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Abstract
With developments in analytical design of pavement structure, there is an increasing demand for knowledge of the mechanical properties of various pavement elements under different conditions encountered in roads, such as tensile strength, stiffness modulus, and repeated-load fatigue resistance of the asphalt concrete mixtures. These parameters provide a good basis for analytical design and performance evaluation of flexible pavements.

In this study, Indirect Tensile Test has been conducted because of its validity and simplicity. However, modifications of the test apparatus and test procedure have been introduced.

Three different types of asphalt concrete mixtures have been examined using indirect tensile method. Two of the mixes are blended with 3% rubber content by total weight. i.e. Rubit (RUBI2), which is a dense asphalt concrete used for surfacing, and a porous mix called Rubdrain (RUBD12). The third mix is a conventional dense asphalt concrete (HAB12T) used for surfacing. The maximum size of the aggregate was 12 mm for all types.

Stress-deformation-strain relationships have been established in order to examine the effect of stress and/or strain level on the resilient modulus found by the indirect tensile test and to define an approximate linear viscoelastic zone for bituminous mixtures at different temperatures. Resilient modulus has been measured using the modified indirect tensile method for mixtures studied at four different temperatures.

Keywords: Asphalt Material, Rubberized Asphalt, Indirect Tensile Test, Resilient Modulus, Linear Viscoelastic, Stress-Strain Relation, Temperature.

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1 Introduction

With developments in analytical design of pavement structure, there is an increasing demand for knowledge of the mechanical properties of various pavement elements under different conditions encountered in roads, such as tensile strength, stiffness modulus, and repeated-load fatigue resistance of the asphalt concrete mixtures. These parameters provide a good basis for analytical design and performance evaluation of flexible pavement.

In the last three decades a lot of research has been focused on the response of various layers and materials subjected to possible conditions in the field by using a wide variety of methods and apparatus, which have provided a valuable knowledge platform for further investigation. Indirect tensile test has been conducted in this study because of its validity and simplicity. However, modifications of the test apparatus and test procedure have been introduced.

Three different types of asphalt concrete mixtures have been examined using indirect tensile method. A conventional mix HAB12T, which is a dense asphalt concrete used for surfacing, Rubit (RUB12), which is a rubber granular blended asphalt mix with 3% rubber content, and a porous mix, called Rubdrain (RUBD12) also containing 3% rubber used as a drainage layer, have been used. The maximum size of the aggregate was 12 mm for all types. Rubit and Rubdrain mixtures are marketed by the ABV (NCC) company. The specimens were supplied by the ABV laboratory.

Stress-deformation-strain relationships have been established in order to examine the effect of stress and/or strain level on the resilient modulus found by the indirect tensile test and to define an approximate linear viscoelastic zone for bituminous mixtures at different temperatures.

Resilient modulus has been measured using the modified indirect tensile method for mixtures studied at four different temperatures.

2 Test apparatus

Due to its simplicity and validity the Repeated-load Indirect Tensile Test [1-8], with modification in test apparatus and test procedure, has been used to study the mechanical properties of bituminous mixtures. The principle of this test is that a cylindrical specimen is loaded in the vertical diametral plane, the compressive load is applied through a couple of curved loading strips. The resultant deformation is measured at horizontal diameter.

The expressions given by Schmidt [2] and Kennedy et. al. [1] for tensile stress at the center of specimen, resilient modulus, Poisson's ratio and strain across horizontal diameter are the following:
\[ \sigma = \frac{2P}{\pi t D} \] \hspace{1cm} (1)

\[ n = 3.4 \left[ \frac{\Delta H}{\Delta V} \right] - 0.27 \] \hspace{1cm} (2)

\[ M_r = \frac{P}{t. \Delta H} \left[ \frac{4}{\pi} + n - 1 \right] = \frac{P(n+0.27)}{t. \Delta H} \] \hspace{1cm} (3)

\[ \varepsilon_r = \left( \frac{2P}{M_r \pi t D} \right) \left[ \frac{4D^2 n - 16D^2 x^2}{(D^2 + 4x^2)^2 + (1-n)} \right] \] \hspace{1cm} (4)

\( \sigma \) = Tensile stress (MPa)
\( P \) = Applied load (N)
\( t \) = Specimen thickness (mm)
\( D \) = Specimen diameter (mm)
\( n \) = Poisson's ratio
\( \Delta H \) = Total resilient horizontal deformation (mm)
\( \Delta V \) = Total resilient vertical deformation (mm)
\( M_r \) = Resilient modulus (MPa)
\( \varepsilon_r \) = Tensile strain at horizontal diameter

By substituting Equation (1) in Equation (3) and solving for resilient modulus:

\[ M_r = \frac{(\pi D/2) \left( \sigma/\Delta H \right)}{(n+0.27)} \] \hspace{1cm} (5)

To find the tensile strain at the center of the specimen \((x=0)\), substituting Equation (3) in Equation (4) and solving for strain we get:

\[ \varepsilon_o = \left( \frac{2\Delta H}{D} \right) \left[ \frac{(1+3n)}{(4+\pi n + \pi)} \right] \] \hspace{1cm} (6)

If \( n = 0.35 \) then

\[ \varepsilon_o = 2.1 \left( \frac{\Delta H}{D} \right) \] \hspace{1cm} (7)

where, \( \Delta H \) and \( D \) are defined as before.

The testing machine is capable of applying compressive pulse loads over a range of frequencies and load durations for repeated load testing.

In this investigation the repeated load pulse was applied at a frequency of 0.33 Hz with 0.2 sec loading time and 2.8 sec rest period. The load applied in the vertical diameter plane is sensed by a load cell under the specimen. Deformation across the horizontal diameter of the specimen is sensed by one extensometer instead of two LVDTs, which are normally used. Instron dynamic strain gauge (2620-601, with resolution of 20*10^-5 mm and weight 20 grams), and MTS extensometer (632-11c, resolution 8*10^-5 mm and weight 25 grams) have been shown to be adequate. The strain gauge is fixed to two curved zinc strips (2 mm thick, 10 mm wide and 80 mm long) which are glued at opposite sides of the horizontal diameter. The total weight of extensometer and the
two deformation strips is less than 75 gm (See Plate 1 and Figure 1). However, a couple of LVDTs with the frame which carry out the two LVDTs is more than 700 gm which might influence the recorded deformation.

Plate 1. Horizontal extensometer mounted on the specimen.

Fig.1. Deformation strips.
The deformation is measured at the same points where the two zinc strips are glued in order to avoid any error in recording deformations due to specimen movement or inadequate contact between extensometer (strain gauge) and specimen. Brown and Cooper [9] have mentioned the shortcomings of indirect tensile test, using LVDTs, in deformation measurement. The recorded deformation was found to be influenced by the strength of the spring used to keep the LVDT core in contact with the specimen, and by the vibration of the frame which carries the deformation transducers. In addition, it is easier to use just one extensometer rather than two LVDTs.

The loading device is shown in Plate 2 and Figure 2. The upper steel loading strip is not fixed on the upper platen of loading device in order to bring a good contact between loading strips and specimen even at low stresses and high stiff asphalt specimens. An alignment bar is fixed to the upper aluminum platen to bring the loading strips into the same vertical plane. Figure 3 shows three different cases which could happen depending on the contact between loading strips and specimen when the loading strips are fixed on the platens. Case 1 shows a good contact, while cases 2 and 3 show insufficient contact which is a result of a rough surface. For more details see reference 22.
1 Precision Pillar  
2 Ball Bushing  
3 Upper Plate  
4 Float Loading Strip  
5 Specimen  
6 Alignment Bar  
7 Fixed Loading Strip  
8 Bottom Plate  
9 Hardened Disk

Fig. 2. Loading device for indirect tensile test.
3 Viscoelastic property of bituminous materials

Various investigators have emphasized the effects of stress or strain levels on the modulus of asphalt concrete mixtures [2,10-21]. The increasing use of elastic theory in pavement evaluation and for comparing various asphalt materials in terms of their rheological characters makes the fundamental properties in stress-strain relationship an important parameter [16]. With regard to the non-linear viscoelastic behavior of bituminous materials, the stress or strain level has an essential influence when measuring the moduli. Sayegh [17] does not exceed a strain value of $4.10^{-5}$ when measuring moduli. Monismith et. al. [11] consider the stiffness of asphalt mixtures independent of applied stress at strains less than $1.10^{-3}$ in/in. Bonnaure et.al. [13] determine stiffness modulus for strains $5.10^{-6}$ at $-15^\circ$C and $+9^\circ$C; $20.10^{-6}$ at $+30^\circ$C. Bonnaure et.al. also report that the phenomenon of non-linearity appears at strains close to $100.10^{-6}$. Kennedy and Anagnos [1] and ASTM [3] recommend a load range to induce 10 to 50 percent of the tensile
strength as determined in the static indirect tensile test, or in lieu of tensile strength data, loads ranging from 4 lb (25 lb according to Kennedy) to 200 lb per inch of specimen thickness can be used. Schmidt [2] uses a stress range from about 1 psi up to 15 psi at the specimen center at 73 °F (24 °C). So a wide variety of limits have been recommended. Therefore, an approximate linear zone (the resilient modulus is independent of applied stress or strain level) should be well defined to make the modulus more reliable.

4 Linearity

The test series consist of testing three specimens from each type of asphalt mixture at temperatures of -10, +5, +25 and +40 degrees Celsius and at a loading frequency of 0.33 Hz. Totally, 36 specimens have been tested with this method. The test procedure is the following:

* The test specimens were stored in a temperature cabinet for 24 hours at testing temperature. (A dummy specimen has shown that it takes at least four hours to bring the specimen from room temperature to -10°C).

* Repeated-load pulse, at a frequency of 0.33 Hz, was applied with 0.2 sec loading time and 2.8 sec rest period.

* The load level was increased gradually up to a level which resulted in a recordable deformation by extensometer.

* A minimum of 50 load repetitions were applied before the first reading.

* The load level was increased gradually to a higher level with about 25 load repetitions at each load level. The maximum load level used was about 4000 N.

* Stresses and strains were calculated at each load level, a curve was fitted by regression analysis for all three specimens, which represent the material response at defined temperature. The zero point has normally been adjusted due to surface irregularities.

The isochronous stress-horizontal deformation-strain diagrams were produced for bituminous mixtures to study the stress and strain effect on resilient modulus using repeated load indirect tensile test. Figure 4 shows isochronous diagram for HAB12T mix. Similar curves have been found for the other two mixtures (See Figure 5 and 6). The stress was calculated at the center of the specimen by Equation 1. These diagrams are represented by stress-deformation-strain...
curves and not only by the more familiar stress-strain curves, hence the deformation distribution on the horizontal diameter is not uniform [2,4,5,23]. This is done in order to eliminate the effect of using an assumed value for the Poisson's ratio for strain calculation at the center of the specimen, which might affect the strain value. However, for the sake of comparison, the tensile strain at the center of the specimen is calculated by Equation 7.

The correlation coefficients (R) are higher than 0.94, except for the porous graded mix tested at 25 degrees Celsius, which is 0.83. In all the cases, the stress-deformation relationships show curves which are concave downwards. This means that strain increases faster than stress and results in a reduction in resilient modulus. The nonlinearity relationships are obvious even at low stress and deformation levels. The non-linear viscoelastic relationships confirm the importance of stress and deformation levels when measuring the resilient moduli of asphalt mixtures.

The above discussion shows the dominance of viscous properties at high strain and stress levels. Therefore, and in order to measure the resilient moduli of bituminous materials with consistent results, a viscoelastic linear zone should be defined in which the effect of stress or strain levels on the resilient modulus is negligible. If resilient modulus is measured at higher stresses or strains, it could be justified in some cases in order to simulate field
Fig. 5. Stress-deformation-strain relationships for RUB12.

Fig. 6. Stress-deformation-strain relationships for RUBD12.
conditions, in this case the stress or strain level should be reported.

The viscoelastic linear zone is defined, in this study, as the zone where stress in the stress-deformation curve diverges with less than 10 percent from the rectilinear stress-deformation relation shown in Figure 7. The rectilinear stress-deformation relation is represented by the slope of the curve at the origin.

The 10 percent divergence of stress cause a 10 percent reduction in resilient modulus from the initial modulus value (modulus at origin). This variation is believed to be acceptable because of the heterogeneity and unisotropy of asphalt concrete mixtures.

Figure 4 through 6 also show the limits of deformations and stresses at 10 percent reduction of resilient modulus. The stress limits decrease with increased temperatures but for deformations it is the opposite, i.e., the deformation limits increase with increased temperatures. A similar conclusion is reported by other investigators [24,25,26] when exposing asphalt mixture specimen to different deformation rates, using the tensile strength method, higher elongation is reported at lower deformation (high temperatures correspond to low deformation rates) and vice versa. At low temperatures the bituminous mixtures are stiff and brittle. They tolerate low strains with high stresses. At high temperatures these mixtures have low stiffness and high flexibility. They tolerate high strains but with very low stresses.

Figure 8 shows a relation between temperatures and the logarithm of deformation limits, as defined before for
Fig. 8. Relationship between the logarithm of deformation and temperature.

Tested mixtures (with 0.2 sec loading time and a frequency of 20 cycle/min.). The correlation coefficient (R) for all materials together is 0.986, using regression Equation 8.

\[ \log(D) = \exp(0.0138T + 0.313) \]

where
- \( D \): Horizontal deformation in mm \( \times 10^{-4} \)
- \( T \): Temperature in Celsius.

5 Resilient modulus

In accordance with the discussion in the above section regarding stress-strain relationships and the effect of irregularities of specimen surface the following procedure has been used for resilient modulus measurement. Indirect tensile test has been used on cylindrical bituminous sample.

* The test specimens were stored in a temperature cabinet to the proper temperature.
* Repeated-load pulses at a frequency of 0.33 Hz were applied with 0.2 sec loading time.
* A minimum of 50 load repetitions were applied before the first reading and until the resilient deformation became constant.

* The resilient horizontal deformation were measured at the maximum allowable load level and at 50 and 75% of this value. The test began at the lowest load level and increased gradually to higher load levels with about 25 load repetitions at each load level.

* After the test had been completed, the tensile stress was calculated at each load level according to Equation (1).

* Stress-resilient horizontal deformation curve was plotted. Curve fitting by linear regression analysis was used. In such cases, the zero point was adjusted as shown in Figure 9 to compensate for surface irregularities and insufficient contact between loading strips and specimen.

* The resilient modulus was calculated with constant Poisson's ratio according to Table 1 at different temperatures by Equation 5:

![Fig.9. Correction of the stress-strain curve.](image-url)
Table 1. Constant Poisson’s ratio

<table>
<thead>
<tr>
<th>T°C</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td>0.20</td>
</tr>
<tr>
<td>+5</td>
<td>0.25</td>
</tr>
<tr>
<td>+20</td>
<td>0.35</td>
</tr>
<tr>
<td>+40</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Fig. 10. Effect of temperature on resilient modulus.
Figure 10 shows the resilient modulus at different temperatures. The relationship between temperature and the log of resilient modulus is not linear. The rubberized mix (RUB12) shows lower moduli than conventional mix (HAB12T), a fact which indicates the higher flexibility of the rubberized mix. The porous mix (RUBD12) has shown, as expected, the lowest moduli. Furthermore, there were no problems in measuring resilient modulus for the porous mix.

6 Conclusions

1- An approximate linear viscoelastic zone for practical use has been defined for asphalt mixtures at different temperatures (with 0.2 loading time and 20 cycles/min.).

2- The upper loading strip should be free in order to create satisfactory contact between loading strips and specimen even at low stresses and stiff asphalt specimens.

3- One extensometer may be used instead of two LVDTs with carrying frame. In that case the recorded deformation will not be influenced by the following: (1) the strength of the spring that keeps the LVDT cores in contact with the specimen, (2) the vibration of the frame which carries the deformation transducers, and (3) the extensive load on the specimen.

7 References


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L’ANALYSE D’EXTENSION INDIRECTE DES MODULES RÉSILIENTS

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Résumé
Les progrès faits dans le domaine du design analitique des structures de pavé ont rendu nécessaire un croissant besoin de connaissances sur les propriétés mécanique des différents composants du pavé dans les conditions des routes; telles que la résistance à l’extension; la rigidité des modules et la résistance à plusieurs réprises des mélanges de pavé en béton. Ces paramètres constituent une base convenable pour le design analytique et l’évaluation des performances du pavé flexible.

Dans ce rapport-ci on a choisi l’analyse d’extension indirecte à cause de sa validité et simplicité. En tout cas; on a effectué des modifications de l’appareillage et des procedures d’analyse.

On a examiné trois types différents de mélanges de pavé en béton par utilisant la méthode d’extension indirecte. Deux d’entre les mélanges sont mélangés à 3% de contenu de caoutchouc par le poids total, c’est à dire le Rubit (RUB12), qui est un asphalt dense en béton, utilisé pour la réfection des routes, et un mélange poreux appelé Rubdrain (RUBD12). Le troisième mélange est un asphalt dense conventionnel en béton (HABI2T), utilisé pour la réfection des routes. La dimension maximum de l’aggréagat a été 12 mm pour tous les types.

La relation entre la tension et la déformation (stress-deformation-strain) a été établie pour examiner l’influence du niveau de la tension et/ou la déformation sur le module résilient trouvé par l’analyse d’extension indirecte et pour définir une zone viscoélastique approximativement linéaire pour les mélanges de bitume à temperatures différentes. Les modules résiliens ont été mesurés par utilisant la méthode d’extension indirecte, modifiée pour les mélanges analysés à 4 temperatures différentes.