture energy average to mastics composed by 50/70 PEN and Portland cement, limestone and hydrated lime fillers, unaged, aged on the standard PAV procedure (20hours at 100°C) and aged on the modified PAV procedure (100hours at 60°C). It can be notice that both PAV procedures decrease the fracture energy values of the pure asphalt binder, and the modified PAV procedure cause a smaller fracture energy decrease that the standard PAV procedure.

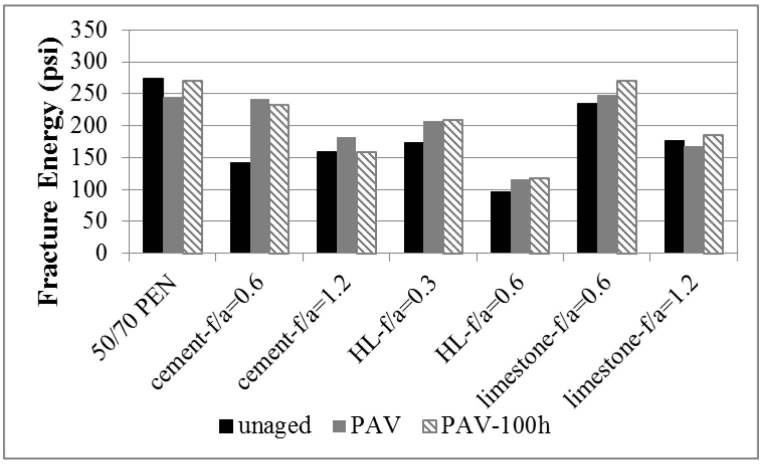

Figure 6: Fracture Energy of mastics composed 50/70 PEN, unaged, aged in the standard PAV procedure and aged in the modified PAV procedure.

The aging increases the fracture energy to mastics with low filler concentration; however, the type of aging do not influences the fracture energy values. The different types of aging leads to a different behavior of the mastics with higher filler concentration, for example, for the Portland cement filler, in the ratio f/a of 1.2, the standard PAV procedure increase the fracture energy, however the modified PAV do not change the fracture energy fracture.
Figure 7 presents the summary of the fracture energy average to mastics composed by 85/100 PEN and Portland cement, limestone and hydrated lime fillers. As for the mastics composed by the 50/70 PEN, the addition of filler to the asphalt binder decrease the energy fracture value, compared to the pure asphalt binder, and as the filler amount increases, the fracture energy value decrease even more, including the Portland cement filler.

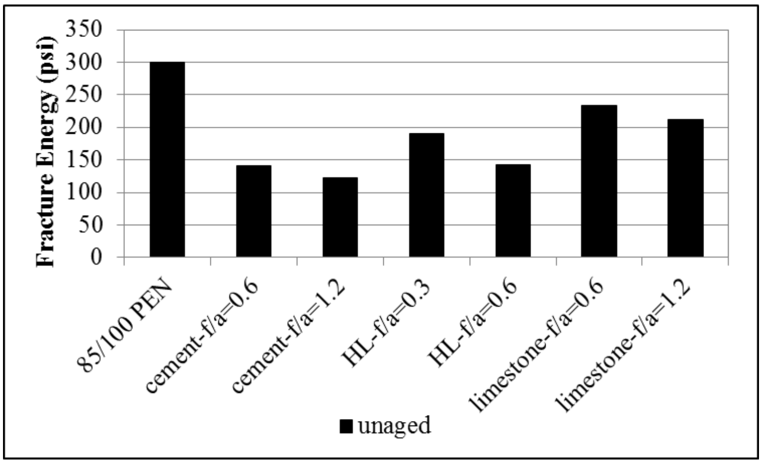

Figure 7: Fracture Energy of mastics composed 85/100 PEN (unaged).

Figure 8 presents the summary the fracture energy average to mastics composed by 85/100 PEN and Portland cement, limestone and hydrated lime fillers, unaged and aged on the standard PAV procedure (20hours at 100°C). It can be notice that the aging decrease the fracture energy of pure asphalt binder; however, increase the fracture energy of the mastics, except for the one composed by the limestone filler at the ratio f/a of 1.2 and by hydrated lime at the ratio f/a of 0.6. It can also see that for the mastics composed by the Portland cement, the fracture energy increasing is greater to the mastic with low filler concentration.

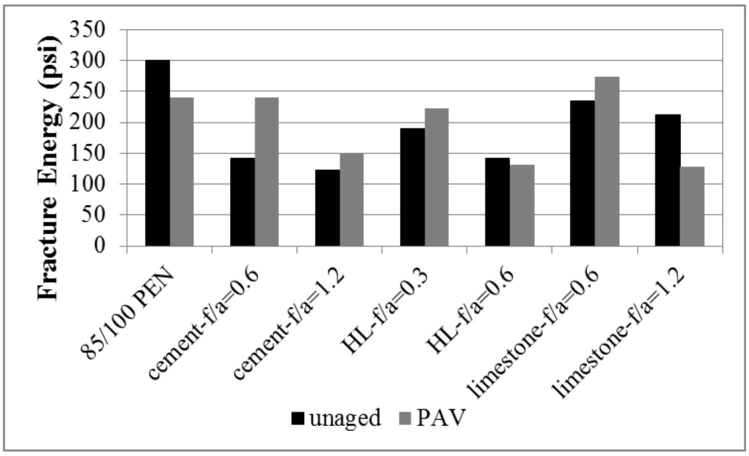

Figure 8: Fracture Energy of mastics composed 85/100 PEN, unaged and aged in the standard PAV procedure.

Figure 9 presents the summary of the fracture energy average to mastics composed by 85/100 PEN and Portland cement, limestone and hydrated lime fillers, unaged, aged on the standard PAV procedure (20hours at 100°C) and aged on the modified PAV procedure (100hours at 60°C). It can be notice that both PAV procedures decrease the fracture energy values to the pure asphalt binder, and the modified PAV procedure cause a smaller fracture energy decrease that the standard PAV procedure, the same behavior than the 50/70 PEN. The modified PAV procedure increase the mastics fracture energy, except for the one composed by the hydrated lime in the ration f/a of 0.6.

2.1 Analysis of Variance

A factorial experiment was performed to investigate the effect of the type and amount of filler, and type of binder on the fracture energy. The experiment were divided, because the mastics composed by the Portland cement and limestone fillers were testes in the ratio f/a of 0.6 and 1.2; and the hydrated lime filler were tested in the ration f/a of 0.3 and 0.6.

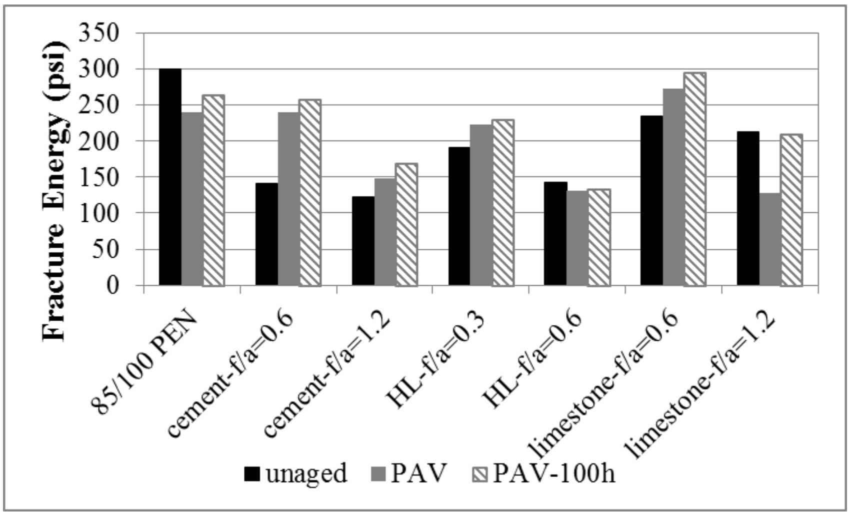

Figure 9: Fracture Energy of mastics composed 50/70 PEN, unaged, aged in the standard PAV procedure and aged in the modified PAV procedure.

It was also evaluate if the aging influences the fracture energy, comparing the data of mastics unaged and aged in the standard PAV procedure (20hours at 100 °C), unaged and aged in the modified PAV procedure (100hours a 60 °C), and also if the different aging procedures influence the fracture energy. The Table 3 shows the different factors levels combination of the analysis.

Table 3: Analysis of Variance fracture energy factors and levels combinations

Factor	A Filler Type	B f/a ratio	C Asphalt Binder Type	D Aging Procedure
		analysis 1		
	Cement	0.0	50/70 PEN	Unaged
Level	limestone	0,6	85/100 PEN	standard PAV
		1.2		
		analysis 2		
	Cement	0.0	50/70 PEN	Unaged
Level	limestone	0.3	85/100 PEN	standard PAV
	Hydrated lime			
		analysis 3		
	Cement	0.0	50/70 PEN	standard PAV
Level	limestone	0,6	85/100 PEN	modified PAV
		1.2		
		analysis 4		
	Cement	0.0	50/70 PEN	standard PAV
Level	limestone	0.3	85/100 PEN	modified PAV
	Hydrated lime			
		analysis 5		
	Cement	0,0	50/70 PEN	Unaged
Level	limestone	0,6	85/100 PEN	modified PAV
		1,2		
		analysis 6		
	Cement	0,0	50/70 PEN	Unaged
Level	limestone	0,3	85/100 PEN	modified PAV
	Hydrated lime			

The fracture energy ANOVA values are summarized in Tables 4, 5 and 6, the f_0 values ($\alpha = 0.10$) and the factors and interactions influence, to the analysis (1) and (2)), that compare the unaged and standard PAV procedure (20hours at 100 °C); (3) and (4), that compare the different type of aging procedure; and (5) and (6), that compare the unaged and modified PAV procedure (100hours at 60 °C), respectively.

Table 4: Fracture Energy ANOVA summary data, f_0 values and the factors and interaction influence, to analysis (1) and (2).

Factor	analysis (1)			analysis (2)		
	F_0	f_0	influence	F_0	f_0	influence
A (filler type)	9.83	8.53	yes	84.93	9.00	yes
B (filler amount)	56.80	9.00	yes	388.02	8.53	yes
C (asphalt binder type)	0.03	8.53	no	8.63	8.53	yes
D (aging procedure)	0.08	8.53	no	0.05	8.53	no
AB	4.44	9.00	no	84.93	9.00	yes
AC	0.99	8.53	no	1.38	9.00	no
AD	9.17	8.53	yes	13.00	8.53	yes
BC	1.29	9.00	no	0.23	8.53	no
BD	16.08	9.00	yes	121.74	8.53	yes
CD	1.42	8.53	no	4.72	8.53	no
ABC	0.39	9.00	no	1.38	9.00	no
ABD	2.29	9.00	no	13.00	9.00	yes
ACD	0.30	8.53	no	1.00	9.00	no
BCD	0.92	9.00	no	3.47	8.53	no

Table 5: Fracture Energy ANOVA summary data, f_0 values and the factors and interaction influence, to analysis (3) and (4).

Factor	analysis (3)			analysis (4)		
	F_0	f_0	influence	F_0	f_0	influence
A (filler type)	14.43	8.53	yes	104.40	9.00	yes
B (filler amount)	322.04	9.00	yes	68.17	8.53	yes
C (asphalt binder type)	0.18	8.53	no	4.10	8.53	no
D (aging procedure)	40.34	8.53	yes	8.57	8.53	yes
AB	7.15	9.00	no	79.16	9.00	yes
AC	0.78	8.53	no	0.53	9.00	no
AD	12.51	8.53	yes	1.36	8.53	no
BC	7.24	9.00	no	3.18	8.53	no
BD	1.48	9.00	no	0.92	8.53	no
CD	14.29	8.53	yes	1.91	8.53	no
ABC	0.39	9.00	no	0.73	9.00	no
ABD	5.32	9.00	no	0.39	9.00	no
ACD	0.05	8.53	no	0.35	9.00	no
BCD	6.11	9.00	no	0.04	8.53	no

Table 6: Fracture Energy ANOVA summary data, f_0 values and the factors and interaction influence, to analysis (5) and (6).

Factor	analysis (5)			analysis (6)		
	F_0	f_0	influence	F_0	f_0	influence
A (filler type)	51.67	8.53	yes	29.33	9.00	yes
B (filler amount)	139.15	9.00	yes	113.26	8.53	yes
C (asphalt binder type)	4.60	8.53	no	5.46	8.53	no
D (aging procedure)	20.46	8.53	yes	2.74	8.53	no
AB	14.48	9.00	yes	22.09	9.00	yes
AC	2.02	8.53	no	0.65	9.00	no
AD	6.10	8.53	no	4.58	8.53	no
BC	0.06	9.00	no	0.02	8.53	no
BD	30.65	9.00	yes	25.54	8.53	yes
CD	0.32	8.53	no	0.07	8.53	no
ABC	2.01	9.00	no	0.00	9.00	no
ABD	2.51	9.00	no	2.18	9.00	no
ACD	0.98	8.53	no	0.03	9.00	no
BCD	3.15	9.00	no	0.70	8.53	no

4. CONCLUSIONS

Analyzing the fracture energy results, it can be noticed that adding filler to the asphalt binder decrease the energy fracture value, compared to the pure asphalt binder, as the filler amount increases, the fracture energy value decrease even more, except for the Portland cement filler.

The aging decrease the fracture energy of pure asphalt binder, however, increase the fracture energy of the mastics, except for the one composed by the limestone filler at the ratio f/a of 1.2; it can also see that for the mastics composed by the Portland cement and hydrated lime, the fracture energy increasing is greater to the mastic with low filler concentration.

Both PAV procedures decrease the fracture energy values of the pure asphalt binder, and the modified PAV procedure cause a smaller fracture energy decrease that the standard PAV procedure. The aging increases the fracture energy to mastics with low filler concentration; however, the type of aging do not influences the fracture energy values. The different types of aging leads to a different behavior of the mastics with higher filler concentration, for example, for the Portland cement filler, in the ratio f/a of 1.2, the standard PAV procedure increase the fracture energy, however the modified PAV do not change the fracture energy fracture.

About the Analysis of Variance, it can be concluded that:

- the factors that influence more the fracture energy is the filler type and amount, and the standard PAV procedure doesn't influence the property;
- the main factors is the type and amount of filler, but it is also observed that different aging procedures influences the response;
- the factors that influences more the fracture energy are the filler type and amount; also, the modified PAV procedure influences the mechanical response.

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