EFFECT OF THE FAILURE CRITERION ON THE LABORATORY FATIGUE RESPONSE PREDICTION OF HOT-MIX ASPHALT MIXTURES

EFECTO DEL CRITERIO DE FALLO SOBRE LA PREDICCIÓN DE LA RESPUESTA A FATIGA EN LABORATORIO DE MEZCLAS ASFÁLTICAS

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ABSTRACT: The primary objective of this research was to determine the effect of the failure criterion, used to compute the laboratory fatigue response of hot mix asphalt (HMA) mixtures specified by the Institute of Urban Development of Bogota D.C. (i.e., md10 and md20 mixtures), on the fatigue response prediction. The fatigue equations (i.e., fatigue curves) were determined using the controlled-strain trapezoidal fatigue test. The criteria used to establish the fatigue life corresponded to the classic (50% of the initial load)-, damage-, and breakage-failure criterion. Corresponding results suggested that the failure criterion selection can lead to significant differences in the laboratory fatigue life prediction (i.e., fatigue curves). However, for the dense-graded md10 mixtures, the fatigue curve was similar in disregarding the failure criteria applied. On the contrary, for the dense-graded md20 mixtures, application of the three failure criteria led to significant differences in fatigue life prediction; the smallest load cycles to failure (most critical) was determined based on the classic criterion. Future research should focus on establishing the failure criterion to be used for subsequent pavement structural design, especially for asphalt mixtures with a maximum aggregate size of 20 mm or higher.

KEYWORDS: Fatigue failure criterion, Fatigue equation, Hot mix asphalt, Trapezoidal fatigue test

RESUMEN: El objetivo principal de esta investigación fue establecer la influencia del criterio de fallo, empleado para calcular el comportamiento a fatiga en laboratorio de mezclas asfálticas en caliente especificadas por el Instituto de Desarrollo Urbano de Bogotá D.C. (i.e., mezclas md10 y md20), en la predicción de la respuesta a fatiga. Las leyes de fatiga (i.e., curvas de fatiga) se determinaron a flexo-tracción con muestras trapezoidales ensayadas a desplazamiento controlado. Los criterios utilizados para establecer la vida de fatiga correspondieron al clásico (50% de la fuerza inicial), de daño y de rotura. Los resultados correspondientes sugirieron que la selección del criterio de falla puede conllevar a diferencias significativas en la predicción de la vida de fatiga en laboratorio (i.e., curvas de fatiga). Sin embargo, se estableció que para las mezclas con granulometría densa md10, la ley de fatiga fue similar al emplear cualquiera de los tres criterios analizados. Por el contrario, para las mezclas asfálticas con granulometría densa md20, la aplicación de los tres criterios de falla conllevó a diferencias significativas en la predicción de vida de fatiga; el menor número de ciclos de carga a la falla (más crítico) fue determinado con el criterio clásico. Investigaciones futuras deberán profundizar en establecer que criterio de fallo se debe utilizar para el subsecuente diseño estructural de pavimentos, especialmente para mezclas asfálticas con curvas granulométricas que contengan agregados de tamaño igual o superior a 20 mm.

PALABRAS CLAVE: Criterio de fallo por fatiga, Ley de fatiga, Mezcla asfáltica en caliente, Ensayo de fatiga por flexo-tracción

1. INTRODUCTION

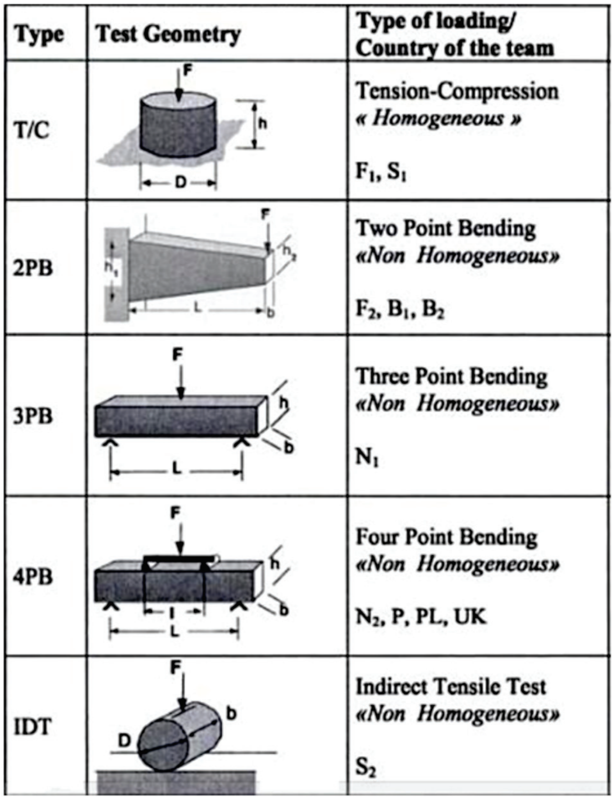
Load-associated cracking is still one of the most critical distresses affecting the performance of hot-mix asphalt (HMA) mixtures used as paving material. This distress results as a consequence of repeated vehicle load application on HMA mixtures, without reaching the ultimate strength, leading to material fracture by *fatigue* [1]. Thus, fatigue is a progressive phenomenon starting with micro-cracking (actually from the zero stiffness zones: the air voids in the HMA mixture) and progressing to an interconnected cracking pattern. This cracking pattern—a well known distress type termed *alligator skin*—is often manifested in or near the wheel path, or in both locations.

In addition, as a consequence of the fatigue process, the HMA mixture exhibits the reduction of stiffness [2] and the progressive cracking allows for air and water entrance. These conditions can further contribute to the pavement structure deterioration through oxidative aging and moisture damage in the HMA mixture [3] as well as an increase in the saturation level of the unbound granular materials underlying the HMA course.

Thus, the fatigue cracking of HMA mixtures is considered to be a structural distress affecting pavement service life and often related to costly maintenance and rehabilitation activities. Therefore, proper laboratory characterization of the HMA mixtures' fatigue life (e.g., the number of load cycles to failure) for mix design and evaluation, is of paramount importance for reducing the possibility of premature fatigue failure in the field.

In this context, several fatigue testing procedures for HMA mixtures are reported in the literature, which make use of different equipment, specimen geometry, and loading configurations. Figure 1 shows the geometric configuration of the different laboratory fatigue tests currently being used. These tests include: tension-compression fatigue test (T/C), trapezoidal cantilever fatigue test (2PB) (or trapezoidal fatigue test), three point flexural test (3PB), four point bending beam test (4PB), and diametral loading test (IDT) [4,5]. While in Europe the trapezoidal fatigue test has been widely adopted, in the USA the four point bending beam test has been more commonly used [6]. However, previous research [7] has concluded that these fatigue testing devices are equivalent for all practical purposes. In addition, these tests can be conducted under controlled stress or under controlled displacement. The last testing condition is the most frequently used for fatigue testing of HMA mixtures [8], although applications for each test condition are discussed in the classic literature on HMA fatigue characterization [2].

Thus, under laboratory-controlled conditions (e.g., temperature and time, frequency, and configuration of load), these tests evaluate the fatigue life of HMA mixture specimens (i.e., number of load cycles to reach "fatigue failure"). For a controlled-displacement test, the fatigue life is determined for specimens tested at different displacement values to subsequently plot the *fatigue curve* of the HMA mixture.



Type	Test Geometry	Type of loading/ Country of the team
T/C	F, h, D	Tension-Compression *« Homogeneous »* F_1, S_1
2PB	F, h_1, h_2, L, b	Two Point Bending *«Non Homogeneous»* F_2, B_1, B_2
3PB	F, h, b, L	Three Point Bending *«Non Homogeneous»* N_1
4PB	F, h, b, l, L	Four Point Bending *«Non Homogeneous»* N_2, P, PL, UK
IDT	F, D, b	Indirect Tensile Test *«Non Homogeneous»* S_2

Figure 1. Geometric configuration of fatigue tests for HMA mixtures [9]

The fatigue curve relates the number of load cycles to reach the fatigue failure versus corresponding strain values, computed for each displacement value used for laboratory testing. A *shift factor*, relating the laboratory and field fatigue models of the HMA mixture [10], allows for determinations of the fatigue curve applicable for pavement structural design (i.e., computation of the required HMA mixture thickness to control fatigue in the HMA mixture course).

Since previous research [11] reported that this shift factor can range between 3 and 100, its effect must be considered for proper fatigue structural design. Although at present these concepts are widely applied for pavement structural design under the mechanistic pavement design approach [12], a unified criterion for defining the fatigue failure of individual HMA mixture specimens is not available at this time in order to consistently define the laboratory fatigue curves.

In this context, the main objective of this paper is to analyze the influence of the failure criterion adopted for defining the laboratory fatigue life of individual specimens on the determination of the laboratory fatigue curve (i.e., fatigue equation) of HMA mixtures. Three failure criteria are analyzed based on trapezoidal fatigue test data gathered in the laboratory for two HMA mixtures.

In terms of the layout of this paper, after this introduction, a section on the failure criteria applied to determine the fatigue life of the HMA mixture specimens is presented. The methodology and materials are then discussed. Results and corresponding analyses are then presented, followed by the conclusions and recommendations.

2. FAILURE CRITERIA FOR DETERMINATION OF THE FATIGUE LIFE OF HOT MIX ASPHALT (HMA) SPECIMENS

This section presents a brief review on the three failure criteria analyzed to determine the fatigue life of HMA mixtures. These criteria correspond to the classic-, damage-, and breakage-failure criterion as subsequently described.

The *classic failure criterion* for determining the fatigue life (i.e., number of load cycles to failure) of HMA mixture specimens was proposed by Monismith (1969) [13] and Pell and Cooper (1975) [14]. In accordance with this criterion, for a displacement-controlled trapezoidal fatigue test, the failure (i.e., fatigue life, $N_{failure}$, in Fig. 2) is reached when the load value drops to a half of the "initial load value" (F_0 in Fig. 2). In the present research, the initial load value was defined as the first stable load value obtained after starting the fatigue test. For a stress-controlled trapezoidal fatigue test, the failure (i.e., fatigue life) is reached when the displacement value doubles the "initial displacement value" (D_0 in Fig. 3).

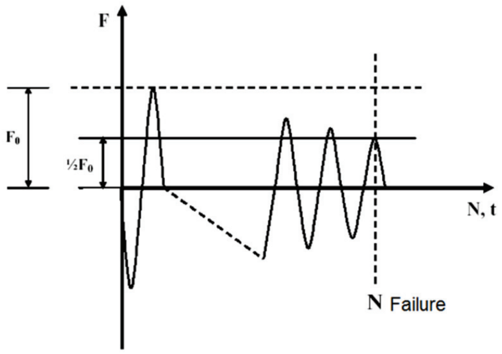


Figure 2. Load reduction and classic failure criterion for a displacement-controlled fatigue test [15]

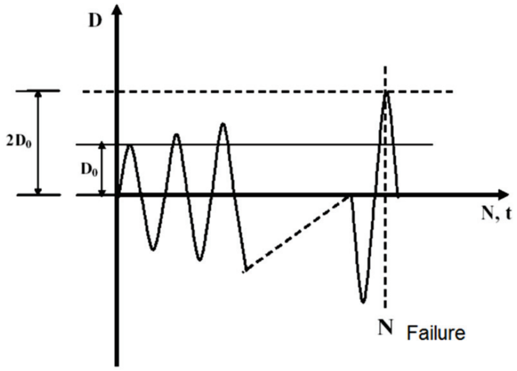


Figure 3. Displacement increase and classic failure criterion for a stress-controlled fatigue test [15]

The *damage failure criterion* is applied based on the analysis of the stiffness modulus, *E*, values along the fatigue loading process. For a given load cycle, this modulus is calculated as the slope of the corresponding hysteresis loop. As shown in Fig. 4, along the mixture fatigue process three particular phases can be distinguished, namely adjustment, quasi-static, and failure (or phases I, II, and III, respectively, in Fig. 4).

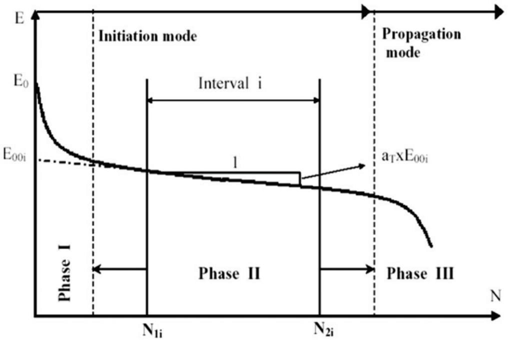


Figure 4. HMA fatigue response based on the damage failure criterion [16]

In the first phase, the stiffness modulus decreases rapidly as the load application progresses. This response is related to local effects in the particles and heat generation in the specimen. The second phase (Fig. 4) exhibits a linear decrease of the stiffness modulus and allows for the characterization of the fatigue progress rate. Finally, a rapid loss of stiffness modulus characterizes the third phase—fatigue failure—, which is related to crack development [16,17]. For computational purposes, the fatigue life was defined as the threshold load cycle between phases II and III and it was determined at the intersection point of the corresponding slopes representing each phase.

The *breakage failure criterion,* for a displacement or stress controlled test, determines the specimen fatigue life (i.e., $N_{failure}$) as a function of the change in the displacement or stress (alternative force) along the repeated loading process (Fig. 5). Based on this criterion, the specimen fails when the displacement or stress values exhibit an accelerated increase while the loading process progresses [15,18,19].

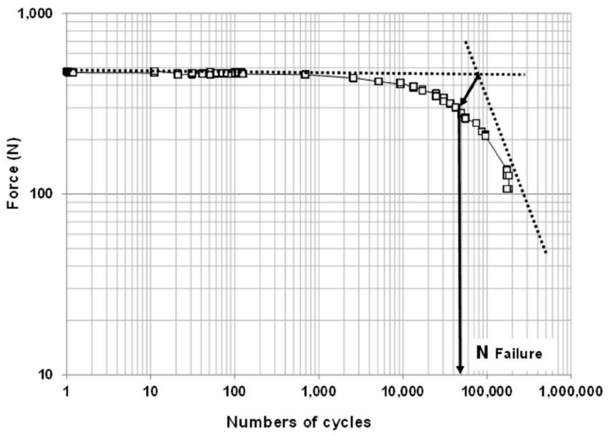


Figure 5. Evolution of force as a function of load cycles (breakage-failure criterion)

3. METHODOLOGY AND MATERIALS

Figure 6 shows the methodology applied in this research. After the aggregate- and asphalt-characterization testing and definition of the design aggregate gradation, the Marshall mix design method was applied to determine the optimum asphalt content for the HMA mixtures. Then, replicate HMA mixture specimens were fabricated for fatigue testing and the corresponding determination of fatigue life based on the three failure criteria previously discussed. The study was completed by plotting the fatigue curves, obtained after applying each fatigue failure criteria, and conducting the corresponding analysis of these results. Additional details of the materials and laboratory testing performed are provided subsequently.

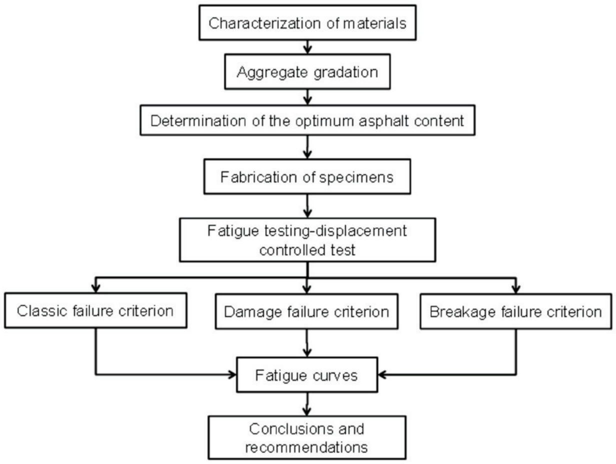


Figure 6. Research methodology

3.1. Aggregate gradation

Two dense-graded HMA mixtures were evaluated, namely the md10 and md20 mixtures specified by the Institute of Urban Development (IDU) of Bogota D.C. [20]. Figure 7 shows the gradations used (i.e., mean gradation curve defined for each band limit). The md10 and md20 mixtures are typically used in Bogota D.C., respectively, as surface course and binder course (also called *asphalt base course* [2]) for asphalt pavements. However, both HMA mixtures have been used as asphalt base course.

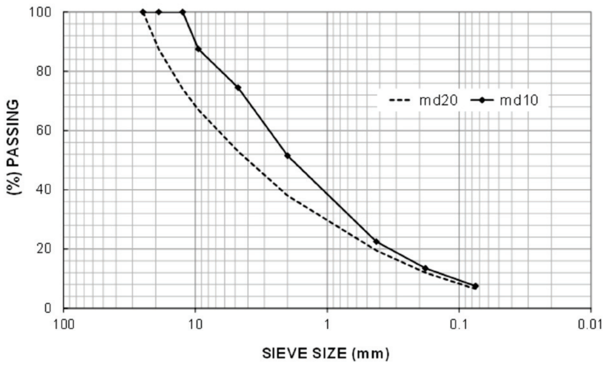


Figure 7. Aggregate gradation for the mixtures evaluated [20]

3.2. Materials characterization

Table 1 summarizes the results of the characterization tests conducted on the aggregates used for the fabrication of the HMA mixtures evaluated.

Table 1. Aggregate characterization tests

Test	Standard [21]	Result
Coarse aggregate absorption	ASTM C 127	3.36%
Coarse aggregate apparent specific gravity	ASTM C 127	2.38
Fine aggregate absorption	ASTM C 128	2.57%
Fine aggregate apparent specific gravity	ASTM C 128	2.46
Los Angeles abrasion	ASTM C 535	25.6%

The HMA mixture specimens were fabricated using a 60/70 (1/10 mm) penetration asphalt, fabricated by the Barrancabermeja refinery (Colombia). Table 2 summarizes the results of the asphalt characterization tests conducted.

Table 2. Asphalt characterization tests

Test	Standard [21]	Result
Penetration	ASTM D 5-97	62 (1/10 mm)
Ductility	ASTM D 113-99	115 cm
Viscosity	ASTM D 2170-95	1550 poises
Softening point	ASTM D 36-95	43ºC
Flash and fire point	ASTM D 3143-98	220 ºC and 225 ºC

3.3. Fatigue testing

The optimum asphalt content, determined based on the Marshall mix design method, was 5.5% for both the md10 and md20 mixtures, and the design total air voids content for these mixtures was 4.2%. The same total air voids content was targeted for subsequent fabrication of rectangular beams (300 × 300 mm and 25 mm in thickness) by vibro-compaction [8]. These beams were then sawed to trapezoidal specimens for fatigue testing. These specimens had top and base widths of 25 and 75 mm, respectively; 25 mm in thickness and 250 mm in height.

The displacement-controlled trapezoidal fatigue tests were conducted in accordance with the UNE-EN-12697 standard [8]. These tests were performed at 20 °C and a load frequency of 10 Hz. Four replicate specimens were tested under these conditions at a minimum of 3 displacement values. Then, the fatigue curves were plotted based on the mean fatigue life values computed from the 4 replicate specimens tested at each displacement value.

4. RESULTS AND ANALYSES

Figure 8 shows a typical curve of load evolution as a function of the number of load cycles applied. The figure also exemplifies the computation of the number of load cycles to fatigue failure based on both the classic- and breakage-failure criterion. In addition, Fig. 9 shows a typical load-displacement response curve obtained for a load cycle in the trapezoidal fatigue test. The stiffness modulus for each load cycle was then computed as the slope of this hysteresis curve (see Fig. 9), which allowed for subsequent computation of the fatigue life applying the damage failure criterion as discussed, based on Fig. 4.

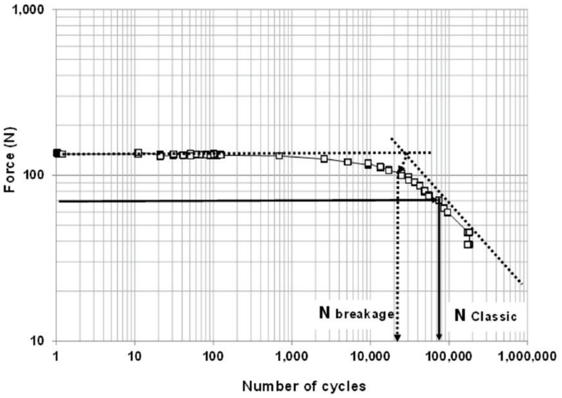


Figure 8. Force evolution as a function of load cycles and cycles to failure based on both the classic- and breakage-failure criterion

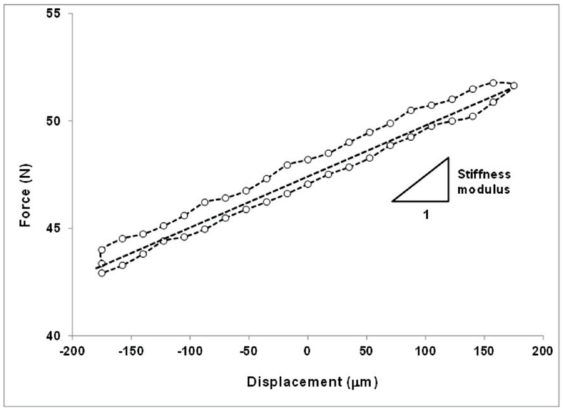


Figure 9. Load-displacement response in the fatigue test (i.e., hysteresis loop for a load cycle)

Figure 10 shows the fatigue curves computed using the classic failure criterion to determine the fatigue life of the HMA mixture specimens in the laboratory. The tendency and slope of the fatigue curves shown, which define the admissible tensile strain values for a given number of load cycles, suggest a better fatigue response for the md10 mixture as compared to that of the md20 mixture.

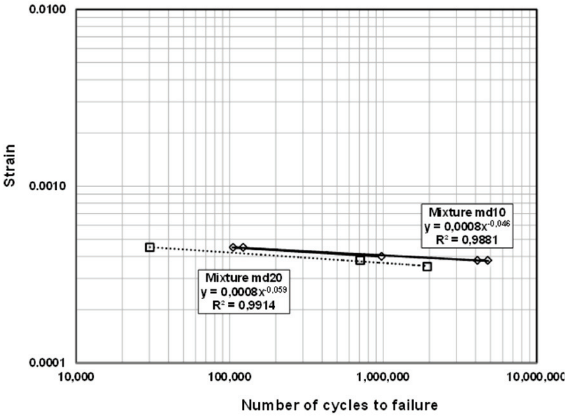


Figure 10. Fatigue curves for md10 and md20 mixtures based on the classic failure criterion

In fact, at a given strain value, the md10 mixture exhibited higher number of load cycles to failure (i.e., longer fatigue life) than the md20 mixture. For example, at a strain value of 0.0004, the md10 mixture failed at 1,000,000 load cycles, whereas the predicted number of cycles to failure for the md20 mixture was 200,000 load cycles. Given the magnitude of these differences, the computation of the HMA mixture design thickness for pavement structural design is expected to be modified. In other words, and as expected theoretically, the required HMA mixture thickness, under similar pavement structural design conditions, should be different when using the md10 and md20 mixtures as structural surface courses in HMA pavement structures. However, this analysis is only valid as an illustration of the design principle, since a valid determination of the HMA mixture thickness must include the laboratory-field shift factor.

Figure 11 shows the fatigue curves determined using the damage failure criterion for computing the fatigue life of the HMA mixture specimens. Similar conclusions to those that have been stated with their basis on the data shown in Fig. 10, can be reported. The fatigue curve slope for both mixtures evaluated is similar and consistent with the classic failure criterion; at similar tensile strain values, the md10 mixture again exhibited longer fatigue life than the md20 mixture.

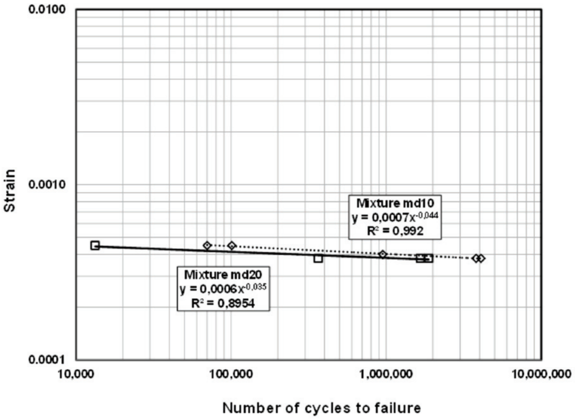


Figure 11. Fatigue curves for md10 and md20 mixtures based on the damage failure criterion

The fatigue curves determined by applying the breakage failure criterion are shown in Fig. 12. Based on this criterion, smaller discrepancies were obtained between the fatigue life of the md10 and md20 mixtures as compared to those reported based on the classic- and damage-failure criterions.

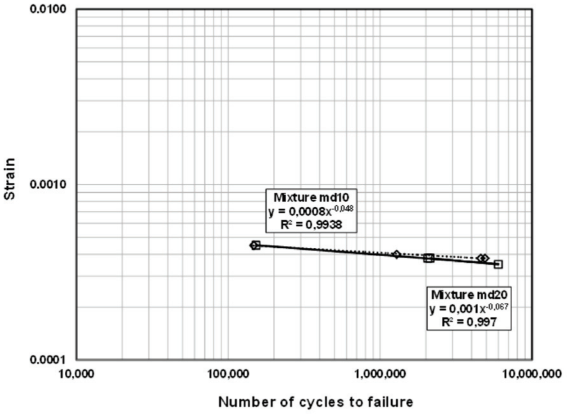


Figure 12. Fatigue curves for md10 and md20 mixtures based on the breakage failure criterion

Figures 13 and 14 show a comparison of the fatigue curves computed using the three failure criteria analyzed for the md10 and md20 mixtures, respectively. The comparison shown in Fig. 13 suggests that comparable fatigue curves were obtained for the md10 mixture disregarding the fatigue-life failure criterion applied. However, significant differences were reported for the md20 mixture (Fig. 14). For this mixture, the best fatigue response was predicted based on the breakage failure criterion. The worst fatigue response (i.e., most critical for structural pavement design leading to the higher required HMA mixture thicknesses under comparable design conditions) can be related either to the classic- or the damage-failure criterion depending on the strain value. At high strain values, the classic failure criterion led to larger values of admissible repetitions of load cycles as compared to those computed using the damage failure criterion.

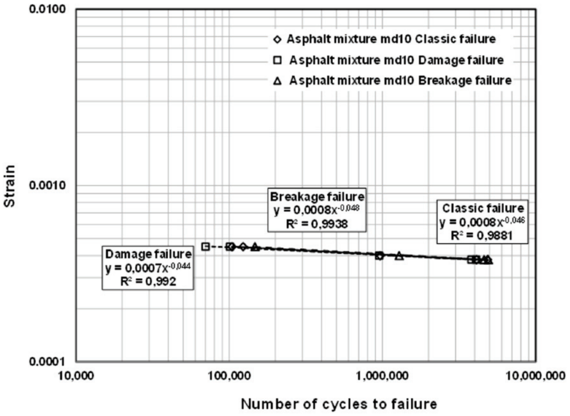


Figure 13. Fatigue curves for the md10 mixture based on the classic-, damage-, and breakage-failure criterions

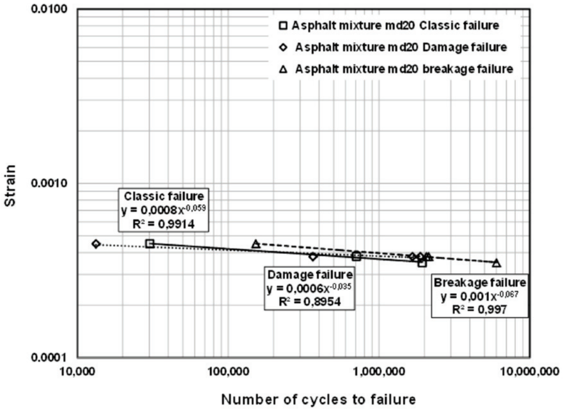


Figure 14. Fatigue curves for the md20 mixture based on the classic-, damage-, and breakage-failure criterions

As discussed earlier, a comparison of the fatigue curves based on the three failure criteria analyzed suggests potential differences in the laboratory fatigue predictions for subsequent structural design (i.e., after properly accounting for the fatigue shift factor). The classic-failure criterion relies on an arbitrary condition to define the specimen failure (i.e., 50% reduction of load or displacement during the test) [2], which is not necessarily related to the material properties—and/or response parameters—involved in the fatigue process of HMA mixtures. This condition can limit its general application for different mixtures types and materials.

On the contrary, the analysis of the specimen fatigue life based on the stiffness modulus progression—damage failure criterion—corresponds to a closer evaluation of the mixture damage process and its macroscopic effect (i.e., stiffness reduction as the fatigue process takes place). Similarly, the breakage failure criterion is related to the macroscopic mixture response in terms of damage progression, which is captured through the evaluation of load reduction (i.e., for a displacement-controlled fatigue test) as the number of load cycles progresses.

Additional research is suggested to further explore the applicability of the specimen fatigue failure criteria analyzed and recommend a specific criterion to standardize the procedure of fatigue-life determination. This research effort will contribute to improve the reliability of the corresponding laboratory fatigue curves and the subsequent pavement structural design. Additional research should also include fatigue characterization of HMA mixtures with different maximum aggregate sizes.

5. CONCLUSIONS AND RECOMMENDATIONS

This paper analyzed the effect of the fatigue failure criterion applied to estimate the fatigue life of HMA mixture specimens in the laboratory. Three fatigue failure criteria were compared (i.e., classic-, damage-, and breakage-failure criterions) based on the fatigue laboratory testing of two dense-graded HMA mixtures. Based on the results gathered and corresponding analyses, the following conclusions can be offered:

- Selection of the failure criterion used to determine specimen fatigue life can lead to differences in the fatigue curves of the HMA mixture (i.e., laboratory fatigue life prediction). In turn, these differences can affect the computation of the HMA mixture design thickness—after properly accounting for the *shift factor*—to control fatigue cracking in the corresponding flexible pavement structure.

- Therefore, additional research should be conducted to standardize the procedure for determination of fatigue life of HMA mixture specimens. In addition, the effect of the aggregate gradation on the fatigue resistance should be further assessed to optimize the HMA mixture selection process for pavement structural design purposes.
- Similar fatigue curves were computed for the dense-graded md10 mixture using the three failure criteria analyzed. However, for the dense-graded md20 mixtures, the application of the three failure criteria led to differences in both the slope and tendency of the fatigue curves. For both mixtures, the smallest load cycles to failure (most critical) was determined based on the classic-failure criterion, whereas the largest number of load cycles to failure were related to the breakage failure criterion.
- Disregarding the failure criterion applied, the md10 mixture exhibited better fatigue resistance as compared to that of the md20 mixture.

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REFERENCES

[1] Reyes, O. J., Análisis del fallo a fatiga de los ligantes hidrocarbonados. Parámetros que definen su comportamiento [Ph.D. Dissertation]. Barcelona, Spain: Universidad Politécnica de Cataluña, 2009.

[2] Huang, Y. H., Pavement analysis and design, Upper Saddle River, NJ: Pearson, Prentice Hall, 2004.

[3] Walubita, L. F., Epps Martin, A. and Mikhail, M. Y., Investigation of a surrogate fatigue test protocol for asphalt mix-design and mixture screening, International Conference on Advanced Characterization of Pavements and Soil Engineering Materials, 2007.

[4] Doan, H. and Soliman, S., Influence des parameters de formulations sur le module et la resistence a la fatigue des graves/bitumes: Bulletin de lianson des laboratoires de ponts et chauusees, 1977.

[5] Partl, M. and Franckewn, M., Rilem interlaboratory test on stiffness properties of bituminos mixtures. Mechanical test for bituminous materials. RILEM, Balkema, Rotterdam, 1998.

[6] Rowe, G. M. and Bouldin, M. G., Iimproved techniques to evaluate the fatigue resistance of asphaltic mixtures, 2nd Eurasphalt & Eurobitume Congress Barcelona 2000, 2000.

[7] Tayebali, A. A., Deacon, J. A., Coplantz, J. S., Harvey, J. T. and Monismith, C. L., Fatigue response of asphalt-aggregate mixes, part 1 - test method selection. SHRP Project A-003A, Strategic Highway Research Program, National Research Council, Washington, D.C., 1992.

[8] AENOR, Método de ensayo para mezclas bituminosas en caliente. Resistencia a la fatiga. Serie de Normas UNE-EN 12697 y UNE-ES 13108, Madrid, 2008.

[9] RILEM, Performance testing and evaluation of bituminous materials. In: Proceedings PRO 28, 6th International RILEM Symposium. Zurich, 2003.

[10] Kim, R. Y., Modeling of asphalt concrete, New York: McGraw-Hill, 2009.

[11] Lytton, R., Chen, C. W. and Little, D., Fundamental properties of asphalts and modified asphalts, vol iii: A micromechanics fracture and healing model for asphalt concrete. Final Report No FHWA-RD-98-143. Federal Highway Administration, Washington D.C., 2001.

[12] Reyes, O., Alvarez, A., Botella, R. F. A., Study of a hot asphalt mixture response based on energy concepts.,Revista Dyna, año 78, Nro 168, pp 45-52. Medellin, Agosto 2011.

[13] Monismith, C. and Deacon, J. A., Fatigue of asphalt paving mixtures, Journal of Transportation Engineering, ASCE, 95 (2), pp. 317-346, 1969.

[14] Pell, M. and Cooper, K., The effect of testing and mix variables on the fatigue performance of bituminous materials, Proceedings of the Association of Asphalt Paving Technologist, 44, 1975.

[15] Alonso, J., Estudio del proceso de deformación y agrietamiento por fatiga de mezclas bituminosas sometidas a cargas cíclicas [Doctoral Dissertation]. Universidad Politécnica de Cataluña, 2006.

[16] Di Benedetto, H., De La Roche, C. and Francken, L., Fatigue of bituminous mixtures: Different approaches and rilem interlaboratory tests". Mechanical tests for bituminous materials, 5th mtbm rilem, pp. 15-26, 1997.

[17] Baaj, H., Comportement á la fatigue des matériaux granulaires trités aux liants hydrocarbones [These de Docteur-Ingénieur]. Villeurbanne, INSA, 2002.

[18] Rodriguez, M., Análisis de la propagación de fisuras y de los criterios de fallo en el comportamiento a fatiga de las mezclas bituminosas [Doctoral Dissertation]. Universidad Politécnica de Cataluña, 2009.

[19] Perez, F. E., Miro, R., Martinez, A. and Alonso, J., Desarrollo de un nuevo procedimiento para la evaluación del comportamiento a fatiga de las mezclas bituminosas a partir de su caracterización en un ensayo a tracción. Primer Premio Internacional a la Innovación en Carreteras-Asociación Española de la Carretera, ed., Madrid, 2006.

[20] INSTITUTO DE DESARROLLO URBANO-IDU, Especificaciones técnicas generales de materiales y construcción para proyectos de infraestructura vial y de espacio público en bogotá. Bogotá D.C., 2007.

[21] ASTM INTERNATIONAL, Annual book of astm standards. West Conshohocken, PA, 2001.