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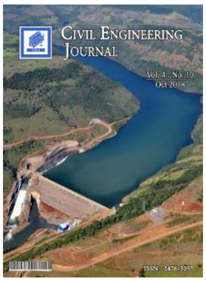


# Equivalent Modulus of Asphalt Concrete Layers

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**Abstract**

A flexible pavement structure usually comprises more than one asphalt layer, with varying thicknesses and properties, in order to carry the traffic smoothly and safely. It is easy to characterize each asphalt layer with different tests to give a full description of that layer; however, the performance of the whole; asphalt structure needs to be properly understood. Typically, pavement analysis is carried out using multi-layer linear elastic assumptions, via equations and computer programs such as KENPAVE, BISAR, etc. These types of analysis give the response parameters including stress, strain, and deflection at any point under the wheel load. This paper aims to estimate the equivalent Resilient Modulus (MR) of the asphalt concrete layers within a pavement structure by using their individual MR values. To achieve this aim, eight samples were cored from Iraqi Expressway no. 1; they had three layers of asphalt and were tested to obtain the MR of each core by using the uniaxial repeated loading test at 25 and 40 °C. The samples were then cut to separate each layer individually and tested for MR at the same testing temperatures; thus, a total of 60 resilient modulus tests were conducted. A new approach was introduced to estimate the equivalent MR as a function of the MR value for each layer. The results matched the values obtained by KENPAVE analysis.

*Keywords:* Equivalent Resilient Modulus; Asphalt Concrete; Multi-Layer; Linear Elastic.

## 1. Introduction

Flexible pavement analysis is required to understand the behavior of asphalt mixtures under different conditions. There are different approaches to analyse the behavior of asphalt mixtures ranging from linear elastic to complex non-linear analysis. Layered Elastic Theory (LET) has been successfully used over the past 50 years to analyze flexible pavements [1]. LET was first developed by Burmister as an analytical solution for a two-layered system and then improved to a multi-layered system. The method is considered as a mathematically exact solution. It gives the response (stresses, strains and deflections) when subjected to a wheel load at any point in a multi-layered, linear elastic pavement, assuming the layer is horizontally infinite and lying on a semi-infinite subgrade [2]. Al-Mosawe (2016) [3] conducted a study based on the multi-layer elastic system to predict the permanent deformation in asphalt mixtures and the results showed good agreement with laboratory data.

The key parameter of pavement layers which is needed for the evaluation, design, and to estimate the remaining life of an existing pavement for the overlay design in pavements maintenance is the Resilient Modulus (Mr). The evaluation of Mr for asphalt concrete mixes is well documented in the ASTM and AASHTO standards, but for the existing pavement structure the calculation of the layer modulus or the entire structure modulus required two types of tests. The first type is the destructive test (DT) which is achieved by coring the asphalt concrete pavement then testing the cores in the laboratory to determine the resilient modulus. The second type is the non-destructive test (NDT), where the

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obtained deflection data are used to quantify the Mr with the aid of back-calculation method achieved using mechanistic method, the mechanistic method assumes the pavement response parameter (i.e., stress, strain and deflection) can be modelled in term of elastic multi-layer system. One of the NDT methods that is used in evaluating the pavement modulus in the field is the use of Falling Weight Deflectometer (FWD). There is amount of research focusing on the accuracy of this instrument to estimate the stiffness of the pavement. Ahmed and Rafiqul [4] conducted a study to evaluate the efficiency of using Ground Penetration Radar (GPR) and Falling Weight Deflectometer (FWD) in predicting the pavement performance. They found that the GPR is more efficient in estimating the thicknesses of asphalt layer rather than the base layer, and there is inconsistency of FWD moduli prediction in different pavement sections. There are other researchers introduced analytical approaches using further back-calculations methodologies or laboratory measurements and process the FWD and GPR results to increase their accuracy [5, 6].

After that and based on the trial and error procedure, initial pavement layers properties are assumed, and the surface deflection is calculated and compared to the measured surface deflection, whenever the two values are matches, the value of Mr is abstracted. such back-calculation methods of analysis have been developed using different assumptions or algorithms concerning the layer material properties, all of which have the trial-and-error procedure as their basis. One drawback of all the available programs is the computation efficiency which essentially influences their use in the routine design and evaluation works.

The Method of Equivalent Thicknesses (MET) was introduced by Odemark and has been widely used for pavement analysis [7] and in several applications [8-14]. Ullidtz (1987) [7] investigated the accuracy of the MET compared to the theory of elasticity by calculating the response parameters (stress, strain, and deflection) of a certain pavement structure and compared them with the results of the same structure using the Elsym 5 program. The results showed an accuracy of 89-92% compared to the elastic theory values.

Lu et al (2008) [15] conducted three methods of analysis of a 3-layered structure (Odemark, single-layer elastic, and multi-layered elastic analysis) when back-calculating the layer moduli, with differences of less than 7% between the three methods. Pologruto (2001) [16] calculated deflection, from 30 test sites, by using MET and found that the predictions were within 10% of the measured data (by FWD).

On the other hand, Elbadawy and Kamel (2011) [17] conducted an extensive study based on a two-layered system with a wide range of layer thicknesses and modular ratios. They used MET and layered elastic theory to compare the stresses and strains with the same pavement structure properties and they found that using Odemark without a correction factor gives inaccurate results when compared to KENPAVE analysis.

The use of equivalent Resilient Modulus (MR) of the asphalt concrete layers suggested in this research combined with the use of Burmister two-layer equations could be applied in the modulus back- calculation method (i.e., all asphalt concrete layers are considered one equivalent layer rested on elastic subgrade-infinite layer). The matter which resulted in much faster back-calculation method due to the simplicity of suggested approach.

There is a contradiction among different researchers regarding the accuracy of the MET compared to the layered elastic method; therefore, this paper investigates the possibility of proposing a transformation criterion to accurately estimate the resilient modulus of the pavement.

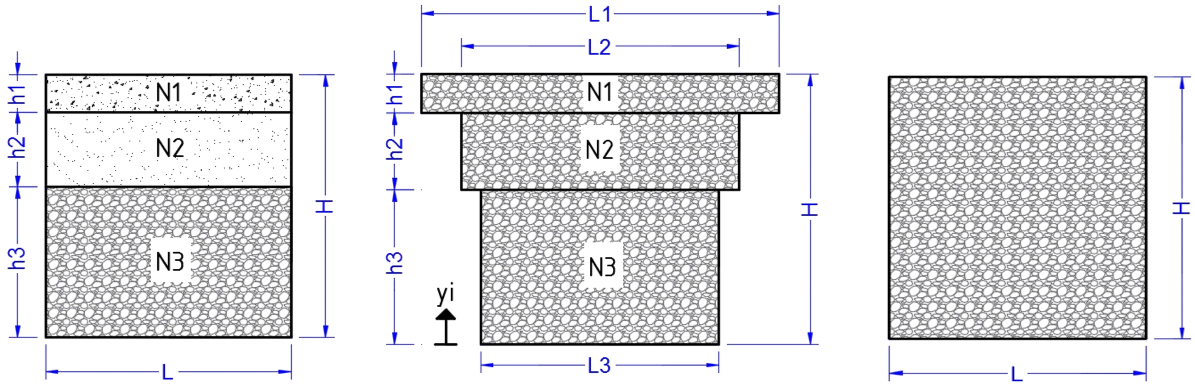
## 2. Methodology

In general, a flexible pavement consists of multiple layers of asphalt concrete resting on unbound materials and subgrade. A composite (laminated) pavement in this configuration refers to a pavement with layers of material having different resilient moduli ($M_R$). The differences in modulus will result in a shift in neutral axis towards the stiffer layer under wheel load. It is a potentially worthwhile aim to determine an equivalent pavement layer, substituting the actual multiple layers to achieve better understanding of pavement structure performance. The basic concept is to make a pavement layer out of one material so that it has the same functionality as the original pavement.

For a pavement consisting of three layers (shown in Figure 1), N1, N2 and N3 with stiffness moduli E1, E2 and E3, the transformation factors for replacing N1 and N2 with N3 are:

$$N_1 = \frac{E_1}{E_3}, \qquad N_2 = \frac{E_2}{E_3}, \qquad N_3 = \frac{E_3}{E_3} = 1$$

$$Then, L_1 = N_1 L, \qquad L_2 = N_2 L, \qquad N_3 L_3 = L$$




**(a) Original section** **(b) Transformed section** **(c) Equivalent section**

**Figure 1. Section properties**

The new pavement (Figure 1c) consists of a single material and can be treated easily in the analysis. The first step is to calculate the location of the centroid of the transformed equivalent section shown in Figure (1b) as follows:

$$Y = \frac{\sum_{i=1}^{n} y_i A_i}{\sum_{i=1}^{n} A_i} \tag{1}$$

The neutral axis of this pavement coincides with the centroid of its transformed equivalent section; therefore, all calculations should be made with respect to this neutral axis position. After that, the second step is to calculate the moment of inertia (I) according to Equation 2, where $d_i$ is the distance from the centroid of each layer to the neutral axis, Y.

$$I_i = \frac{L_i h_i^3}{12} + A_i d_i^2 \tag{2}$$

Hence, the rigidity of the equivalent pavement section ($E_{eq}.I_{eq}$) shown in Figure (1c) is expressed as:

$$E_{eq}\, I_{eq} = \sum_{i=1}^{n} E_i\ I_i \tag{3}$$

The equivalent modulus ($E_{eq}$) and the equivalent moment of inertia ($I_{eq}$) are calculated based on the following equations:

$$E_{eq} = \frac{\sum_{i=1}^{n} E_i I_i}{I_{eq}} \tag{4}$$

$$I_{eq} = \frac{L\, H^3}{12} \tag{5}$$

Equation 4 can be used to convert the modulus of wearing, binder and base layers into an equivalent modulus of a single layer. This equivalent transformation method will simplify the analysis of pavement response calculations (stress, strain, and deflection). In addition, the method has been successfully used in the prediction of permanent deformation parameters for flexible pavements as presented by Albayati (2006) [18]. It is worth mentioning that (E) refers to the resilient modulus ($M_R$) that will be used hereafter in the next section. The $M_R$ value is more representative of the stiffness of flexible pavement layers because it simulates reality by considering the effect of repeated loading of traffic during the test.

## 3. Materials and Experimental Works

The asphalt concrete used in this research was derived from the flexible pavement of Iraqi expressway No.1 (Section 4, R4). Expressway No.1 has a length of 1250 km connecting the western borders of Iraq (Syria and Jordan) with the southern border of Iraq (Kuwait). For ease of construction it is divided into 13 sections; section four (R4) has a length of 105 km. The flexible pavement structure for this expressway consists of three courses of asphalt concrete (wearing, binder and base) and a subbase course over the subgrade soil.

Both fieldwork and laboratory work were carried out to achieve the requirements of this study. In the field, 8 deep cores were taken from the existing pavement of the expressway with a total thickness equal to the combined thicknesses of the asphalt concrete layers. The coring process and the core samples are shown in Figures 2 and 3 below, respectively.

The laboratory work comprised the determination of the resilient modulus ($M_R$) for the cylindrical core samples. Fifteen resilient modulus tests were carried out on the deep core samples, which had a diameter of 101.6 mm (4 inches) and an average height of approximately 260 mm (10.23 inches), by using a uniaxial repeated load at two testing temperatures, 25°C (77°F) and 40°C (104°F). The $M_R$ result for one of the cores at 40 °C was not included due to laboratory technical error in the LVDTs during the test causing an incorrect reading. After the completion of these tests, each core sample was then cut into three specimens using a saw cutter, representing wearing, binder and base courses. The average height for the binder and base course specimens was 63.5 mm (2.5 inch) whereas the height of the wearing course varied according to the existing pavement wearing course thickness. 45 resilient modulus tests were performed on these specimens using diametral repeated loading; 24 tests were performed at 25°C (77°F) and the other 21 tests conducted at 40°C (104°F).

**Figure 2. Coring process**


*For technical reasons during the test, the $9^{th}$ specimen was excluded

**Figure 3. Core samples**

## 3.1. Materials

The mixture compositions, including aggregate gradation and asphalt content recovered from the core specimens, are presented in Tables 1 to 3 for the wearing, binder and base course specimens after cutting them from the deep core samples. The physical properties of the recovered asphalt cement from the cores are listed in Table 4.

**Table 1. Composition of asphalt concrete mixture as recovered from core samples (wearing course)**

| | | Percent passing by weight of total aggregate (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sieve size (mm)** | **Sieve size (in.)** | **S1** | **S2** | **S3** | **S4** | **S5** | **S6** | **S7** | **S8** | **Specification limit (ASTM D 3515, D-5)** |
| 37.0 | 1.5 | … | … | … | … | … | … | … | … | … |
| 25.0 | 1 | … | … | … | … | … | … | … | … | … |
| 19.0 | 3/4 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 12.5 | 1/2 | 90 | 92 | 94 | 88 | 91 | 93 | 89 | 90 | 90-100 |
| 9.5 | 3/8 | 80 | 82 | 82 | 79 | 81 | 82 | 81 | 82 | … |
| 4.75 | No.4 | 62 | 64 | 58 | 63 | 64 | 59 | 62 | 64 | 44-74 |
| 2.36 | No.8 | 47 | 42 | 43 | 38 | 44 | 41 | 43 | 46 | 28-58 |
| 0.3 | No.50 | 16 | 20 | 22 | 19 | 21 | 20 | 22 | 23 | 5-21 |
| 0.075 | No.200 | 8 | 7 | 8 | 9 | 6 | 8 | 9 | 7 | 2-10 |
| | | Percent asphalt cement by weight of total mixture (%) | | | | | | | | |
| % | | 4.23 | 4.16 | 4.28 | 4.10 | 4.22 | 4.08 | 4.34 | 4.04 | 4-11 |

**Table 2. Composition of asphalt concrete mixture as recovered from core samples (binder course)**

| | | Percent passing by weight of total aggregate (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sieve size (mm)** | **Sieve size (in.)** | **S1** | **S2** | **S3** | **S4** | **S5** | **S6** | **S7** | **S8** | **Specification limit (ASTM D 3515, D-4)** |
| 37.0 | 1.5 | … | … | … | … | … | … | … | … | … |
| 25.0 | 1 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 19.0 | 3/4 | 90 | 88 | 94 | 93 | 92 | 93 | 88 | 92 | 90-100 |
| 12.5 | 1/2 | 83 | 78 | 81 | 84 | 83 | 84 | 76 | 83 | … |
| 9.5 | 3/8 | 73 | 69 | 73 | 71 | 67 | 62 | 63 | 65 | 56-80 |
| 4.75 | No.4 | 56 | 54 | 60 | 58 | 51 | 49 | 52 | 58 | 35-65 |
| 2.36 | No.8 | 40 | 48 | 45 | 42 | 40 | 40 | 43 | 45 | 23-49 |
| 0.3 | No.50 | 18 | 24 | 21 | 20 | 22 | 19 | 23 | 21 | 5-19 |
| 0.075 | No.200 | 7 | 6 | 6 | 8 | 7 | 6 | 7 | 8 | 2-8 |
| | | Percent asphalt cement by weight of total mixture (%) | | | | | | | | |
| % | | 3.74 | 3.62 | 3.84 | 3.59 | 3.78 | 3.68 | 3.88 | 3.79 | 4-10 |

**Table 3. Composition of asphalt concrete mixture as recovered from core samples (base course)**

| | | Percent passing by weight of total aggregate (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sieve size (mm)** | **Sieve size (in.)** | **S1** | **S2** | **S3** | **S4** | **S5** | **S6** | **S7** | **S8** | **Specification limit (ASTM D 3515, D-3)** |
| 37.0mm | 1.5 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 25.0mm | 1 | 96 | 100 | 97 | 98 | 93 | 94 | 100 | 97 | 90-100 |
| 19.0mm | 3/4 | 84 | 90 | 89 | 82 | 87 | 89 | 88 | 89 | … |
| 12.5mm | 1/2 | 71 | 76 | 75 | 75 | 80 | 78 | 74 | 78 | 56-80 |
| 9.5mm | 3/8 | 63 | 62 | 65 | 62 | 69 | 65 | 67 | 66 | … |
| 4.75mm | No.4 | 42 | 46 | 42 | 45 | 50 | 48 | 42 | 45 | 29-59 |
| 2.36mm | No.8 | 35 | 39 | 34 | 37 | 41 | 38 | 36 | 39 | 19-45 |
| 0.3 µm | No.50 | 18 | 20 | 19 | 21 | 23 | 21 | 23 | 24 | 5-17 |
| 0.075µm | No.200 | 6 | 6 | 5 | 6 | 5 | 6 | 5 | 4 | 1-7 |
| | | Percent asphalt cement by weight of total mixture (mm) | | | | | | | | |
| % | | 3.10 | 3.08 | 2.95 | 3.03 | 3.12 | 3.07 | 3.15 | 3.09 | 3-9 |

**Table 4. Physical properties of recovered asphalt cement**

| Property | Layer | | |
|---|---|---|---|
| | Wearing | Binder | Base |
| 1- Penetration at 25°C (100 gm,5 sec.), 1/10mm | 21 | 24 | 26 |
| 2- Viscosity, at 60 °C, poises | 23688 | 18645 | 17859 |
| 3-Viscosity, at 135 °C, cSt. | 1108 | 1123 | 1240 |

## 3.2. Uniaxial Resilient Modulus Test

The uniaxial repeated loading tests were conducted on the deep core samples obtained from the field. The tests were performed using a pneumatic repeated load system (shown in Figure 4). In this test, repetitive compressive loading with a stress level of (20 psi) was applied in the form of a rectangular shaped load pulse and a constant loading frequency of 1 Hz (0.1 sec. load duration and 0.9 sec. rest period), as shown in Figure 5. The axial resilient deformation was measured using an LVDT (Linear Variable Differential Transducer). As mentioned earlier, the uniaxial resilient modulus test was performed at two testing temperatures, 25°C (77°F) and 40°C (104°F). Based on this test, the resilient modulus was calculated using the following equation.

$$M_R = \frac{\sigma\, t}{\delta} \tag{6}$$

Where:

$M_R$= Resilient modulus, MPa (Psi)

$\sigma$= Uniaxial v/ertical stress, MPa (Psi)

$t$= Height of the specimen, mm (in)

$\delta$= Total recoverable vertical deflection, mm (in)

**Figure 4. Uniaxial resilient modulus test using pneumatic repeated load**

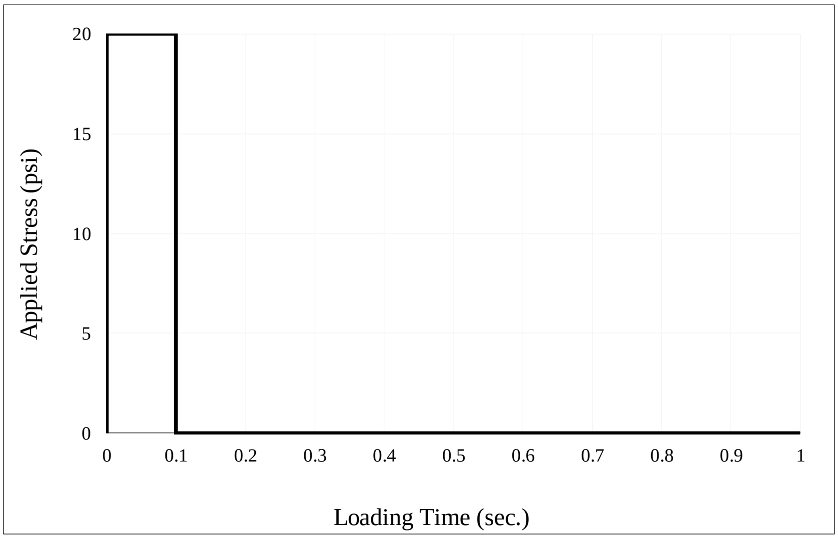



**Figure 5. Typical Loading cycle subjected to the specimen**

### 3.3. Diametral Resilient Modulus Test

After cutting the deep core samples into three specimens representing the wearing, binder and base courses, the height to diameter ratio of these specimens became lower than 2. Therefore, it was decided to use the diametral resilient modulus test to avoid the stress interference which would have occurred in the uniaxial test. The diametral resilient modulus test was performed using the procedure outlined in ASTM D4123 "Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures". During this test, a rectangular pulsed diametral loading stress was applied to the specimen with 20 psi stress magnitude and a constant loading frequency of 1 Hz (0.1 sec. load duration and 0.9 sec. rest period). The resulting total recoverable diametral deformation was then measured on an axis 90 degrees from the applied force. The resilient modulus was calculated according to the following equation:

$$M_R = \frac{P\ (v + 0.2734)}{\delta\ t} \tag{7}$$

Where:

$P$ = Peak load, N (lb)

$v$ = Poisson ratio, assumed as 0.35

$M_R$ , $\delta$ and $t$ were previously defined.

## 4. Results

As mentioned earlier, the samples were tested as a 3-layer system under the repeated load test. Two temperatures were considered during the test, 25 and 40 °C to cover a range of possible conditions in the field. Because the test is non-destructive, the samples were then cut to separate each layer individually and these were then tested under the same loading conditions and temperatures. This section will show the performance of the proposed simplifying approach for determining the resilient modulus for the whole pavement structure and compare it with the performance of the measured individual stiffness values by using the KENPAVE program.

The proposed method showed a very good prediction of resilient modulus compared with the measured values as can be noted in Figure (6). The reason behind this is that the new proposed method is calculating the neutral axis of the pavement structure precisely. It also can be notices that the two groups are gaped because of the two values of temperatures.

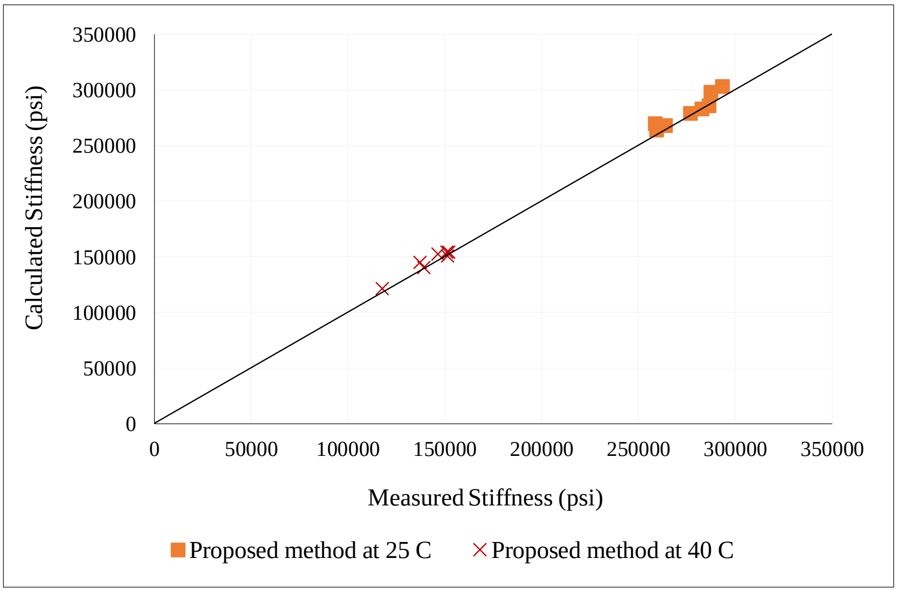
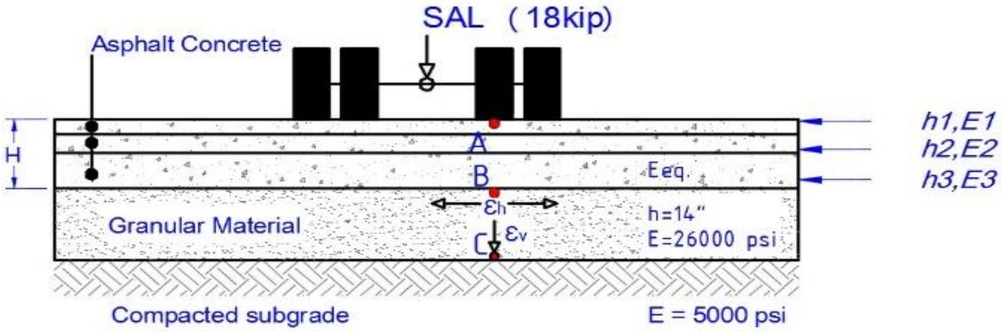



**Figure 6. Predicted stiffness at two temperatures for the two methods**

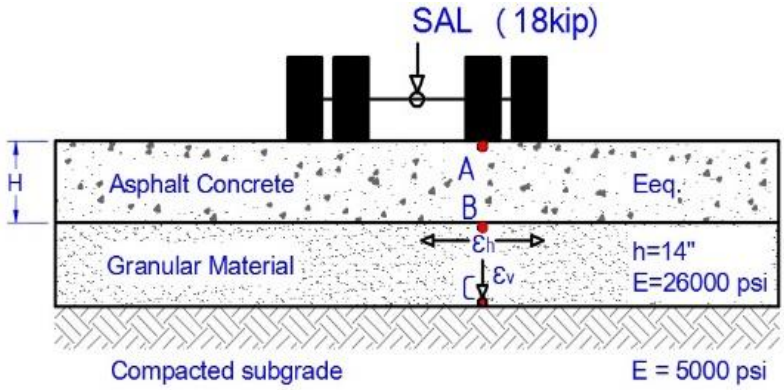
### 4.1. KENPAVE Analysis

There were two KENPAVE analyses for each sample at a certain temperature; the first involved in putting the individual measured stiffnesses for each layer with their real thicknesses followed by subbase and subgrade materials. The second analysis used the equivalent values of asphalt layer stiffness, which were calculated based on the stiffness values of the individual layers, and the sum of the heights of individual layers.

Two strain values were obtained from both analyses for each sample, together with the vertical displacement at the critical position (as shown in Figure 7 below). These were the horizontal strain at the bottom of the asphalt layer(s) and the vertical strain at top of the subgrade layer. The critical position for displacement was directly under the tire. Strains from the first analysis are termed "actual strain" because they use individual layer stiffnesses measured in the laboratory; the second is termed "equivalent strain" because it comes from calculated equivalent stiffnesses.




**(a) Multi-layer section**




**(b) Equivalent section**

**Figure 7. Multi-layer and equivalent pavement structure**

Figures (8) and (9) show the relationships between the measured and equivalent horizontal and vertical strains at the two temperatures. The strains from the equivalent stiffness values are close to the measured strains in both cases. In addition, the proposed method also predicts the displacement under the wheel at the two different temperatures as can be seen in Figure (10).

The Mean Absolute Percentage Error (MAPE) was calculated for each case to investigate the accuracy of the results. The MAPE is shown in Table (5) and it can be seen that the subgrade compressive strain and vertical displacement are predicted more precisely than asphalt tension strain.

**Table 5. Mean absolute percentage error for the different cases**

| Temperature, °C | MAPE (%) | | |
|---|---|---|---|
| | Asphalt tensile strain | Subgrade Compressive strain | Displacement (in.) |
| 25 | 6.0 | 0.45 | 0.63 |
| 40 | 4.1 | 0.36 | 0.97 |

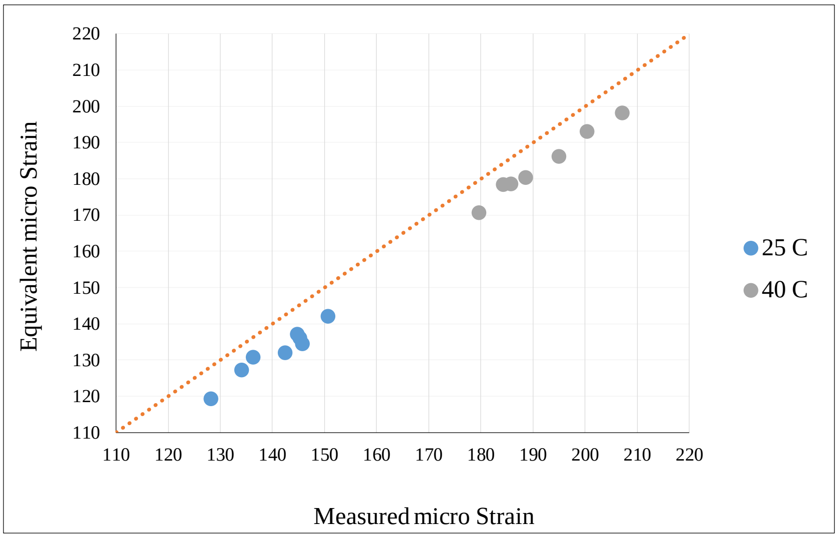



**Figure 8. Relationship between measured and equivalent asphalt tensile strain at 25 and 40 C°**

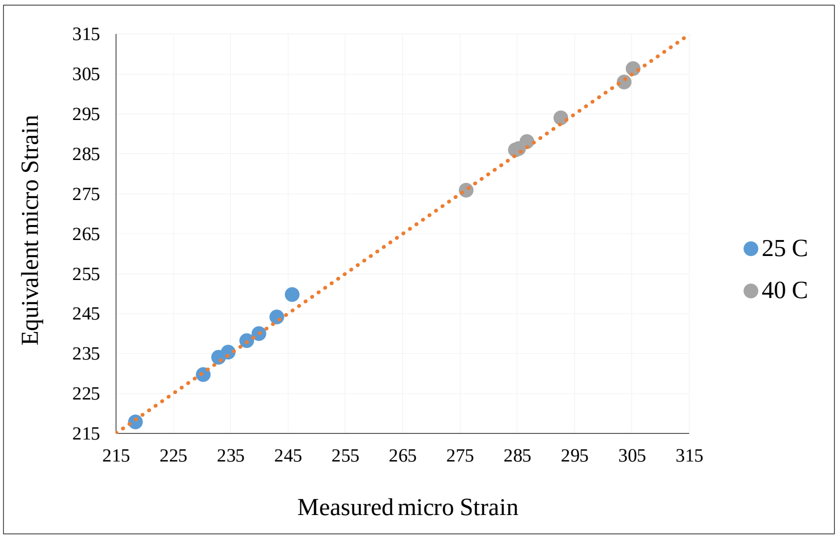



**Figure 9. Relationship between measured and equivalent subgrade compressive strain at 25 and 40 C°**

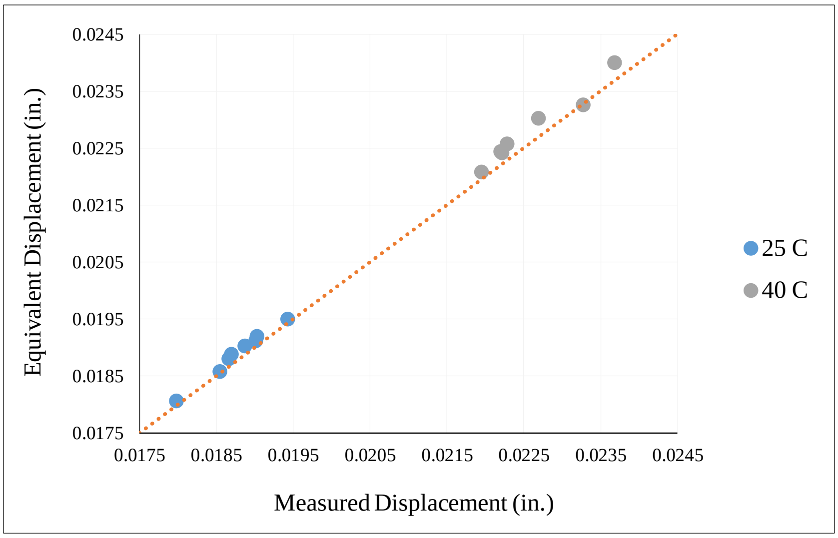



**Figure 10. Relationship between measured and equivalent vertical displacement at 25 and 40 °C**

Interestingly, it is evident from Figures (8) to (10) and Table (5) that the increase in testing temperature did not negatively affected the accuracy of the prediction of the equivalent $M_R$. The temperature increase to 40 °C would tend to bring the mixture performance into the non-linear behavior zone, and at very high temperatures it may be difficult to rely on this method in evaluating the $M_R$ due to non-linear behavior.

## 5. Conclusions

Eight samples cored from Expressway No. 1 were tested to obtain their resilient modulus for the whole pavement structure and then for each layer in the cored sample. A new approach was proposed to estimate the whole pavement structure $M_R$ and this was compared with results KENPAVE analysis. The outcomes of this paper can be concluded as:

- The proposed approach can give reasonable results when compared with results from laboratory $M_R$ and KENPAVE analysis
- The error in the results obtained from the proposed method compared to the results from KENPAVE was less than 1% for the critical deflection and subgrade compressive strain at the two temperatures, while for the asphalt tensile strain the accuracy decreased to 6 and 4 % at 25 and 40 °C respectively
- The proposed approach can easily be used in the field to get an estimate of pavement performance if the properties of each layer are originally known. The method is considered as a simpler solution than using the Falling Weight Deflect meter (FWD).
- The method was used at high testing temperature (40 °C) and also gave good results. The high testing temperature tends the pavement performance towards non-linear behavior, which is usually the real behavior in the field.

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