UGR-FACT test in the study of fatigue and cracking phenomena in asphalt pavements

Fernando Moreno-Navarro[1, a], **Mª Carmen Rubio-Gámez**[1, b]

[1] *Ingeniería de la Construcción y Proyectos de Ingeniería, Universidad de Granada, Granada, Spain*

[a] fmoreno@ugr.es
[b] mcrubio@ugr.es

Digital Object Identifier (DOI): dx.doi.org/10.14311/EE.2016.341

ABSTRACT

The understanding of fatigue and cracking phenomena is crucial to design more durable asphalt pavements. For this purpose UGR-Fact test has been recently developed. This paper describes this test method that consists of a device that is able to simulate traffic loading and climatic stresses in asphalt pavement at laboratory scale. The asphalt material is performed through a controlled fatigue cracking process that allows the analysis of the cracking propagation in the initiation, progression and failure stages. Among its main advantages to highlight: the test can be carried out in stress or strain controlled mode, it allows the study of laboratory specimens and also cores from pavements, multi-layers section can be analysed, it is easy to reproduce at a low economic cost. On the other hand the use of dissipated energy concepts in material fatigue processes establishes a series of parameters that accurately define the fatigue cracking performance of a bituminous mix

Keywords: Crack propagation, Fatigue Cracking, Mechanical Properties, Mixture design, Performance testing

1 INTRODUCTION

One of the most common pathologies in asphalt pavements all over the world is fatigue cracking. This distress can also be considered as one of the main factors which cause the end of the service life of roads. These infrastructures are designed to support the loads transmitted by the traffic as well as the effects produced by a number of climatological phenomena (rain, thermal changes, solar radiation, etc.). Nonetheless, most of these efforts are cyclical and they exert a fatigue process upon the asphalt pavements that leads to the appearance of cracks, which in the medium to long term cause the structural failure of the infrastructure (bad load transfers that eventually lead to deformations and shear failure; penetration of moisture and of other chemical agents that cause potholes, peeling, washing of fines, reduced bearing capacity, etc.). In addition, the presence of cracks can also significantly reduce user comfort as well as safety (an uneven pavement surface makes driving more risky, increases noise level, and reduces tire friction) [1]. Therefore, it is very important to develop more resistant materials against fatigue cracking and due to this, it is necessary to provide new laboratory tests that could offer a more accurate analysis of their mechanical performance.

Currently, there are various tests used to evaluate fatigue cracking [2, 3], but there is no common reference test to evaluate fatigue cracking in asphalt mixtures (in contrast to other pavement pathologies such as rutting, and pathologies caused by water action). On the one hand, common fatigue tests only evaluate fatigue without specifically focusing on cracking, and do not use suitable geometries or loading and test conditions (do not correspond to the actual loads that the pavement must sustain during its service life). On the other hand, sophisticated tests that are based on more realistic loading conditions lead to interesting one-off laboratory studies (and are often very expensive which prevents them from being widely applied to mix design), but the results obtained cannot be compared to those of other mixtures developed under the same conditions in other research centers [4].

In addition, most of the existing laboratory tests present some drawbacks when analyzing the fatigue performance of bituminous materials. One aspect that prevents an accurate analysis of fatigue cracking in bituminous mixtures is the presence of other phenomena that co-exist with damage during cyclic loading (plastic deformations, heating, thixoptropy, etc.) [5-7]. Whilst these phenomena cannot be considered as fatigue damage, their appearance changes the visco-elastic properties of the material and therefore it is very difficult to quantify the changes that are due only to real damage [8]. Another aspect is the difficulty in selecting a homogenous failure criterion. The propagation of the global (micro-cracks) and local (macro-cracks) damage will directly depend on many variables [9, 10] including the type of bituminous mixture evaluated, the test conditions (amplitude, frequency and temperature), the type of test used, the geometry of the specimen, etc. It is therefore very difficult to clearly separate and identify a damage limit which defines a failure criterion (global or local) that could be generalized in any fatigue test [10, 11].

For this purpose, a simple and low-cost laboratory test, the UGR-FACT test method (University of Granada – Fatigue Asphalt Cracking Test), has been developed at the University of Granada (Spain) , in order to improve the mechanical resistance of bituminous materials (which could extend the service life of roads and highways, and reduce the investment in their maintenance). This test method attempts to reproduce the efforts generated by traffic loads and thermal gradients, which lead to the appearance of fatigue cracking in pavements. In addition, by analyzing the dimensional variations and the energy dissipated by the material in each load cycle, the method is able to accurately evaluate the damage produced as well as its mechanical performance (avoiding the problems previously mentioned). The most significant advantage is that the test method is able to monitor the cracking process by avoiding the problems of randomness and tridimensional dispersion of the phenomenon. Finally, the test device is capable of evaluating both simple and compound materials of variable dimensions (complete pavement sections), it can be adapted to any dynamic press, simple to operate, and from a technical viewpoint, it is easy to reproduce.

The present paper describes the main characteristics of this test method (i.e. the device developed, its geometry, and the theoretical approach used for the analysis of the results and the definition of the failure criterion to be used), as well as some application examples in order to demonstrate its potential as a new tool for improving the design of bituminous mixtures for resisting fatigue loading.

2 UGR-FACT METHOD

2.1 Test device

The UGR-FACT test reproduces the efforts that lead to the appearance of fatigue cracking in pavements (traffic loads and thermal gradients), by using a simple device. This device is composed of a platform with two sloping surfaces and two rails where two supports are placed (Figure 1). These supports are composed of a carriage (which is adapted to the shape of the rails and allows an effective load transmission and the sliding of the supports without residual movements that could lead to errors in deformation measurements), a plate to which the test specimen is attached with epoxy resin, and a rubber pad under these plates (which allows the flection of the specimen). One of the supports is also equipped with a recovery spring, which simulates the presence of the foundation layers.

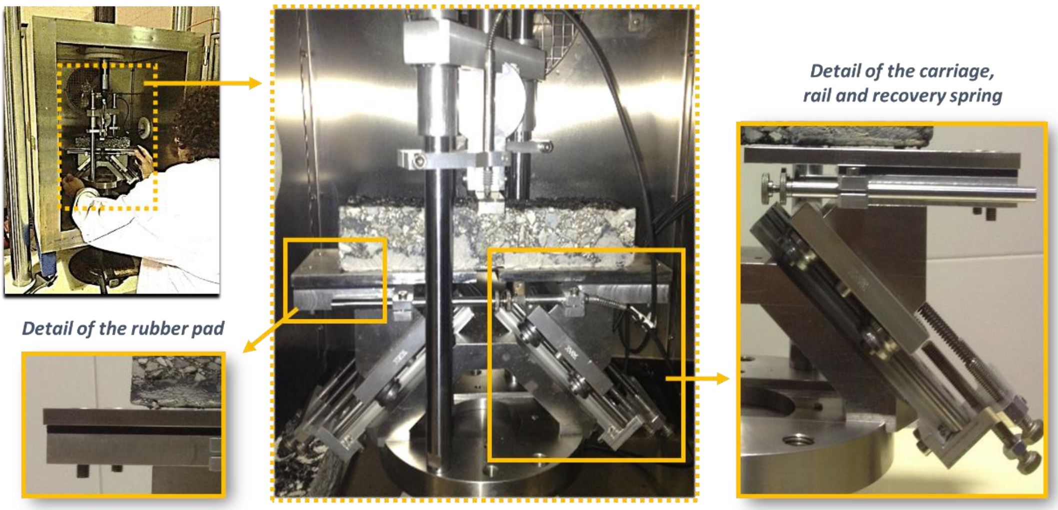

Figure 1: UGR-FACT test device

The distance between the supports can vary (Figure 2), depending on the type of deterioration to be reproduced (e.g. a crack, pre-crack or a dilatation joint, a pothole or patch, or an undamaged pavement).

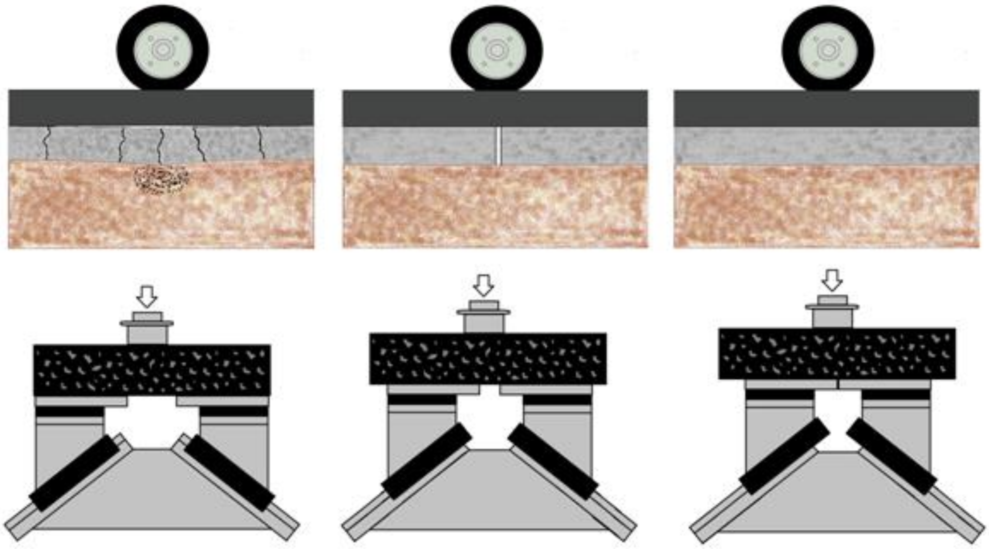

Figure 2: Sketch of the different configurations of the test.

The horizontal supports have two auxiliary elements (one on each face) where the horizontal deformation gauges (LVDT) are located. Similarly, two vertical spindles are used to locate the vertical deformation gauges in the upper part of the test specimen (Figure 3). Finally, the head of the load application is composed of a piece of steel that is thick enough to prevent deformations from appearing during the load application. This avoids the differential errors that can arise due to its own deformation and which are unrelated to the test specimen, whilst providing a flat surface for the vertical deformation gauges.

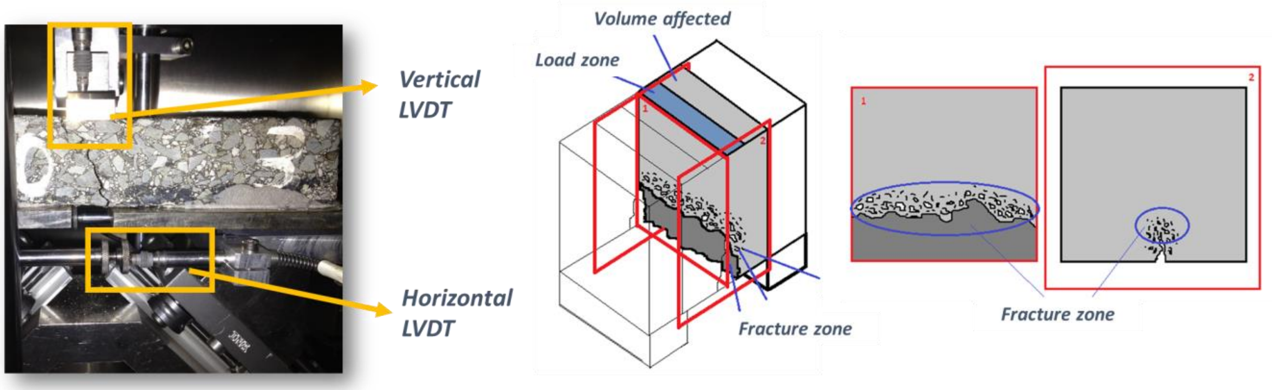

Figure 3: Detail of the LVDT position and random propagation of the fracture.

The simple geometry of the test device is capable of generating horizontal as well as vertical deformations in the test specimen, which reproduce the bending and shear stresses due to traffic loading, as well as the tensile strains induced by thermal gradients (Figure 4).

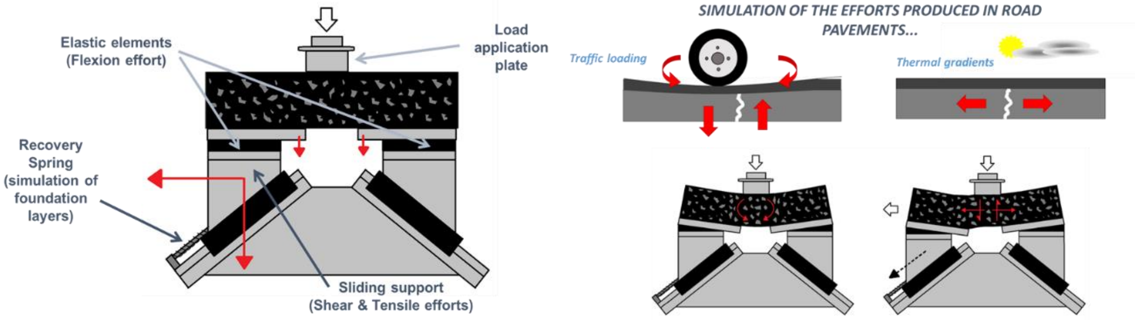

Figure 4: Sketch of the efforts generated with the UGR-FACT device.

For this purpose, a combined load function is used (Figure 5): a main up and down ramp that simulates thermal effects (with lower frequencies and higher amplitude) and a secondary verse-sine that represents traffic loads (with higher frequencies and lower amplitudes).

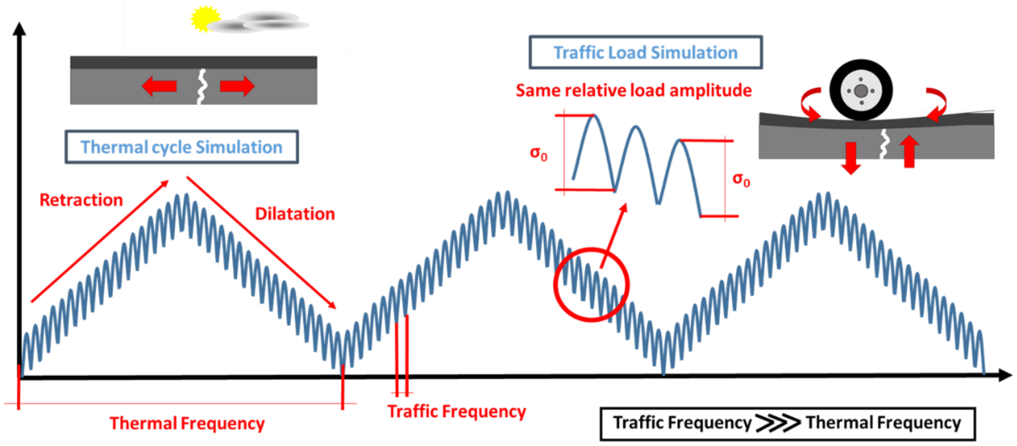

Figure 5: Sketch of the loading function used.

The test is performed at a controlled temperature inside a climate chamber, and the parameters (load amplitude, frequency, and rest periods) and test conditions (test temperature and distance between supports) can also be varied, depending on the needs of the test. The test device presented is therefore able to generate and propagate a controlled fatigue cracking process under similar circumstances to those expected to occur during the service life of asphalt pavements. Furthermore, due to its reduced dimensions and its specific geometry, it is a versatile device that allows for the evaluation of individual bituminous materials, as well as complete asphalt pavement sections or anti-cracking systems (Figure 6).

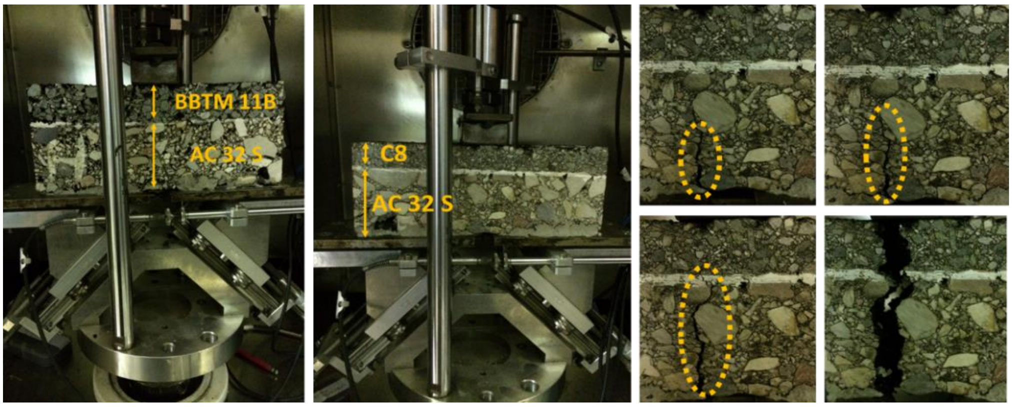

Figure 6: Testing example of different pavement sections.

2.2 Theoretical approach for analysis of the results and definition of the failure criterion

During the UGR-FACT test, the vertical and horizontal displacements produced in the material in each load cycle are controlled using four LVDTs (one vertical and one horizontal in each face of the specimen - see Figure 3). Based on the measures made, two different types of displacements can be observed in each direction (horizontal and vertical) and load cycle: a "permanent" one (hi, vi) that remains after the load cycle and is related to the non-recoverable deformations or the damage produced in the material; and a "maximum" one (Hi, Vi) that is related to the consistency of the material in the given cycle (Figure 7).

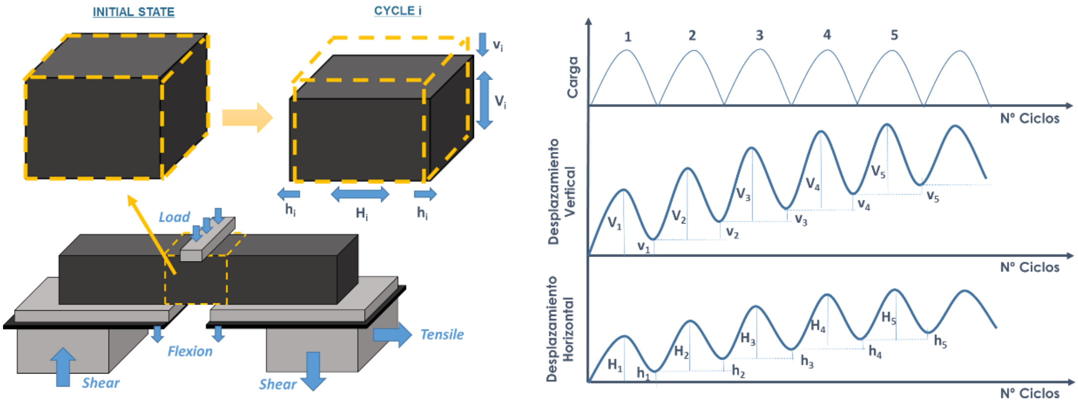

Figure 7: Outline of the efforts and displacements produced in the bituminous material during the UGR-FACT test.

Based on these considerations, the "permanent" displacements (h_i, v_i) can be used to define the variation in the geometry ($\Delta\varepsilon_i$) of the material in the zone where the fatigue phenomenon takes place. This variation in the volume (measured in percentage) is calculated from the changes produced in the dimensions of the material in the vertical and horizontal directions (Eq. 1).

$$\Delta\varepsilon_i = \frac{(\delta_{hi}\cdot\delta_{vi})-(\delta_{hi-1}\cdot\delta_{vi-1})}{(\delta_{hi-1}\cdot\delta_{vi-1})}\cdot 100 \qquad (1)$$

Where $\Delta\varepsilon_i$ is the variation of the geometry of the specimen in the cycle i; δ_{hi} and δ_{vi} are the horizontal and vertical dimensions of the specimen in the cycle i; and δ_{hi-1} and δ_{vi-1} are the horizontal and vertical dimensions of the specimen in the previous cycle.

The hysteresis loop described due to the "maximum" displacements (H_i, V_i) produced in the material are also used to define the dissipated energy in each load cycle (which is obtained by the addition of the dissipated energies calculated from the values of the areas inside the hysteresis loops in the vertical and horizontal directions, Eq. 2). In this respect, the use of the areas are more accurate than the use of the absolute value of the "maximum" displacements (which are commonly used to define parameters such as modulus), since the areas take into account the viscous and elastic nature of the material.

$$\omega_i = \omega_{hi} + \omega_{vi} \qquad (2)$$

Where ω_i is the dissipated energy in cycle *i* (in J/m^3); ω_{hi} is the horizontally dissipated energy in cycle *i* (in J/m^3); and ω_{vi} is the vertically dissipated energy in cycle *i* (in J/m^3).

In this respect, both parameters ($\Delta\varepsilon_i$ and ω_i) can be used for a combined analysis, which allows for a precise evaluation of the evolution of the fatigue damage process occurring in bituminous materials. Figure 8 shows a typical graph obtained from the representation of these two parameters (ω_i in the x axel, and $\Delta\varepsilon_i$ in the y axel). As can be observed, the different stages of the fatigue cracking process (plastic deformations, thixotropy, etc.; micro-damage; and macro-damage [5]) can be clearly identified in the material. During the first part of the test, high variations are produced in the geometry of the materials due to their molecular mobility [12, 13], which are reduced as the number of load cycles applied increases, due to the strain hardening phenomenon [14]. In spite of this significant variation in the geometry of the material, the dissipated energy measured in each load cycle during this first part does not change considerably (thus, first part of the curve almost represents a vertical descent). This fact means that the variations produced in the material due to the cyclic loads do not produce any damage, since its dissipated energy remains similar to the initial one (which represent the visco-elastic response of the undamaged material). Based on this consideration, in the example shown in Figure 8, the first 15000 load cycles do not cause fatigue damage in the material – rather, they induce the appearance of plastic deformations and other visco-elastic phenomena such as thixotropy or heating. The value of the initial dissipated energy obtained represents the molecular mobility capacity of the material evaluated under the test conditions employed (frequency and temperature). As this initial dissipated energy decreases (low temperatures and high frequencies), the material shows a lower molecular mobility and therefore the stresses applied in each load cycle will be mainly absorbed in the form of strains at molecular bonding level (reducing the variations produced in the geometry of the specimen due to plastic deformations), until they produce its fracture by molecular scission. In contrast, a high initial dissipated energy means a high molecular mobility in the material (high temperatures and low frequencies). In this case, the stresses transmitted in each load cycle produce a rapid development of plastic deformations, which cause the appearance of the strain hardening phenomenon that will induce the ductile failure of the material.

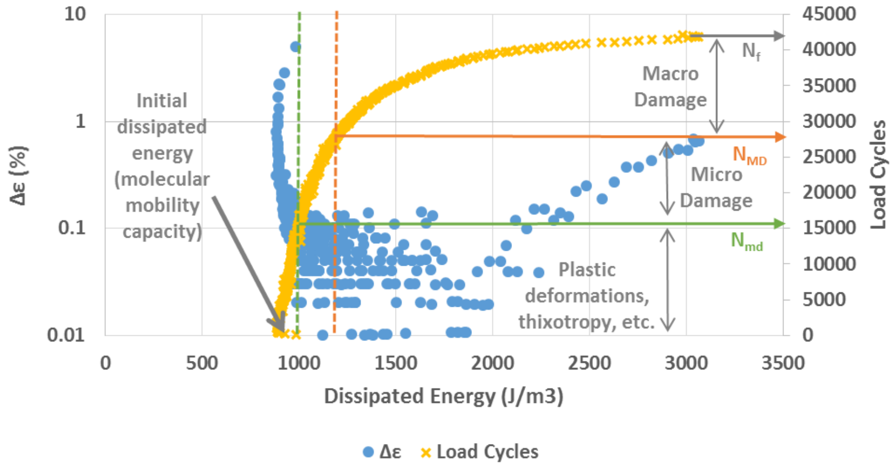

Figure 8: Example of the values obtained in the representation of Δε and load cycles as a function of the dissipated energy.

On the second part of the test, the variations in the geometry of the material become very small (in the example shown, less than 0.1%) and the dissipated energy increases little by little. This is due to the reduction of the molecular mobility capacity of the material (caused by the strain hardening phenomenon), which induces an increase in the energy absorbed at molecular bonding level. Because of this fact, molecules begin to fracture and the dissipated energy measured in each additional cycle increases (N_{md}, showing that the internal properties of the material are being altered). Therefore, in this part of the test each additional load cycle does not produce plastic deformations, but instead they start to produce micro damage due to molecular rupture. Finally, after a certain number of cycles, the dissipated energy begins to increase considerably by maintaining the changes produced in the geometry (N_{MD}, which means the initiation of the macro-crack due to the coalescence of micro-cracks), until a point is reached where the values of $\Delta\varepsilon_i$ began to increase again (due to the propagation of the macro crack, third part of the test), and the total failure of the specimen is reached (N_f).

Therefore, using this approach it is possible to obtain a precise measurement of the propagation of the damage appearing in the material at the two levels: damage in the volume (micro-cracks) and localized damage (macro-crack). This information could be very useful for taking into account the macro-damage in the estimation of the fatigue life (which traditionally cannot be included because of its randomness and dispersion), or for the definition of a more accurate failure criterion (global or local) that could offer an analysis under the same level of damage (in spite of the type of materials tested or the testing conditions used). In addition, this approach highlights the various phenomena occurring during cyclic loading and is able to identify which of them is causing real damage in the material. In this respect, it can be argued that the real fatigue life (N_{fl}) of the material can be defined as $N_{fl}=N_f-N_{md}$, as it marks the number of cycles from the initiation of damage until its total propagation through the specimen. Based on these considerations, the calculus of the mean damage parameter (which determines the susceptibility of the material to be damaged by cyclic loads [15]) must be obtained from the values measured during those cycles.

3 APPLICATION EXAMPLES

The repeatability of the UGR-FACT test method has been validated under various test conditions [4], obtaining satisfactory results in terms of the parameters measured (r=18%, dissipated energy and variation in the geometry) as well as failure cycle (r=16%). In addition, the test method has demonstrated a high sensitivity to the test conditions (load amplitude, frequency, temperature, etc.), aggregate nature, type of binder used or type of mixture, which allows a precise evaluation of different materials under specific circumstances [16]. This aspect is highly valuable when considering the optimization of the asphalt mixture design at laboratory level, since it permits the selection of the most accurate materials (aggregates, binders, additives, etc.) and dosages for the manufacture of the mixture.

The main objective of this section is to demonstrate the practical application of this test method. For this purpose, a range of research studies conducted using UGR-FACT will be summarized. Figure 9 shows some specimens tested in a study where the effect of aggregate nature on the fatigue cracking behavior of bituminous mixtures was assessed [16]. In this study, two asphalt mixtures with the same mortar (bitumen, filler and fine aggregate) but different types of coarse aggregate (ophite and limestone) were studied. The results showed that although the two mixtures behaved similarly in terms of cohesion (measured by the moisture sensitivity), the fatigue cracking behavior of a mixture manufactured with ophite aggregates was superior to that manufactured with limestone aggregates. The damage caused in each cycle was greater in the case of the limestone mixture, which was found to have a considerably shorter fatigue-cracking life than the ophite mixture. Therefore, the nature of the coarse aggregate tested did not significantly affect its adhesion to the mortar, but it did have an evident impact on fatigue-cracking behavior. The ophite aggregate, which is more resistant to fragmentation, made the asphalt mixture respond better to fatigue cracking. Accordingly, when the aggregate is more resistant, more energy (i.e. more load cycles) is necessary for the cracking process to develop since the macro-crack must either fracture the aggregate or go around it. These results show that a correct selection of coarse aggregate is important not only in terms of shape or gradation, but also in terms of resistance since it can considerably extend the fatigue-cracking life of the bituminous mixture.

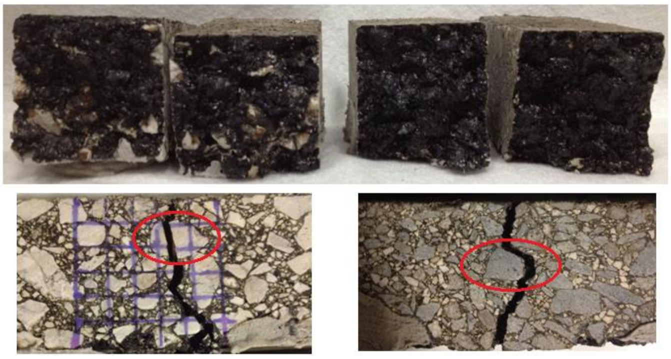

Figure 9: Detail of macro-crack propagation: limestone aggregate fractured (left); ophite aggregate rounded by the macro-crack [16].

Figure 10 shows the macro-cracks obtained in several asphalt mixture specimens manufactured with different binders. In this research study [17], four BBTM asphalt mixtures with the same mineral skeleton, but different types of bitumen (neat, polymer modified, crumb rubber modified wet and dry process) were studied by applying the UGR-FACT test procedure. Based on the findings of this study, it is clear that the type of binder used has an important influence on the fatigue cracking damage caused in a specimen (under the same loading conditions) and therefore on the service life of asphalt mixtures. Similarly, the type of bitumen will influence the characteristics of the resulting macro-cracks (more or less thinner and ramified).

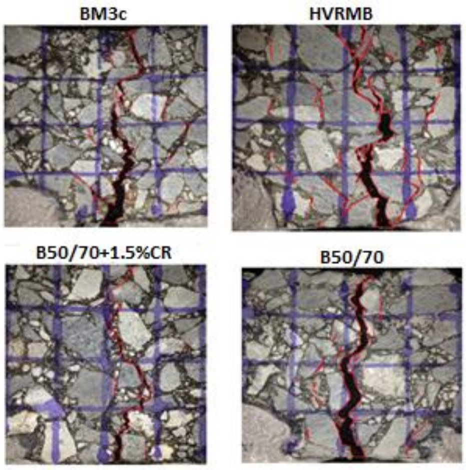

Figure 10: Detail of the macro-crack propagation as a function of the type of binder used [17].

The UGR-FACT test can also be used to investigate sensitive phenomena such as the influence of the temperature on the fatigue resistance of bituminous materials or their healing capability [18-21]. Figure 11a shows the mean values obtained in the parameters ω_i and $\Delta\varepsilon_i$ in the different UGR-FACT tests carried out with the mixture AC at various temperatures. It is clear that, for a given set of test conditions, as the test temperature increases the variations produced in the geometry of the material during the early stage of the loading process also increase. This occurs because the molecular mobility of bituminous materials increases with temperature. In this case, most of the energy introduced into the material in each cycle (which is provided by the constant stress loading and is the same regardless of the test temperature) is consumed in the re-orientation of the molecules (which produce phenomena such as plastic deformations or thixotropy). On the contrary, as the temperature decreases, the molecular mobility of the AC mixture is reduced, and therefore the stresses produced in each load cycle are mainly absorbed in small movements at molecular bonding level (the material is stiffer and behaves more elastically). If these stresses are not high enough to produce movements that cause the molecular scission, the material could support a higher amount of load cycles as no energy is consumed in the creation of damage (the dissipated energy in each additional cycle does not increase - see Figure 11a). The molecular re-orientation is in this case very slow and limited, and as a consequence, the initial dissipated energy measured is lower. Thus, permanent deformations that precede the appearance of damage in the material (molecular rupture) are smaller, and after the fatigue process, the resulting fracture is brittle. This aspect can be observed in the tests carried out at a temperature of 5 °C, which were stopped at 2,000,000 cycles and where no signs of fatigue damage were found in the AC material (because of this fact the dissipated energy remains constant). Figure 11b shows the damage parameter of different types of BBTM mixtures at a range of temperatures. It is therefore clear that temperature could have a considerable impact on the resistance of the asphalt mixtures.

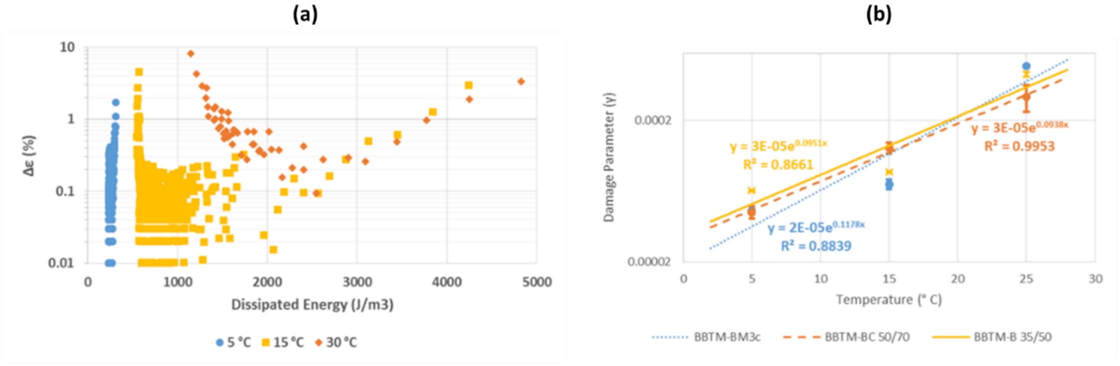

Figure 11: Results obtained when testing asphalt mixtures at different temperatures [19].

Finally, it should be highlighted that UGR-FACT can also be used to test complete pavement sections or anti-cracking solutions (such as geotextiles, grids, etc.). As an example, Figure 12 summarizes some of the materials used in a study that focused on the evaluation of deconstructed tires as anti-reflective cracking mats [22]. For this purpose, a standard pavement section composed of a binder and a surface course was tested, introducing in the interlayer zone different anti-reflective cracking solutions: none, a geotextile, an anti-reflective cracking system manufactured from the carcass ply layer of the tires, and an anti-reflective cracking system manufactured from the steel belt layer of the tires. The results obtained from this research demonstrate the efficiency of this test method to assess different type of pavement sections and anti-cracking systems.

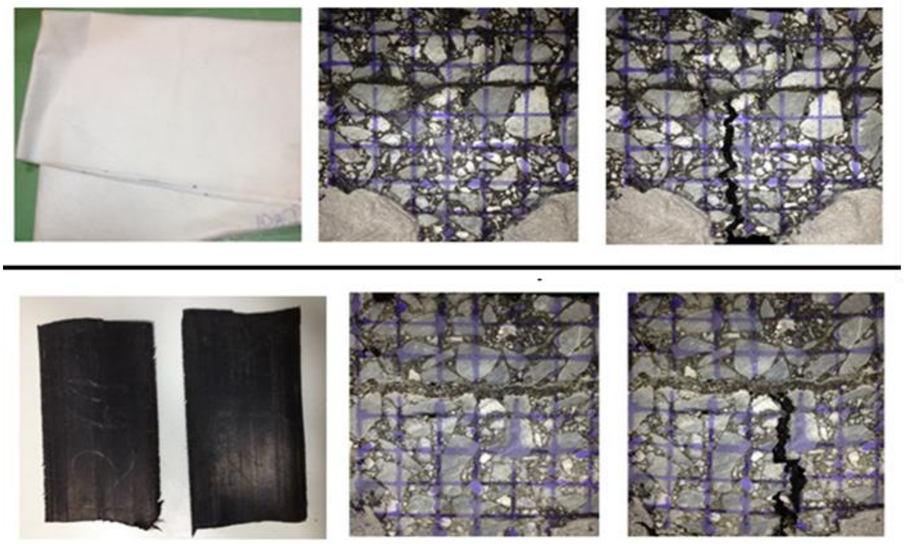

Figure 12: Detail of the evaluation of two anti-cracking systems [20].

Similarly, the UGR-FACT test method can be used to evaluate the development of the field performance of asphalt mixtures (Figure 13). In this regard, the data on residual fatigue life obtained from the cores extracted from the road at various times of service can be used to predict future actions of rehabilitation of the pavement or to improve the pavement design systems.

Figure 13: Detail of the evaluation of a cores obtained from an asphalt pavement using the UGR-FACT method.

4 CONCLUSIONS

This paper describes the UGR-FACT laboratory test method, developed at the University of Granada (Spain) for the evaluation of fatigue cracking in bituminous mixtures. The main conclusions that can be derived from this study can be summarized as follows:

- The UGR-FACT test device is able to simulate the loads sustained by an actual pavement. Under these circumstances, it induces a controlled fatigue cracking process (crack initiation, propagation, and failure) in a test specimen manufactured at the laboratory or in a core obtained from a road.

- The device has reduced dimensions, is easily adapted to any dynamic press, is simple to operate, and easy to reproduce at a low economic cost (which means that it can be used in different research centers). It allows for an evaluation of individual asphalt mixtures as well as complete pavement sections, and can also assess the efficacy of anti-cracking systems (grids, geotextile, etc.).

- The theoretical approach developed for this test method, which combines the study of the changes produced in the geometry of the material and the energy dissipated by the material in each load cycle, allows for the identification of the different phases that appear during fatigue loading conditions. Thus, it provides an interesting tool to develop a full analysis of fatigue damage in bituminous materials, excluding the effects of other phenomena that cannot be regarded as damage. Similarly, it establish a homogenous failure criterion that takes into account a similar level of damage in each material studied (even when the macro-damage level is considered). Finally, the approach presented has been shown to be sensitive to variations in the test parameters and the type of materials evaluated.

- The UGR-FACT method has been validated in terms of repeatability and it has been successfully used for the study and evaluation of different types of asphalt mixtures and pavement sections. It can thus be considered a very interesting tool for improving the design of bituminous materials.

REFERENCES

[1] Cracking in pavements: nature and origin of cracks, Colombier, G., Prevention of Reflective Cracking in Pavements – RILEM Report 18. Edited by Vanelstraete A. et Franckien L., pp. 1-15, 1997.

[2] Reflective cracking of flexible pavements. Phase II: Review of analysis models and evaluation test, Hajj, E., Sebaaly, P., Loria, L., Research Report No. 13JF-1, University of Nevada Reno, Nevada, 2008.

[3] Procedimientos de Estudio en laboratorio, García Carretero, J., Jornadas sobre Reflexión de Grietas en Carreteras, Centro de Estudios y Experimentación de Obras Públicas, CEDEX, Madrid, 1992.

[4] Diseño de un método de ensayo de laboratorio para el análisis de la resistencia a fisuración de mezclas bituminosas, Moreno Navarro, F., Tesis doctoral, Universidad de Granada, Granada, 2013.

[5] Non-linearity, heating, fatigue and thixotropy during cyclic loading of asphalt mixtures, Di Benedetto H, Nguyen QT, Sauzéat C., Road Materials and Pavement Design, 12(1): 129-158, 2011.

[6] Differentiating between damage and thixotropy in asphalt binder's fatigue tests, Pérez-Jimenez F, Botella R, Miró R., Construction and Building Materials, 31: 212-219, 2012.

[7] Damage and Thixotropy in Asphalt Mixture and Binder Fatigue Tests, Pérez-Jimenez F, Botella R, Miró R., Transportation Research Record: Journal of the Transportation Research Board, 1: 8-17, 2012.

[8] Separation of thixotropy from fatigue process of asphalt binder, Shan L, Tan Y, Underwood B, Kim YR., Transportation Research Record: Journal of the Transportation Research Board, 2207: 89–98, 2011.

[9] Influence of Asphalt Mixture Stiffness on Fatigue Failure, Lundstrom R, Di Benedetto H, Iacsson U., Journal of Materials in civil Engineering, 16: 516-515, 2004.

[10] Comparison of fatigue test procedures for asphalt mixes, Mollenhauer K, Wistuba MP., Proceedings of te 5th Int. Conference of the European Asphalt Technology Association (EATA), Braunschweig, Germany, 2013.

[11] False failure in flexural fatigue tests, Pérez-Jimenez F, Miró R, Martínez A, Botella R, Reyes O, Valdés G., Proceedings of the 2nd Workshop on Four Point Bending, Pais (ed.), University of Minho, Portugal, 2009.

[12] Molecular motions and rheological properties of asphalts: An NMR study, Netzel DA, Miknis FP, Thomas KP, Wallace JC, Butcher CH., Asphalt Science and Technology, Marcel Dekker, New York, USA, pp. 11-58, 1997.

[13] Apparent activation energies for molecular motions in solid asphalt, Netzel DA., Energy and Fuels, 20: 2181-2188, 2006.

[14] Additional cyclic strain hardening and its relation to material structure, mechanical characteristics, and lifetime, Borodii MV, Shukaev SM., International Journal of Fatigue, 29: 1184–1191, 2007.

[15] Mean damage parameter for the characterization of fatigue cracking behavior in bituminous mixes, Moreno-Navarro F, Rubio-Gámez MC., Materials and Design, 54: 748-754, 2014.

[16] Effect of aggregate nature on the fatigue-cracking behavior of asphalt mixes, Moreno, F., Rubio, M. C., Materials and Design, 47, pp. 61-67, 2013.

[17] Tire crumb rubber effect on hot bituminous mixtures fatigue cracking behavior, Moreno-Navarro, F.; Rubio-Gámez, M. C.; Jiménez del Barco, A., Journal of Civil Engineering and Management, doi:10.3846/13923730.2014.897982, 2015.

[18] The influence of temperature on the fatigue behaviour of bituminous materials for pavement rehabilitation, Moreno-Navarro, F.; Rubio-Gámez, M. C.; Miró, R.; Pérez-Jiménez, F., Road Materials and Pavement Design, 16, pp. 303-315, DOI: 10.1080/14680629.2015.1029676, 2015.

[19] The effect of polymer modified binders on the long-performance of bituminous mixtures: The influence of temperature, Moreno-Navarro, F.; Sol-Sánchez, M; Rubio-Gámez, M. C., Materials and Design, 78, 5-11, 2015.

[20] Analysis of the influence of binder properties on the mechanical response of bituminous mixtures, Moreno-Navarro, F.; Sol-Sánchez, M.; Jimenez del Barco, A.; Rubio-Gámez, M. C., International Journal of Pavement Engineering, (Accepted, In Press), 2015.

[21] Exploring the recovery of fatigue damage in bituminous mixtures: the role of healing, Moreno-Navarro F, Sol-Sánchez M, Rubio-Gámez MC., Road Materials and Pavement Design, 16, pp. 75-89, DOI: 10.1080/14680629.2015.1029706, 2015.

[22] Reuse of deconstructed tires as anti-reflective cracking mat systems in asphalt pavements, Moreno-Navarro, F.; Sol-Sánchez, M.; Rubio-Gámez, M. C., Construction and Building Materials, 53, pp.182–189, 2014.