Viscous behaviour of asphaltic mixtures: Simplified fatigue test method

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A continuously increasing demand on roads and the need to reduce the construction costs has led to the industry requiring simplified test methods which measure the mechanical properties of bituminous materials. The method traditionally used in the industry is based on Marshall mix design, which basically determines the stability and flow test values and do not measure any fundamental property of the mix thereby pavement performance. In contrast, there are a number of key properties that can be measured to determine the mechanical properties of a bituminous mix, which are vitally important in determination of long-term performance of the mixtures. This paper describes a method, the AKAL test method, which simplifies the ITFT test and measures viscous behaviour to predict the development of permanent strain accumulation, therefore, fatigue-life and long-term performance of asphalt mixtures.

Bituminous pavements are subjected to a variety of loading conditions increasing in both magnitude and quantity over the years, which are the principle factors contributing to road deterioration and therefore are the main cause of the failure. The design of flexible pavements has rapidly evolved from empirical and semi-empirical procedures to design methods based on elastic or visco-elastic theories. Today various form of test methods are used by highway agencies in assessment of asphalt pavements. Several tests and test equipments have been developed and used in laboratories to evaluate the structural properties of asphaltic mixtures. It was found that different test yield different results and that the test results are difficult to reproduce.

For more than forty years, "Marshall Design Method" has been in use throughout the world, for design in Hot Rolled Asphalt (HRA) mixtures. However, its empirical nature does not provide any fundamental property from which the performance of bituminous mixtures, which is stiffness over short loading times, resistance to permanent deformation, durability and fatigue cracking resistance, can be predicted. Therefore, there is a need to measure the fundamental property of bituminous mixture and to evaluate the new mix properties (SMA, porous asphalt, thin surfacing etc.). Because of the poor testing procedure, the mixes have mostly been prematurely failed before expected design life.

It is well-known that cyclic plastic strains are ultimately responsible for fatigue damage and the consequent fatigue failure. The loading applications lead to the development of internal tensile stresses, which causes fatigue and rut deformation, which is a significant form of distress in bituminous materials, which is an exceeding uniaxial strains or stress leads to fatigue phenomena.

Bituminous mixtures have visco-elastic properties, which are effected by loading, temperature and time. The mixture is subjected to a repeated loading. After removal of the loading from the bituminous surface, some of the deformation/strain occurring is recovered. However, as can be seen from Fig. 1, the strain is not fully recovered back, therefore, a strain accumulation is occurring with the repeated load application. The maximum strain is occurring at the centre of the pavement where the crack initiation starts. Thereby, visco-elastic response of bituminous mixture to cyclic load application will determine fatigue life.

Fatigue Phenomena

Fatigue is a significant form of distress in bituminous pavements. The simple theory of fatigue cracking is shown in Fig. 1, a moving-wheel is applying a repeated loading over a bituminous surface, where horizontal strains ($k_x$) represent fatigue cracking, vertical strain ($k_y$) rate represents viscous deformation, hence, strain accumulation in the mix. The maximum tensile strain will occur at the base of the bituminous layer. If the structure is inadequate for the imposed loading conditions, the tensile strength of the material will be exceeded and cracks are likely to initiate. These will be manifested as
cracks on the surface of the pavement. The failure occurs depending on factors affecting the material, which are load cycle, magnitude, and temperature\(^1\) are the most effective factors on the formation of the fatigue failure in bituminous mixture.

The fatigue regime occurs in four different phases that can be subdivided into four regimes (i) initial specimen-heating, (ii) micro crack formation, (iii) crack formation and propagation and (iv) sample breakdown.

Vehicles that travel over an asphalt pavement will introduce strains which is gradually building up depending on the stress magnitude over the time. This is because of the visco-elastic property of bituminous material, in which plastic deformation occurs by repeated load cycle as illustrated in Fig. 2. Figure 3 shows the permanent deformation hence strain accumulation occurs with repeated load application within the mix. The fatigue properties of a bituminous mixture cannot be considered in isolation from the stiffness of the mix which determines the magnitude of the tensile strain experienced by the material and its life to both crack initiation and crack propagation\(^4,6\). The important question has always been how to determine fatigue life therefore design life of asphaltic mixtures. Varieties of test methods have been introduced in the industry in fatigue assessment\(^{11}\).

**Fatigue test method available**

The accurate measurement of fatigue response requires testing of specimens in the laboratory. Normally, this would involve the application of a stress or strain level, which is applied repetitively until failure occurs, either by complete fracture or by a significant reduction in the stiffness of the material\(^1\). The fatigue behaviour of the mix is characterised by the relationship between strain or stress level and the number of load repetitions to failure\(^7\). However, the fatigue life of bituminous specimens tested in the laboratory is not equal to that of the actual road pavement. Trafficking of an actual road pavement is much less damaging than experienced by specimens loaded in laboratory fatigue tests\(^8\). A number of tests have been developed to study the fatigue - characteristics of bituminous mixtures under repeated loading in the laboratory. These tests differ one from another in the loading configuration, load pulse waveform, stress distribution within the specimen and the specimen shape. The laboratory test method used will have a significant effect on the outcome of the fatigue test results. The laboratory fatigue tests reported in the literature are (i) bending test, (ii) wheel tracking test, (iii) indirect tensile test, (iv) direct tension test and (v) push-pull test.
Visco-elastic Properties of Bitumen

Bituminous materials display a visco-elastic behaviour. That is to say that at low temperatures or very short loading times they behave as elastic solids whereas at high temperatures or long loading times they behave as viscous fluids. Under intermediate conditions they display a combination of viscous and elastic behaviour.

This visco-elastic behaviour is illustrated in Fig 2, which shows the effect of application of a load cycle to a bituminous material. Part of the deformation recovers immediately after the load is removed, part recovers after some delay and a small remainder is irrecoverable. The volume of irrecoverable deformation, which builds up with the load application, determines permanent deformation, thereby, fatigue properties of mixture. The irrecoverable deformation building up causes a strain in base layer of bituminous materials, which leads fracture and eventually fatigue failure.

A bituminous material that displays an adequate and lasting recoverable deformation can resist to permanent deformation, therefore, fatigue failure. The most important criteria are to control mix stiffness depending on load application. If it is too stiff it may cause rapid fatigue failure (irrecoverable deformation), if it is too soft it also cause rapid rut deformation. Therefore, it is vitally important the assessment of mix stiffness that has a close relationship with the volume, quantity of strain occurring with the mix.

The mix design is a form of compromise that maximises fatigue life, minimise mix durability and volume of strain. A maximisation on a mix property may cause a detrimental effect on another.

Materials and Methods

Preparation of the samples

The aggregate grading of the mixture, as shown in Fig. 4, (14 mm) was prepared for the SMA mix design, which contains a relatively coarse aggregate grading providing a better surface texture and less bitumen consumption. In order to improve visco-elastic properties of the mix, polymer modified styrene-butadiene-styrene (SBS) was selected in the preparation of bituminous mixtures. The SBS, which is a synthetic rubber co-polymer consisting of molecular blocks of polystyrene linked chemically with poly-butadiene, was mixed with a 100 pen, base-bitumen in different percentages of additives. The mix combination is given in Table 1.

Determination of Marshall stability and flow

The Marshall test method, which determines the Marshall stability and flow value, is used in mix design procedure. However, the method does not provide any other data that determines the mechanical properties of the mixture. As can be seen in Fig. 5, the Marshall method provides no distinguished data that leads the mechanical properties of the mix, thereby, optimisation of mix-design procedure. The figure shows that there is only a small rise in stability and

Table 1 — Percentage of the mixture combination

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>% of combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>55</td>
</tr>
<tr>
<td>10</td>
<td>21</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>Filler</td>
<td>10</td>
</tr>
<tr>
<td>Polymer additives</td>
<td>Styrene-butadiene-styrene (SBS)</td>
</tr>
<tr>
<td>Bitumen (100 pen)</td>
<td>60</td>
</tr>
<tr>
<td>Void (%)</td>
<td>4.5</td>
</tr>
<tr>
<td>Mixing temp. (°C)</td>
<td>170</td>
</tr>
<tr>
<td>Compaction temp. (°C)</td>
<td>150</td>
</tr>
</tbody>
</table>

Fig. 4—14 mm SMA mix aggregate grading

Fig. 5—The Marshall stability and flow value
flow values. A positive relationship would have been expected, however, as regards the ability of the Marshall stability test to predict it, the method may not be able to prove the benefit of its addition such as bitumen and any other additives in SMA mixtures.

Testing equipment and program
In evaluation of fatigue life of bituminous mixture, Nottingham asphalt tester (NAT) was used. Samples prepared were tested in the temperature-controlled chamber. The data taken from the repeated load axial test method was evaluated in a modified version of indirect fatigue test method to determine fatigue properties of mixtures.

AKAL Test Method
The test method was developed by Highway Engineering Research Group, University of Ulster. The test is simply an indirect tensile test where the specimens are subjected to repeated diametric line loading along the vertical diameter which generates an indirect tensile stress on the horizontal diameter. This vertical loading produces both a vertical compressive stress and a horizontal tensile stress on the diameter of the specimen. The repeated load application of the vertical load generates a crack at the centre of the specimen and this continues until the crack failure occurs on the specimen. Read stated that the test temperature was less than 30°C, linear elastic theory was applicable for calculating the stress and strain conditions in the specimen. Eqs (1) and (2) can be used for calculation the maximum horizontal tensile stress (σ\(_{\text{max}}\)) and strain (ε\(_{\text{max}}\)) at centre of the specimen:

\[
\sigma_{\text{max}} = \frac{2P}{\pi dh}
\]  
\[
\varepsilon_{\text{max}} = \frac{\sigma_{\text{max}}}{E_{\text{m}}} \left(1 + 3\nu\right)
\]

where \(P\) is the applied vertical force, \(d\) is diameter of specimen, \(T\) is thickness of the specimen, \(\nu\) is Poisson’s ratio and \(E_{\text{m}}\) is stiffness modulus of the specimen.

The test is conducted in the NAT apparatus with 300 kPa force, rise time, and repetition period selected with 20°C temperature. For each loading pulse the accumulated displacement is continuously calculated and displayed. Permanent vertical deformation/viscous recovery and transient vertical deflection are measured with linear variable differential transformers (LVDT’s) shown in Fig. 6 and the failure point of the test is defined as 8 mm of permanent vertical deformation, ensuring that all the materials have reached the point of crack initiation under the controlled stress condition. At the same time, the test also measures viscous behaviour of bituminous mixtures, which have a visco-elastic response under a load application. When the load is removed part of the strain (deformation) is recovered, however, some of the deformation is not recovered, which is called permanent deformation or plastic deformation which has a close relationship with viscous behaviour of bituminous mixture. This may simply called resistance to repeated strain (visco-recovery) of bituminous mixture.

The analyses are based on the assumption that the maximum tensile strain occurs at the centre of specimen, which is the only form of fatigue failure, which occurs in four different phases, as shown in Fig. 7, in which the first phase is internal heating, the second phase is micro crack formation, the third one is crack formation in which the main crack initiation

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The results are comparable with the reported results. The test can be used to evaluate asphaltic mix properties on fatigue life and plastic deformation, fatigue properties of asphaltic mix properties, the visco-elastic properties of asphaltic mixture and resistance to internal strain building up in course of time. The test method shows a good correlation in resistance to deformation (rut resistance). The fatigue life of bituminous mixtures increases as the polymer additives increases. In evaluation of fatigue life therefore design life of asphaltic mix design, the test method provides to the designer an easy and accurate results in design assessment to optimise the mix.

Conclusions

The AKAL test method is an alternative test method to the Marshall test method to evaluate stone mastic asphalt mix design. The test can be used to evaluate asphaltic mix properties on fatigue life and plastic deformation, fatigue properties of asphaltic mix properties, the visco-elastic properties of asphaltic mixture and resistance to internal strain building up in course of time. The test method shows a good correlation in resistance to deformation (rut resistance). The fatigue life of bituminous mixtures increases as the polymer additives increases. In evaluation of fatigue life therefore design life of asphaltic mix design, the test method provides to the designer an easy and accurate results in design assessment to optimise the mix.

References