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Change in Fatigue Behavior of Asphalt Hot Mixes Produced with Asphalt Rubber Binders

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ABSTRACT: Fatigue life of asphalt hot mixes is given as a function of both stiffness and tensile strains induced in the bottom of the wearing courses of flexible pavements. In conventional asphalt hot mixes the increase of stiffness leads to a decrease of fatigue life. However, this work shows that there is an increase of both fatigue life and stiffness of asphalt rubber hot mixes in comparison with the asphalt hot mixes produced with straight binders. In this work laboratory tests were performed in asphalt hot mixes with dense and gap gradation produced with straight binder (AC 50/70) and asphalt rubber binder manufactured by the wet process. Resilient modulus and fatigue life tests under four point bending procedure were used to determine the mechanical behavior of studied mixtures. The results show that the use of asphalt rubber binder produced an increase of both fatigue life and stiffness of the studied mixtures.

1 INTRODUCTION

Asphalt hot mixes used in wearing courses are designed to present resistance to cracking and permanent deformation compatible with traffic loads and design life expected for flexible pavements. The resistance to cracking of the asphalt hot mixes depends on their flexibility and stiffness at low temperatures and this is usually measured by fatigue life tests whose results are expressed by the fatigue laws. According to most fatigue laws developed for conventional asphalt hot mixes, the increase of stiffness of the mixtures leads to a decrease in their fatigue life.

The objective of this paper is to show the changes in the fatigue life of asphalt hot mixes produced with asphalt rubber binders in relation to those produced with straight binder. For the development of this work, asphalt hot mixes with dense and gap gradation produced with a straight binder (AC 50/70) and asphalt rubber binder produced by the wet process were tested in laboratory. The asphalt rubber binder was produced incorporating 21% in weight of crumb rubber obtained from ground tires into a straight binder classified as AC 50/70. The time and temperature of digestion used to produce the asphalt binder were 60 minutes and 210°C, respectively. Resilient modulus and fatigue life tests, using four point bending procedure, were performed to determine the mechanical behavior of studied mixtures.

The results show that the use of asphalt rubber binder produced an increase of both fatigue life and stiffness of the studied mixtures. So, it can be observed that there was a change of fatigue life behavior when comparing the mechanical properties of the asphalt rubber hot mixes with the conventional asphalt hot mixes.

2 FATIGUE LIFE OF ASPHALT HOT MIXES

According to Motta (1995), the fatigue life of asphalt hot mixes is defined as the number of repeated load cycles applied to the asphalt hot mix that can cause its failure even when the produced tensile stress is less than the tensile strength of the material.

Medina (1997) explains the fatigue of asphalt hot mixes in wearing courses as follows. The repeated traffic loads acting on the surface of flexible pavement induce tensile stresses or strains in the bottom of the wearing course which works under bending. When the number of applied load cycles is equal to the fatigue life of the asphalt hot mix which constitutes the wearing course, a crack is initiated leading ultimately to the failure of the wearing course.

The laboratory tests used to evaluate the fatigue life of asphalt hot mixes can be performed under controlled stress or controlled strain conditions (Monteiro, 1996). The tests performed under controlled stress conditions usually apply diametric force on a specimen inducing indirect tensile stresses (σ_t) as shown in Figure 1. In this type of fatigue life test, the tensile strains increase during the test under constant loading until the complete failure of the specimen. This is the most common type of fatigue life test used in Brazil.

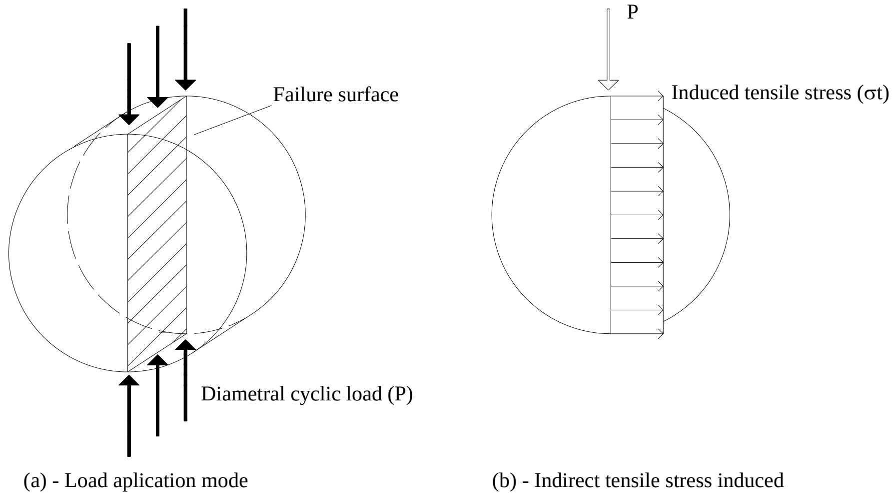

Figure 1. Loading mode in fatigue life tests under controlled stress conditions

In the fatigue life test performed under controlled strain conditions, the tensile strains (ε_t) are induced at the bottom of a prismatic specimen (beam) using usually a four bending point loading system (Figure 2). Here, the repeated loading necessary to induce the specified tensile strains will decrease during the test due the viscoelastic properties of the asphalt hot mix until the failure. The failure is defined by the number of load cycles applied that reduces the stiffness of the specimen in 50% of its initial value.

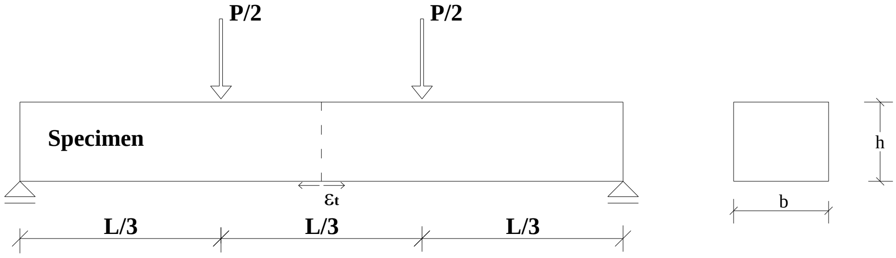

Figure 2. Loading mode in fatigue life tests under controlled strain conditions

The results obtained from fatigue life tests performed under controlled stress conditions are significantly different from those obtained under controlled strain conditions and must be conveniently analyzed. According to Motta (1995), these two fatigue life tests represent the range of repeated loads that can act on the flexible pavements. During its design life it is observed that the flexible pavement may undergo loading conditions that can be represented in terms of controlled stress or strain tests, depending on some factors, as for example, the thickness of wearing courses and the relation between the stiffness of wearing course and subjacent layers.

The results of fatigue life tests are expressed by the fatigue laws as illustrated in Figure 3. The fatigue laws represent the relation between the number of repeated load applied to the specimen to reach failure (N) and the level of stress (controlled stress condition) or strain (controlled strain condition) induced.

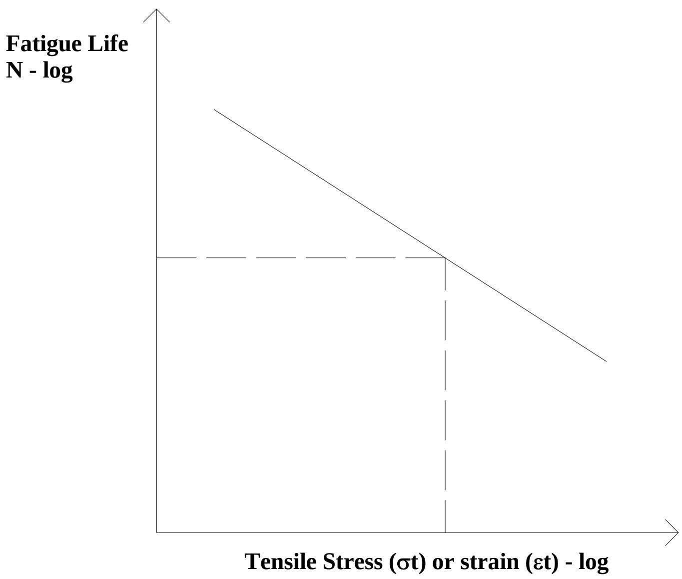

Figure 3. Fatigue curve obtained from fatigue life tests

Equations 1 and 2 present the fatigue laws obtained from the fatigue life tests illustrated in Figure 3 (Medina, 1997). These equations represent the simplest form of fatigue life laws of the asphalt hot mixes, once they do not consider the influence of stiffness of the asphalt hot mix on its fatigue life.

$$N = k1\left(\frac{1}{\sigma_t}\right)^{k2} \tag{1}$$

$$N = k1\left(\frac{1}{\varepsilon_t}\right)^{k2} \tag{2}$$

where N = fatigue life; σ_t = tensile stress; ε_t = tensile strain; k_1 an k_2 = experimental parameters.

According to Huang (1993) a complete fatigue life law must consider the effect produced in the fatigue life of the asphalt hot mix by its stiffness. This influence is expressed in Equation 3 where it can be observed that an increase of stiffness of asphalt hot mix produces a decrease of fatigue life. In the design of a flexible pavement, the stiffness of asphalt hot mixes layers is usually considered equal to its resilient modulus also determined from repeated tests under controlled tensile stress or strain conditions (Dantas Neto, 2001; Dantas Neto, 2004).

$$N = k1\left(\frac{1}{\sigma_t}\right)^{k2}\left(\frac{1}{E}\right)^{k3} \tag{3}$$

where N = fatigue life; σ_t = tensile stress; E = stiffness of asphalt hot mix; k_1, k_2 and k_3 = experimental parameters.

Dantas Neto (2001) studied dense graded asphalt hot mixes produced with two asphalt binders produced in Brazil, designated as CAP 20 and CAP PLUS 104. The penetration grade of CAP 20 and CAP PLUS 104 were 51.8 and 44.4 (1/10 mm), respectively. The asphalt hot mixes studied were produced with the same optimum binder content (5.4%) and void content (3.0%). The resilient modulus at 20ºC obtained from repeated indirect tensile stress tests under controlled stress conditions were 2770 MPa (CAP 20) and 3300 MPa (CAP PLUS 104). Figure 4 show the fatigue life of the dense graded asphalt hot mixes produced with CAP 20 and CAP PLUS 104 binders. These results show that the fatigue life of asphalt hot mix produced with CAP 20 was higher than the fatigue life of asphalt hot mix produced with CAP PLUS 104. Therefore, it can be observed that the increase of the stiffness of asphalt hot mix, represented by resilient modulus, led to a decrease of their fatigue life, according to the behavior presented by Equation 3 proposed by Huang (1993).

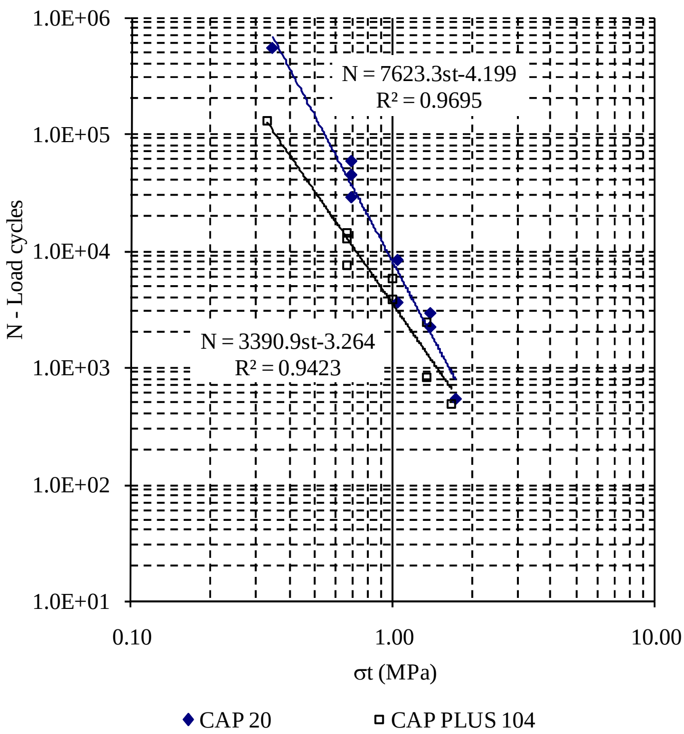

Figure 4. Fatigue laws for dense graded asphalt hot mixes (Dantas Neto, 2001)

3 MATERIALS

3.1 *Straight binder and asphalt rubber binder*

The straight binder used to produce the conventional asphalt hot mixes was classified by penetration grade as AC 50/70. The used asphalt rubber binder was produced by the wet process incorporating 21% in weight of crumb rubber obtained from used ground tires by grinding at ambient temperature. The digestion time and temperature used were 60 minutes and 210ºC, respectively.

Table 1 describes the grain size distribution curves for the used crumb rubber and the grading envelope specified by Arizona Department of Transportation (ADOT). Table 2 presents the results of physical properties characterization tests of conventional binder AC 50/70 and asphalt rubber binder.

Table 1. Grain size distribution of used crumb rubber and grading envelope specified by Arizona Department of Transportation (ADOT)

Sieve size		%Passing		
Inch	mm	ADOT		Rubber
Nº 4	4.75	100	100	100
Nº 8	2.36	100	100	99.9
Nº 10	2.00	100	100	96.8
Nº 16	1.18	65	100	47.7
Nº 30	0.60	20	100	18.7
Nº 50	0.30	0	45	7.5
Nº200	0.075	0	5	0

Table 2. Characterization of straight binder (AC 50/70) and asphalt rubber binder (AR)

Physical properties	AC 50/70	AR
Penetration, ASTM D 5-95 (1/10 mm)	52.0	33.5
Softening point, ASTM D36-97 (ºC)	50.6	86.5
Brookfield viscosity at 175ºC, ASTM D 4402-87 (cP)	87.5	5680
Resilience, ASTM D5329 (%)	14.0	58.0

3.2 *Aggregates*

The following mineral aggregates were used for producing the asphalt hot mixes studied in this paper:

- Grade 1 crushed granitic stone: particle size 11 - 16 mm;
- Grade 0 crushed granitic stone: particle size 4 - 11 mm;
- Fine crushed granitic aggregate: particle size < 4 mm.

Granitic filler available in the Laboratory of Pavements of the University of Minho in Portugal was also used. The aggregate mixture presents a gap in its gradation curve as specified by ADOT.

Table 3 shows the aggregate mixture composition to comply with the specified grain size distribution for studied dense and gap graded asphalt hot mixes. Some results of aggregate characterization tests are also shown. Table 4 presents the grain size distribution of the aggregates used in the asphalt hot mixes and the theoretical values for the designed mixtures. Figure 5 presents the grain size distribution curves of studied asphalt hot mixes designed according to the aggregate mixture composition described in Table 3.

Table 3. Characterization of aggregates used in the asphalt hot mixes

Physical properties	Crushed stone 1	Crushed stone 0	Fine	Filler
Aggregate percentage for gap graded asphalt hot mix (%)	31.7	41.7	25.7	1.0
Aggregate percentage for dense graded asphalt hot mix (%)	10.0	30.0	55.0	5.0
Apparent specific gravity (kN/m^3)	26.41	25.84	25.20	25.20
Specific gravity of grains (kN/m^3)	26.96	26.80	27.10	27.10
Water absorption (%)	0.77	1.39	-	-

Table 4. Grain size distribution of dense and gap graded asphalt hot mixes

Sieve size		% Passing					
Inch	mm	Grade envelope C		ADOT		Dense graded	Gap graded
¾”	19,1	100	100	100	100	100	100
½”	12,5	85	100	90	100	98,2	95.9
3/8”	9,5	75	100	79	89	89,4	77.9
Nº 4	4,8	50	85	34	42	65,9	37.2
Nº 10	2,0	30	75	15	23	47,3	22.1
Nº 40	0,425	15	40	4	14	24,1	10.6
Nº 80	0,18	8	30	-	-	13,6	-
Nº 200	0,075	5	10	1	5	6,9	2.8

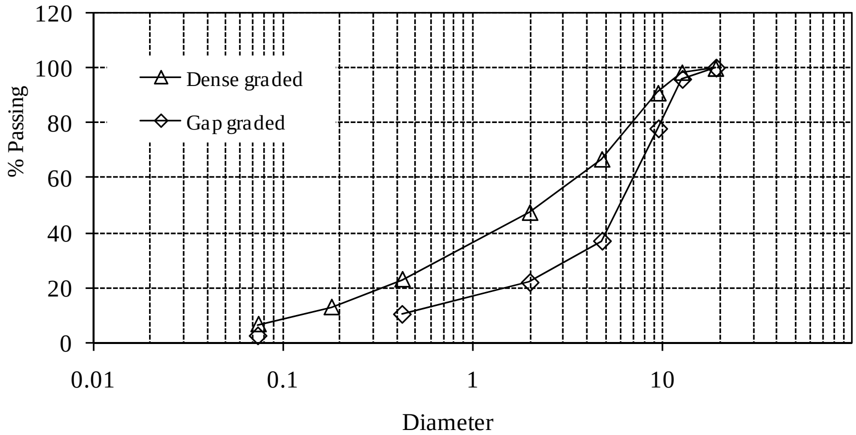

Figure 5. Grain size distribution curves for dense (DG) and gap (GG) graded asphalt hot mixes

4 ASPHALT HOT MIXES: DESIGN, PRODUCTION AND TESTS

The Marshall procedure was used to define the binder content of studied asphalt hot mixes. Table 5 presents the values of temperatures of binders, aggregates and compaction of asphalt hot mixes made with AC 50/70 and AR (asphalt rubber). Table 6 presents all volumetric parameters for the studied asphalt hot mixes defined in the mix design. All manufacturing conditions of asphalt hot mixes studied are also presented.

Table 5. Temperatures used in the production of studied asphalt hot mixes

Temperatures	AC 50/70	AR
Binder heating (ºC)	160	170
Aggregates heating (ºC)	177	190
Compaction of the mix (ºC)	160	164

Table 6. Volumetric properties of studied asphalt hot mixes

Mix properties	Dense graded		Gap graded	
	AC 50/70	AR	AC 50/70	AR
Apparent density (g/cm^3)	2.25	2.25	2.25	2.26
Void content (%)	4.5	4.5	4.5	4.5
Void in the mineral aggregate – VMA (%)	19.3	19.2	19.3	17.1
Void filled with asphalt binder – VFA (%)	76.7	76.7	76.7	74
Optimum binder content (%)	7.5	9.61	7.05	9

After the mix design, specimens of asphalt hot mixes produced with AC 50/70 and asphalt rubber binder (AR) were prepared. A mechanical device with production capability of 50 kg of asphalt mixture was used to thoroughly mix the mineral aggregates and asphalt binders. Compaction of the asphalt hot mixes was performed in a metallic mold with dimensions (7.3 x 49.2 x 75.2 cm) and a vibratory wheel roller was used to achieve the apparent density of the asphalt hot mixes presented in Table 6.

Resilient modulus and fatigue life tests were carried out under controlled strain conditions according to AASHTO TP8/96 standard in beam specimens of bituminous concrete with the following dimensions: 381 ± 6.35 mm in length, 50.8 ± 6.35 mm in height and 63.5 ± 6.35 mm in width. Table 7 presents the conditions imposed during resilient modulus and fatigue life tests. The specimens obtained from studied asphalt hot mixes were submitted to the long-term aging process normalized by AASTHO PP2/94.

Table 7. Test parameter for resilient modulus and fatigue life tests

Test Parameters	Fatigue life	Resilient modulus
Temperature of specimen test (ºC)	20	20
Load frequency (Hz)	10	10; 5; 2; 1; 0.5; 0.2; 0.1

5 RESULTS AND DISCUSSIONS

Figures 6 and 7 show the relation between the resilient modulus and fatigue life of conventional asphalt hot mixes produced with straight binder AC 50/70. In the resilient modulus tests five specimen and in fatigue life tests three specimen were tested. These results show that the dense graded (DG) asphalt hot mixes presented higher resilient modulus and less fatigue life than the gap graded (GG) asphalt hot mixes. This behavior is similar to those presented by Dantas Neto (2001) and Huang (1993) for conventional asphalt hot mixes, showing that there is a decrease of fatigue life when the stiffness of asphalt hot mixes is increased.

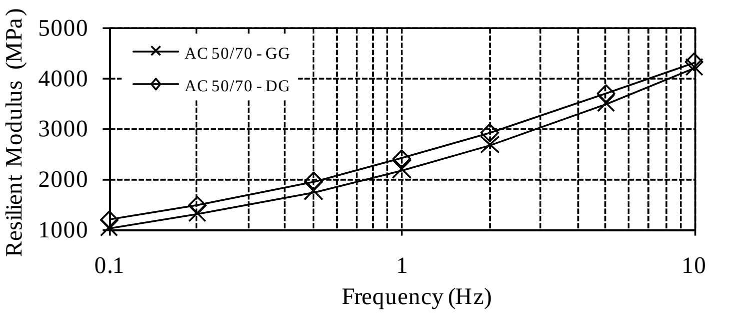

Figure 6. Resilient modulus of conventional asphalt hot mixes

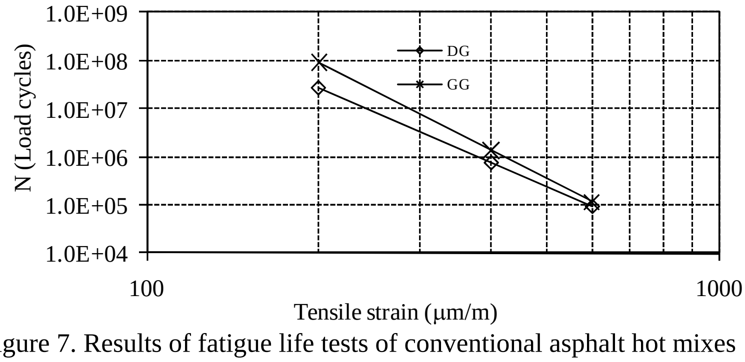

Figure 7. Results of fatigue life tests of conventional asphalt hot mixes

Figures 8 to 11 show the comparison of mechanical behavior between the conventional asphalt hot mixes and asphalt rubber asphalt hot mixes for both dense and gap gradation. In contrast with the results presented in Figures 6 and 7, it can be observed here that the asphalt rubber asphalt hot mixes presented higher resilient modulus and fatigue life than the conventional asphalt hot mixes. This indicates that there was a change of fatigue behavior represented by the Equation 3 proposed by Huang (1993) when comparing the asphalt rubber hot mixes with the conventional hot mixes defined by the four point bending procedure.

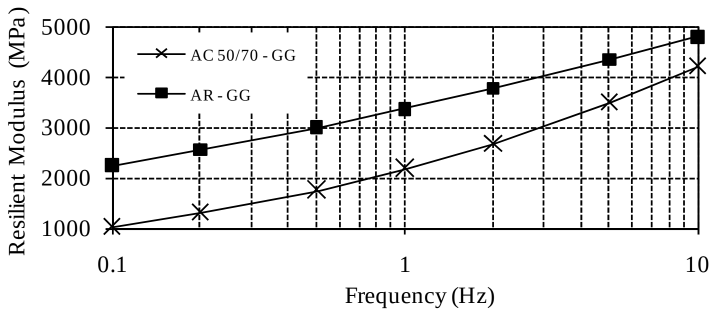

Figure 8. Resilient modulus of gap graded asphalt hot mixes

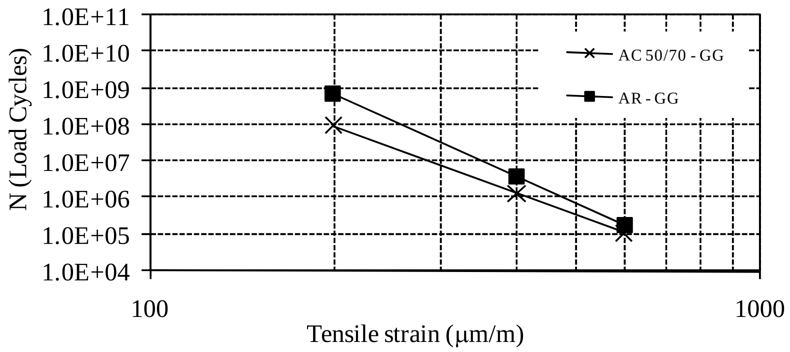

Figure 9. Results of fatigue life tests of gap graded asphalt hot mixes

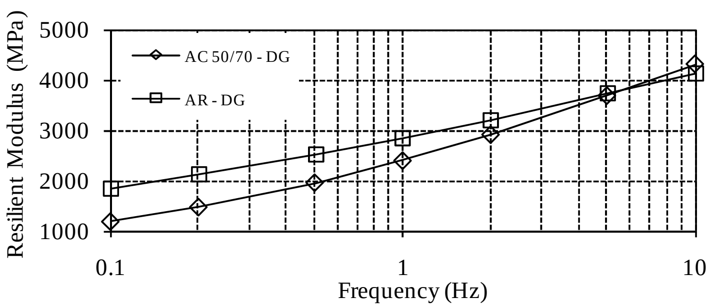

Figure 10. Resilient modulus of dense graded asphalt hot mixes

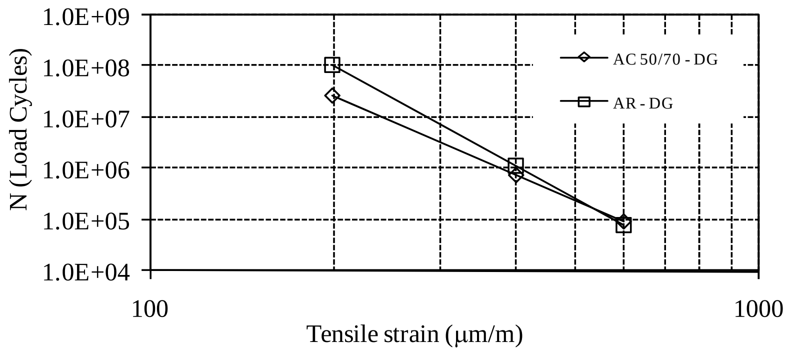

Figure 11. Results of fatigue life tests of dense graded asphalt hot mixes

Figure 12 and 13 show the relation of resilient modulus and fatigue life of asphalt rubber hot mixes with dense and gap gradation. Here, it can be observed once more that the increase of resilient modulus occurred with correspondent increase of fatigue life of the studied mixtures confirming the change of behavior.

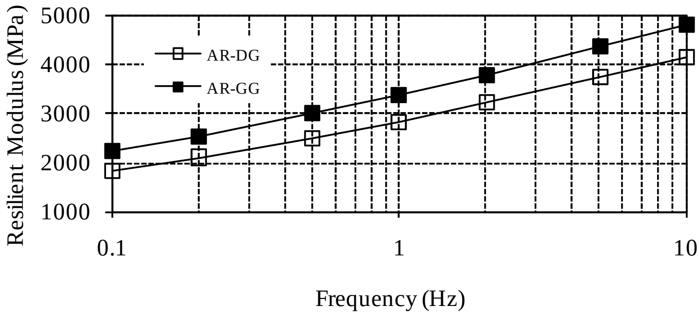

Figure 12. Resilient modulus of asphalt rubber hot mixes

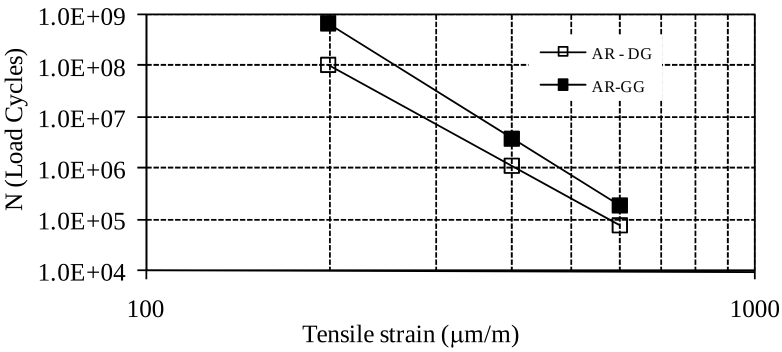

Figure 13. Results of fatigue life tests of asphalt rubber hot mixes

6 CONCLUSIONS

The results of resilient modulus and fatigue life tests of conventional asphalt hot mixes confirm the model proposed by Huang (1993). In these mixtures, the increase of resilient modulus produced a decrease of fatigue life of studied asphalt hot mixes.

Comparing the conventional asphalt hot mixes with those produced with asphalt rubber binders it could be observed that it was possible to increase the resilient modulus and fatigue life of dense and gap graded asphalt hot mixes. This behavior was also observed between the asphalt hot mixes used in this study.

The results of this work show that the use of asphalt rubber binder improves the mechanical behavior of asphalt hot mixes produced with these modified binders.

7 ACKNOWLEDMENTS

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