Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: http://www.science-gate.com/IJAAS.html

Survey of fatigue resistance quantification of asphalt mixture

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ARTICLE INFO

Article history:
Received 20 November 2014
Received in revised form
22 December 2014
Accepted 7 January 2015

Keywords:
Asphalt
Aging
Fatigue resistance
Pre- aged binder
Rheological property
Ethylene-vinyl acetate (EVA)

ABSTRACT

Asphalt binder is man's oldest engineering material; its adhesive and waterproofing properties were known at the dawn of civilization. Asphalt paved roads have been used in the United States for about 100 years. They have been used in Europe since the 1850's. These asphalt pavements suffer from fatigue cracking and thermal cracking, aggravated by oxidation and hardening of asphalt. This negative impact of asphalt oxidation on pavement performance has not been considered adequately in pavement design. No doubt, pioneering pavement engineers soon realized that in the short-term asphalt hardened after heating, mainly due to volatilization, and, in the long term it hardened, mainly due to oxidation. Hardening is primarily associated with loss of volatile components in asphalt during the construction phase (short-term aging), and progressive oxidation of the in-place material in the field (long-term aging). Both factors cause an increase in viscosity of the asphalt and a consequent stiffening of the mixture. This may cause the mixture to become hard and brittle and susceptible to disintegration and cracking failures. Also, the products of oxidation may render the mixture less durable than the original mixture, in terms of wear resistance and moisture susceptibility. However, "aging" is not necessarily negative phenomenon, since some aging may help a mixture achieve optimum properties. Compared to research on asphalt cement and aging of asphalt mixtures, there has been little research on the blown asphalt and, to date, there is no standard test. Pavement engineers understand the need to model the effects of the blown asphalt -aggregate mixtures in structural design procedures, and while some research has addressed this need, as yet no standard procedure as emerged to address it. Part of this reason is that the process of asphalt oxidation in pavement is not well understood. The main contribution of this study is the introduction of a method to quantify fatigue damage accumulation of asphalt binders using a short-duration test procedure that can be easily implemented into current practice.

1. Introduction

The oxidation of asphalt is one of the principal factors causing the deterioration of asphalt pavements (Sengoz and Isikyakar 2008; Zora et al., 2007). But the long term aging is a very complex process, such as the sunshine especially ultraviolet radiation and rainwater have different effect on asphalt binder in different zone. The mechanical properties and chemical structures of asphalt binder's change with aging time. The aging include short term aging that occurs during the mixing, paving, compacting and long term aging during the service life in the pavement. The Rolling Thin Film Oven Test (RTFOT), as described by the ASTM Standard Methods D2872, has been accepted as a reliable procedure to simulate the short term aging. Further aging was carried out on the RTFOT residue using the Pressure Aging Vessel (PAV) following the standard practice outlined by AASHTO to simulate the long term aging (Bahia et al., 2007; Iswandaru, and Richard 2008). The aging properties of asphalt binders were normally characterized by measuring physical and rheological properties (e.g. softening point, penetration, viscosity and complex modulus) before and after artificial aging in the laboratory (Lee et al., (2008); Wu et al., (2006)) .

2. Factors affected aged binder

As a principal mechanism, oxidative aging is an irreversible chemical reaction between components of bitumen and oxygen. It may occur through different reactions, such as photo-oxidation and

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thermal oxidation (Dickinson, 1980). The light (mainly ultraviolet, UV) catalyzed reaction occurs rapidly and generally takes place within the top 5 mm of the exposed binder film, since bitumen is a good light absorber (Dickinson, 1980; Dickinson et al., 1958). In spite of the limited penetration into bitumen, the photo-oxidation induced aging may have an influence on durability, particularly for some polymer modified binders (Durrieu et al., 2007). Nowadays, most of aging on the road is still regarded as thermally induced. The rate of thermal oxidation of bitumen is approximately doubled for every 10°C rise in temperature. Thus aging rate in service depends to a large extent on pavement temperature. Certainly, the oxidative aging is influenced by the chemical nature of bitumen. It has been shown that different bitumen's have very different increase of viscosity with aging time, and the temperature-dependence of aging kinetics are strongly dependent on the bitumen (Petersen et al., 1993).

Another important factor affecting bitumen aging on the road is the void content of asphalt mixture. Much work has indicated that asphalt mixtures of low voids show a low degree of bitumen aging while higher void content facilitates the aging process (Oliver et al., 1992); Leech and Nunn, 1997). Presumptively, void content determines the rate of aging by controlling oxygen access to the bitumen. Thus, the oxidative aging of bitumen as function of depth in the pavement is closely related to void content of the mixture.

3. Ageing tests for bituminous binders

Many attempts have been made recently to correlate accelerated laboratory ageing of bitumen with field performance. Most of this research was based mainly on two major test groups: the use of oven tests and pressure oxidation. Extended heating procedures tend to be used to simulate short-term ageing (hardening) of bitumen associated with asphalt mixture preparation activities while the pressure oxidization technique is mainly used to simulate long term age hardening of the bitumen binder related to the service life of the pavement. Aging procedures can generally be grouped into two categories (1) Oven procedures, and (2) pressure procedures.

3.1. Short term binder ageing

The short term ageing of binder occurs primarily due to air oxidation and the loss of more volatile components during mix production (when heated aggregate is mixed with hot bitumen binder). So the laboratory-accelerated technique for short term ageing should reproduce these effects. According to a literature survey by (Hagos, 2008), the overall mass change in short term ageing of bitumen depends on two competing phenomena. A portion of the sample volatilizes (i.e. volatilization of oily components), causing the sample to lose mass, and oxygen reacts with the sample (oxidation), causing the sample to gain mass. The net sum of these two effects determines whether the sample has an overall mass gain or an overall mass loss.

The most commonly used standardized tests, to simulate the short-term ageing of conventional, unmodified bitumen, are Thin Film Oven Test (TFOT), Rolling Thin Film Oven Test (RTFOT) and the Rotating Flask Test (RFT) (Airey, 2003).

3.1.1. Thin film oven test (TFOT)

The Thin Film Oven Test is a standard binder test (EN 12607-2, ASTM D 1754) used for measuring the combined effects of heat and air on a film of bitumen or bituminous binder. This test method has a main purpose to reproduce the extent of ageing of bituminous binder during mixing in an asphalt mixing plant. In the test, a thin film of bitumen is placed in a pan (50 ml of sample in a cylindrical pan of 140 mm inside diameter and 9.5 mm deep with a flat bottom will give a film thickness of approximately 3.2 mm), which is held in a convection oven at 163ºC for 5 hours. The effect of hardening is determined on the basis of the change in mass (expressed as a percentage) and/or as a change in the bituminous binder's characteristics of penetration, softening point or dynamic viscosity before and after oven ageing.

According to Airey (2003), a major criticism of the Thin Film Oven Test (TFOT) is that the thick binder film which results in a large volume to exposed surface area for the aged binder. As the bitumen is not agitated or rotated during the test, there is a concern that ageing may be limited to the ―skin of the bitumen sample. This concern has led some researchers to the use of a Modified Thin Film Oven Test (Airey, 2003), which tests bitumen in microfilm thickness and extended exposure time (at a temperature of 163 ºC and exposure period of 24 hours).

3.1.2. Rolling thin film oven test (RTFOT)

The RTFOT is one of the most commonly used standardized tests (EN 12607-1, ASTM D 2872) and is probably the most significant modification of the (TFOT) to simulate the short-term ageing of binders. This test is used to measure the combined effects of heat and air on a thin film of bitumen or bituminous binder in permanent renewal. It simulates the hardening which a bituminous binder undergoes during the mixing, transporting and compacting processes, which is the short-term ageing. The RTFOT in accordance with EN 12607-1 involves rotating eight glass bottles, each containing 35 g of bitumen, in a vertically rotating shelf, while blowing hot air into each sample bottle. During the test, the bitumen flows continuously around the inner surface of each container in relatively thin films at a temperature of 163 °C for 85 minutes. The vertical circular carriage rotates at a rate of 15 revolution/min and the air flow is set at a rate of 4 L/min.

The method ensures that all the bitumen is exposed to heat and air and the continuous movement ensures that no skin develops to protect the bitumen. The method described is not applicable to some modified binders or to those where the viscosity is too high to provide a moving film (EN 12607-1:2007). The effects of this treatment are determined from measurements of the properties of the binder before and after the test and from determining the change in mass

3.1.3. Modified rolling thin film oven test (MRTOT)

The major problems related to the use of the RTFOT for binders with high viscosity (example: polymer modified bitumen) is that these binders will flow much more slowly inside the glass bottles during the test under the influence of gravity. On the other hand, a material with low consistency will flow much faster. As a result, in the case of high viscous binders less fresh surface is exposed to air resulting in a lower oxidation and the opposite is true with low consistency binders (Oliver, 1997). In addition, during the test in RTFOT some binders have a tendency to roll out of the bottles.

To overcome these problems, the Modified Rolling Thin Film Oven Test (MRTFOT) was developed. The test is identical to the standard RTFOT except that a set of 127 mm long by 6.4 mm diameter steel rods are positioned inside the glass bottles during oven ageing. The principle is that the steel rods create shearing forces to spread the binder into thin films, thereby overcoming the problem of ageing high viscosity binders. Initial trials of the MRTFOT indicate that the rods do not have any significant effect on the ageing of conventional penetration grade bitumen. Moreover, recent research work has indicated that using the metal rods in the MRTFOT does not solve the problem of roll-out of modified binder and this is the reason that the method is used hardly ever.

3.1.4. The Nitrogen rolling thin film oven test (NRTFOT)

The Nitrogen Rolling Thin Film Oven Test (NRTFOT) is one of the modifications of the RTFOT test. The test procedure is identical to the standard RTFOT test except that nitrogen, instead of air, is blown over the exposed surface of the bitumen samples. The mass change before and after the test is used to evaluate the ageing characteristics of the binder. This test method is developed to enable the determination of the extent of evaporation and oxidation process taking place in the short-term ageing. According to (Parmeggiani 2000), the NRTFOT test reflects the extent of the loss of volatiles and hence the strength of the bonding forces holding the hydrocarbon molecules together at high temperatures occurring during asphalt production. On the other hand, the test can be used to distinguish the sensitivity of different binders to ageing as the loss of oily components is a crucial element in the subsequent performance of the binder.

3.1.5. Rotating flask test (RFT)

The Rotating Flask Test (RFT) is one of the standardized (EN 12607-3) short term ageing tests. The RFT test method consists of ageing a 100 g sample of bitumen in a rotating spherical flask of the rotary evaporator for a period of 150 minutes at a temperature of 165 °C (an oil bath is used to maintain the temperature) and a constant air flow of 0.5 l/min. The material forming the surface of the specimen is constantly replaced because the flask is rotated at 20 rpm, preventing the formation of a skin on the surface of the bitumen. The dynamic nature of the test also has an additional advantage that it avoids the separation or segregation of polymers which makes it suitable to test polymer modified binders. The test is conducted in an oil bath, which allows rapid sample heating and eliminates the radiant heating problems associated with some ovens.

The effect of short term age hardening is determined based on the change in mass (expressed as a percentage) or as a change in the bituminous binders 'characteristics such as penetration, softening point (Ring and Ball) or dynamic viscosity, before and after hardening. Comparison with the RTFOT and TFOT suggest that the RFT is roughly one-third as severe as the other tests in producing volatiles, which means less ageing (Airey, 2003).

3.2. Long term binder ageing

In hot-mixed materials, the bitumen or any other bituminous binder during its life is subjected to two successive types of ageing. The first one is the rapid ageing in construction phase termed as short term ageing. The second one is the slow ageing in service (ageing during service life of the pavement called long term ageing) comprises all the changes occurring on site in the binder, in the prevailing climatic environment of the road surfacing. Standard tests such as RTFOT or RFT discussed in the previous section can simulate ageing during the production and compaction phase in an adequate way. However, their high temperatures make them unsuitable for simulating field ageing (Verhasselt, 1997).

A number of test methods have been developed to simulate field ageing of binders. In the subsequent section attention will be given to the most important existing laboratory test methods.

2.3.1. Pressure ageing vessel (PAV)

The Pressure Ageing Vessel (PAV) was developed in the SHRP project to simulate long term, in-service oxidative ageing of bitumen in the field (long term ageing). The method involves hardening of bitumen in the RTFOT or TFOT (short term ageing) followed by oxidation of trays of binder at elevated temperatures under pressurized conditions in a pressure ageing vessel (Airey, 2003). According to the European standard for the PAV test (EN 14769), the PAV procedure entails ageing 50 g of bitumen in a 140 mm diameter container (giving a binder film that is approximately 3.2 mm thick) within the heated vessel, pressurized with air to 2.1 MPa at typical conditioning temperatures of 85 °C (for 65 hours), 90 °C (for 20 hours), 100 °C (for 20 hours) or 110 °C (for 20 hours). The higher temperatures may make this ageing procedure unsuitable for evaluation of binders containing some polymers as they could exhibit separation and/or degradation in a way that does not occur during natural ageing. Verhasselt and Vanelstraete (2000) have found that the higher temperature of the PAV resulted in some segregation of the polymer in some of the polymer modified binders.

2.3.2. Rotating cylinder ageing test

The Rotating Cylinder Ageing Test (RCAT) is a standardized accelerated ageing test (EN 15323), first developed at the Belgian Road Research Center (BRRC) to simulate both the short and the long-term ageing of binders. This European standard test specifies an accelerated ageing/conditioning procedure for bitumen, bituminous binders (including modified binders) and bituminous mastics. The procedure involves binder ageing at moderate temperatures in a large cylinder rotating in an oven under oxygen flow conditions.

Before commencing the long term ageing test by RCAT, the binder is first preconditioned as necessary to simulate the condition in which it would be applied to the road. This can be done by one of the standard short term ageing test methods RTFOT (EN 12607-1) or TFOT (EN 12607-2). Short-term ageing/conditioning can also be performed directly in the RCAT, which reduces intermediary sample handling operations (Verhasselt, 2002). This is one of the major advantages of RCAT compared to other long term ageing test methods.

4. Ageing tests for bituminous mixtures

In addition to artificially ageing binders, a number of attempts are also made to develop methods for accelerated ageing the bituminous mixture. According to Airey (2003), the methods can broadly be divided into four categories:

- Oxidation tests;
- Ultraviolet/Infrared treatment; and
- Steric hardening.

The effects of ageing on parameters like stiffness, viscosity, strength…etc are assessed after accelerated ageing of the asphalt mixture. Extended heating procedures naturally expose the mixture to high temperatures for a specified period of time while oxidation tests in general make use of a combination of high temperature and pressure. On the other hand Ultraviolet/infrared treatment involves exposing specimens to either ultraviolet or infrared radiation (Airey, 2003).

4.1. Ageing procedures developed under the SHRP-A-003A project

Both short term and long term ageing procedures are developed under the SHRP (Strategic Highway Research Program) project. The short-term methods involved conditioning loose mixtures, while the long-term methods involved conditioning compacted samples.

The Strategic Highway Research Program (SHRP) procedure for short term oven ageing requires that loose mixtures to be heated (aged) in a forced draft oven for 4 hours at 135ºC prior to compaction with the condition that they be stirred and turned every hour. This was found to represent the condition during mixing and placing and also represents less than 2 years in service for dense mixtures.

The recommended procedure for long-term ageing is to age compacted mixture, previously subjected to short term oven ageing, specimens in a forced-draft oven for 5 days at 85°C. Measurements on the aged specimens included resilient modulus, indirect tensile strength and dynamic mechanical analyses. Correlation with field sites (typically 5% air voids) showed that the long term oven ageing method is roughly equivalent to 5-15 years in the field depending on climate.

4.2. Weather meter ageing (A protocol adopted by Hagos, 2008)

Hagos (2008) used in his research a weather meter for long term ageing of porous asphalt mixture. The simulation of ageing in the laboratory was conducted under the influences of temperature, UV light, and humidity to replicate the prevailing environmental factors which have an influence on age hardening of the pavement in the field. He followed three ageing procedures in his research, which are:

- Protocol 1: Temperature ageing
- Protocol 2: Temperature + UV light ageing (the effect of UV on the ageing susceptibility or degradation),
- Protocol 3: Temperature + UV light + moisture/humidity ageing (combined influences of weathering actions)

The first two protocols were conducted using cylindrical specimens. The third protocol was performed with asphalt beams cut from a PA slabs. T1 below shows the test conditions in detail.

Hagos (2008) compared results of laboratory ageing procedure (both the weather meter and the standard ageing procedures) with results from field ageing of porous asphalt. It was found that the laboratory ageing methods are not as severe as the long term field ageing of porous asphalt. The long term laboratory ageing of bitumen using the standard ageing procedure and the new mixture ageing protocol 3 seem to predict only the ageing characteristics of the field binder after construction and 3 years' service, respectively. The binders recovered from the mixture ageing under ageing protocol 1 and 2 in the laboratory have resulted in even less severe ageing compared to the standard binder ageing method and ageing protocol 3.

Table 1: Ageing protocols and conditions used by Hagos (2008) DELETE

Ageing Protocols	Ageing Protocols			
Exposure conditions	Exposure conditions	Exposure conditions	Exposure conditions	Exposure conditions
UV light (300-400nm) (W/m2)	UV light (300-400nm) (W/m2)	UV light (300-400nm) (W/m2)	UV light (300-400nm) (W/m2)	UV light (300-400nm) (W/m2)
Humidity (%)	Humidity (%)	Humidity (%)	Humidity (%)	Humidity (%)
Temperature (°C)*	Temperature (°C)*	Temperature (°C)*	Temperature (°C)*	Temperature (°C)*
*temperature at the surface of the specimen				

4.3. The RILEM (Reunion Internationale des Laboratories et Experts des Materiaus, Systemes de Construction et Overages) TC-ATB-TG5 mixture ageing method

Recently under the framework of the RILEM technical committee of advanced testing of bituminous materials a new experimental laboratory ageing procedure for asphalt mixtures has been developed aiming at reproducing the ageing of bituminous materials until the end of the service life. The protocol is divided in short and long term ageing protocols to simulate the two phases of ageing. For both cases it is proposed to age the loose asphalt mixture. The procedures are:

- For short term ageing process, the loose mix is placed in an air-draft ventilated oven for 4 hours at 135°C. Each hour the material is stirred for 1 minute and placed back into the oven. The stirring action is only for homogenization.
- The long term ageing procedure includes the ageing of the short term aged loose mixture by placing it in air ventilated oven at 85°C for 9 days. The procedure recommends taking samples and stirring the mixture after 2, 5, 7 and 9 days.

As this test protocol is in its experimental stage, comparisons with field ageing data were not available and not found at the time of writing this literature review.

4.4. The New Zealand test method for compacted open graded porous asphalt

A new laboratory test method has been developed in New Zealand to assess the durability of open graded asphalt mixes in the field. The test involves conditioning loose mix at 125°C (or the appropriate plant mixing temperature) for two hours to simulate oxidation during manufacture and handling. The conditioned mix is compacted into standard Marshall test sized specimens (100 mm diameter and 65mm height), which are heated at 80°C and kept at this temperature for three days (72 hours) under 2070 kPa air pressure by using a pressure vessel (Herrington, 2005).

According to Herrington et al, comparison of the viscosity of the recovered binder from field samples of aged open graded porous asphalt shows that the procedure results in oxidation approximately equivalent to 4.5 years in the field. The effect of binder oxidation on the abrasion resistance of the mix is measured with the cantabro test (300 revolutions at 30 rpm and a temperature of 25°C).

One of the main concerns from previous researchers was the possibility that the use of high air pressure in the test may mechanically damage the compacted specimens. Herrington et al mentioned in their report that although no visible damage occurred, specimen dimensions increased slightly. To find out if this was significant they have tested specimens by using an inert nitrogen atmosphere at 2070 kPa to preclude oxidation, leaving other variables unchanged. They compared the mass loss after the cantabro test on Nitrogen treated specimen with un-oxidized specimens and the results showed no significant difference. They concluded that the damage caused by the use of high pressure is negligible.

5. Model developments of long-term aged asphalt binder's

Pavement researchers and engineers often encounter and have to solve some complex problems involving a number of interacting factors or engineering parameters (variables) for asphalt or concrete pavements. However, in some problems, the underlying first principles are not well defined and it is not possible to define a concise relationship between the factors (variables), or the problem is too complicated to be described mathematically. For example, the long-term aging of asphalt binder is involved a number of factors such as construction process, traffic loading, pavement structure or materials, weather conditions and so on. One common approach to solve these problems is to utilize experimental (measured) data to build empirical or semi-empirical models that relate the variables (input–output relationship) in the system. This extraction of knowledge from the data is a formidable task requiring sophisticated modeling techniques as well as human intuition and experience. Increasingly, modern pattern recognition techniques such as neural network and fuzzy systems are being considered to develop models from data to their ability to learn and recognize trends in the data pattern. Artificial Neural Networks (ANNs) are useful in place of conventional physical models for analyzing complex relationships involving multiple variables and have been successfully used in civil engineering applications such as process optimization, slope stability analysis, and deep excavation forecast models (Xiao and Amirkhanian 2009). Asphalt binder long-term aging is a complicated process which might involve irreversible chemical changes and reversible physical hardening. The former mechanism derives from the oxidation, loss of volatile components, and exudation (Lu and Isacsson 2002). As aging progresses, more of the asphaltene fractions are formed, the saturatefractions remain unchanged while both the polar and naphthene aromatics decrease (Tuffour et al., 1989). The advantage of the saturate is that increasing their amount of reactive components and, therefore, probably imparts to the asphalt an ability to resist chemical change and the effects of aging (Tuffour et al., 1989). The latter physical hardening process may be attributed to reorganization of asphalt molecules to approach an optimum thermodynamic state under a specific set of conditions, such as repeated traffic loading (Bahia and Anderson, 1993). The factors affecting asphalt aging include characteristics of the asphalt binder (e.g. source and grade) and its content in the mixture, nature of aggregate and particle size distributions, air void contents of the mixture; production related factors, service temperature and duration as well as the repeated traffic loading (Bahia and Anderson, 1993). Previous researchers found that the aging mechanisms of asphalt at the high-temperature levels employed in accelerated conditions did not differ significantly from those occurring under the relatively mild conditions in the field. The study by Chari et al., (1990) on age hardening of asphalt binder indicated that a high temperature Thin Film Oven Test (TFOT) or Rolling Thin Film Oven Test (RTFOT) procedures and Pressurized Aging Vessel (PAV) could be used to simulate long-term field aging. Penetration Index (PI) values can be used to determine the stiffness (modulus) of an asphalt binder at any temperature, aging state, and loading time. It can also, to a limited extent, be used to identify a particular type of bituminous material. One drawback of the PI is that it relies on the change in asphalt binder properties over a relatively small range of temperatures to characterize asphalt binder. Penetration is related to viscosity and empirical relationships have been developed for Newtonian materials. If the penetration is measured over a range of temperatures, the temperature susceptibility of the bitumen can be established. A series of sequential analytical models developed to predict the aging characteristics of conventional type asphalt cements due to both short and long term effects. These models were developed from a statistical analysis of results in a Master Data Base comprised of asphalt consistency results. The approved models were effective in predicting the aging behavior of asphalt binder. Asphalt binders were separated into four main fractional groups according to its origin, namely: saturates aromatics, resins and asphaltenes (Lu and Isacsson, 2002). However, some researchers found that the definition of three classified groups in the bitumen, namely Large Molecular Size (LMS), Medium Molecular Size (MMS), and Small Molecular Size (SMS), is helpful in analyzing the aging process in High Pressure-Gel Permeation Chromatographic (HP-GPC) analysis method. Kim et al., (1993) discussed the influence of aging on chromatographic profiles and the relationship between selected properties of the binders and the HP-GPC parameters.

6. Fatigue performance

The distress of asphalt concrete like Fatigue Crack, Rutting (Permanent Deformation), Low Temperature Crack, Surface Wearing etc are related to vehicle loads, temperature, speed of load, material properties, soil condition etc. Fatigue cracking is recognized as the load/structural related distress. Rutting and low temperature cracking are temperature related distress. The Mechanistic Empirical Pavement Design Guide requires fatigue related laboratory test to determine pavement performance of the asphalt concrete.

The prediction of fatigue cracking is generally challenging while considering strain level, temperature, loading frequency, and modulus on the asphalt concrete. Fatigue cracking prediction is normally based on the cumulative damage concept. The allowable number of load repetitions is related to the tensile strain at the bottom of the asphalt layer. Fatigue models are developed to predict the number of repetitions at failure of asphalt layer. Most of the fatigue models are related to the horizontal tensile strain and stiffness (modulus) of the asphalt mixture.

The fatigue resistance of asphalt mixture is commonly determined by the flexural bending beam test AASHTO 2008. A constant have sine loading was applied in an asphalt concrete beam with a number of load repetitions to get the failure status of the beam. In this paper, fatigue failure is defined as 50% reduction of initial stiffness. The reduction of stiffness can be related to the micro crack that appeared in asphalt concrete. Beam fatigue test is used to evaluate the different fatigue models. The four-point beam fatigue test was used at a constant strain level of 400, 300, and 200 micro strains and frequency level of 10Hz, 5Hz, and 1Hz. The test temperature of the beam was 21.3°C, 13°, and 4°C. The numbers of cycles measured from laboratory tests are compared with the Shell model and the Asphalt Institute model.

Laboratory fatigue tests can be conducted following many approaches. For example, the

European EN 12697- 24 Standard has five separate Annexes, each of which describes a different test protocol: a two-point bending test with trapezoid and prismatic samples (Annexes A and B); three- and four-point bending tests on prismatic beam specimens (C and D); repeated indirect tensile strength tests on cylindrical samples (E). Although modern laboratory equipment allows the various tests to be conducted with stress and strain control, the Annexes of the EN 12697-24 Standard usually involve just one of the two methods of loading application. More precisely, Annexes B and E prescribe the stress control, while the others the strain control; only Annex D allows both of the loading modes (i.e. constant deflection or constant force). Nevertheless, irrespective of the specifications of the Standard, the stress control tests are generally used for the fatigue study of thick pavements, while strain control tests are applied for flexible ones of the conventional type (Artamendi and Khalid, 2005).

In the stress control procedure, since stress is maintained constant, with a consequent progressive increase in the strain, the complete cracking of the sample is frequently reached at the end of the test. The failure condition is therefore clearly represented by the physical failure of the sample. However, there are other criteria of failure, for example associated to a 90% reduction of the initial stiffness modulus (Van Dijk and Visser, 1977), or with increasing strain, up to a value double that of the initial one. Vice versa, in the strain control tests, strain is maintained constant and a progressive reduction in the stress is registered. Consequently, at a high number of cycles, since the stress will be reduced to a very low value, it is unlikely that an evident crack will be found in the sample, which will therefore not be completely broken. For this reason, within the road scientific community, the criterion of failure for the strain control tests is generally established as a 50% reduction of the initial stiffness (Tayebali et al., 1992), or initial stress.

The cited criteria of failure, although defined by consistent variations of the mechanical parameter considered (stiffness modulus, rather than stress or strain) with respect to the initial conditions of the sample, are purely arbitrary and do not fully represent the state of internal damage in the material.

To overcome this problem, Hopman et al. (1989) and Pronk (1997), for fatigue bending tests, introduced a rational criterion of failure, linked to the concept of dissipated energy, identifying the failure in correspondence to a number of loading cycles N1 at which the micro-cracks coalesce, producing a macro-crack. N1 therefore represents the triggering of that macro-crack, which then propagates in the material (Rowe, G. M., (1993).

In his approach Pronk introduced an energy ratio Rn, defined as the ratio between the cumulative energy dissipated up to the n-th cycle and the energy dissipated at the n-th cycle.

In the strain control tests, the graphical representation of Rn with the varying of the number of cycles allows N1 to be identified as the point at which Rn begins to show a non-linear trend. Vice versa, in the stress control tests, N1 is identified as the peak point of Rn with the varying of the number of cycles. As already outlined by Artamendi and Khalid, (2005), the accurate identification of N1 appears to be more subjective in the strain control test method than in that with constant stress control.

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