A STUDY OF THE STRAIN BEHAVIOR OF ASPHALT PAVEMENT ON STEEL PLATE DECK BY VISCOELASTIC ANALYSIS

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A laboratory experiment on strain change with time in asphalt mixture under dynamic load was carried out in 2010 as previously reported, using composite specimens of asphalt mixture and a steel plate. The results revealed that tensile strain could occur in asphalt mixture under positive bending condition in many cases, depending on the pavement structure, test temperature, or loading time. The current study aimed at reproducing the strain behavior observed during the previous experiment by using linear visco-elastic analysis. The analysis verified that there could be many cases where tensile strain was induced in the asphalt mixture on a steel plate even under positive bending condition, successfully reproducing the strain behavior, which was irreproducible by elastic analysis.

Key Words: asphalt mixture, steel plate deck, strain, viscoelastic analysis

1. INTRODUCTION

Longitudinal cracks are known to occur in asphalt pavement on steel plate deck not only above the stringers, which are under negative bending condition, but also between the webs, which are under positive bending condition. For the purpose of investigating the strain behavior of asphalt mixture on a steel plate, the authors prepared composite specimens in various combinations of a steel plate and different asphalt mixture types. They then conducted a bending test, applying dynamic load (hereinafter referred to as “dynamic bending test”) in a haversine wave for different loading times at different test temperatures of 20°C, 40°C, and 60°C to understand the change with time in strain induced in the asphalt mixture.

The findings of the test are as described below:

(1) At 20°C, specimens with adequate bond between the steel plate and asphalt mixture exhibited no tensile strain in the asphalt mixture, while those with insufficient bond exhibited tensile strain in the bottom surface of the asphalt mixture. These behaviors were reproduced almost successfully by elastic analysis.

(2) At 40°C, specimens exhibited tensile strain in the steel plate and compressive strain in the asphalt mixture as the load increased to the maximum level, which was successfully reproduced by elastic analysis. However, as the tensile
strain recovery increased in the steel plate with the decrease in load from the maximum level, the strain in the asphalt mixture changed from compressive to tensile, with larger tensile strain induced closer to the surface of the asphalt mixture. The strain behavior after the maximum load was irreproducible by elastic analysis.

(3) At 60ºC, asphalt mixture exhibited tensile strain but no compressive strain due to the difference in stiffness between the steel plate and asphalt mixture as suggested by the results of elastic analysis. Like in the case of 40ºC, tensile strain in the asphalt mixture increased during the period of tensile strain recovery in the steel plate after the maximum load.

Both the steel plate and asphalt mixture exhibited elastic behavior at 20ºC. However, the strain behavior of asphalt mixture observed at 40ºC and 60ºC during the period of tensile strain recovery in the steel plate after the maximum load was irreproducible by elastic analysis.

On the other hand, elastic theory is widely accepted for use in the analysis of wheel load-induced strain in the pavement by assuming linearity since such strain accounts for only a few percent of failure strain. However, there have been also many studies based on linear viscoelastic theory, including a viscoelastic analysis in which Laplace transformation was applied to laminar structure.

In this study the authors modeled the results of the previous experiment using linear viscoelastic analysis in an attempt to reproduce the strain behavior observed in the asphalt mixture.

2. VISCOELASTIC ANALYSIS METHOD

(1) Analysis theory

It is known as a correspondence principle of a linear viscoelastic body that Laplace transforming field equations, constitutive equations, and boundary conditions with respect to time give an equation of an elastic body. In this study, using Burger’s model as a model of linear viscoelastic body, a stiffness equation was Laplace transformed based on the correspondence principle to solve it as a linear problem in Laplace space, and the solution was inverse Laplace transformed to obtain a solution in time space.

Burger’s model shown in Fig. 1 consists of one Maxwell element and one Voigt element, which are connected in series. The following relationship is obtained from the Maxwell element:

$$\sigma + \frac{\eta_1}{E_1} \frac{d\sigma}{dt} = \eta_1 \frac{d\varepsilon_1}{dt} \tag{1}$$

The following relationship is obtained from the Voigt element:

$$\sigma = E_2 \varepsilon_2 + \eta_2 \frac{d\varepsilon_2}{dt} \tag{2}$$

For strain, the following equation holds:

$$\varepsilon = \varepsilon_1 + \varepsilon_2 \tag{3}$$

These equations give the following differential equation:

$$\frac{\eta_1}{E_1} \frac{d^2\sigma}{dt^2} + \left(1 + \frac{E_2}{E_1} \frac{\eta_2}{\eta_1} \right) \frac{d\sigma}{dt} + \frac{E_2}{E_1} \sigma = \eta_1 \frac{d^2\varepsilon_1}{dt^2} + \frac{d\varepsilon_2}{dt} \tag{4}$$

Laplace transforming this equation with the initial conditions $\sigma(0) = \dot{\sigma}(0) = 0$ and $\varepsilon(0) = \dot{\varepsilon}(0) = 0$ applied, gives the following equation:

$$\left[\frac{\eta_1}{E_1} s^2 + \left(1 + \frac{E_2}{E_1} \frac{\eta_2}{\eta_1} \right) s + \frac{E_2}{E_1} \right] \overline{\sigma} = \left(\eta_1 s + E_2 \right) \overline{\varepsilon} \tag{5}$$

Here, $s$ is a complex number representing a parameter in Laplace space. Therefore, $\overline{E}$ expressed by the following equation can be regarded as an equivalent Young’s modulus in Laplace space:

$$\overline{E} = \frac{(\eta_1 s + E_2) s}{\eta_1 s^2 + \left(1 + \frac{E_2}{E_1} \frac{\eta_2}{\eta_1} \right) s + \frac{E_2}{E_1}} \tag{6}$$

When a stiffness equation can be described as $K(t)u(t) = P(t)$, Laplace transforming this gives $K(s)\overline{u}(s) = \overline{P}(s)$; where, $K(s)$ is a stiffness matrix with $\overline{E}$ obtained by Equation (6) taken as Young’s modulus. Therefore, solving a linear stiffness equation expressed as $K(s)\overline{u}(s) = \overline{P}(s)$ in Laplace space and taking a numerical inverse Laplace transform of the solution such as displacement $\overline{u}(s)$, strain $\overline{\sigma}(s)$ or stress $\overline{\sigma}(s)$ gives a solution in time space. For handling a specific load, it is necessary to take the numerical Laplace transform of the term of load $P(t)$ and obtain $\overline{P}(s)$.

Fourier and inverse Fourier transforms are defined as follows:
\[
F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-i\omega t} \, dt
\]  
(7) 

\[
f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) e^{i\omega t} \, d\omega
\]  
(8) 

Laplace and inverse Laplace transforms are defined as follows:

\[
F(s) = \int_{0}^{\infty} f(t) e^{-st} \, dt \quad (f(t) = 0, t < 0)
\]  
(9) 

\[
f(t) = \frac{1}{2\pi i} \int_{Br} F(s) e^{st} \, ds = \frac{1}{2\pi i} \int_{\gamma - \infty}^{\gamma + \infty} F(s) e^{st} \, ds
\]  
(10) 

Here, \(Br\) is a Bromwich-Wagner integration contour, which is expressed by an infinite straight line \((s = \gamma)\) parallel to the imaginary axis.

With an assumption that \(s = \gamma + i\omega\), Equation (9) can be rewritten as follows:

\[
F(s) = \int_{0}^{\infty} f(t) e^{-\gamma t} e^{-i\omega t} \, dt
\]  
(11) 

This shows that the Laplace transform of \(f(t)\) is identical with the Fourier transform of \(f^*(t) = f(t)e^{-i\omega t}\). Similarly, with \(ds = id\omega\) given by the assumption that \(s = \gamma + i\omega\), Equation (10) can be rewritten as follows:

\[
f(t) = e^{\gamma t} \left\{ \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\gamma + i\omega) e^{i\omega t} \, d\omega \right\}
\]  
(12) 

This shows that the inverse Laplace transform of \(F(s)\) is identical with the inverse Fourier transform of \(F(s)\) multiplied with \(e^{\gamma t}\).

FFT was used for Fourier and inverse Fourier transformations in numerical calculation. Referring to Iwasaki et al.\(^3\), \(\gamma\) in Bromwich-Wagner integration contour, \(s = \gamma\) was determined as \(\gamma = \Delta\omega\) to make it close to the interval of discrete points \(\Delta\omega = 2\pi / (N\Delta t)\), where \(N\) is the number of discrete points (number of data) and \(\Delta t\) is the analysis time interval.

(2) Analysis model

An analysis model was created by modeling the specimens and loading plate used in the previous experiment as shown in Fig. 2, and the loading process during the dynamic bending test was simulated in viscoelastic analysis. Strain was analyzed for the positions where measurement was taken using strain gauges during the experiment: 10 mm above the binder course bottom, 10 mm below the binder course top, and 10 mm above the surface course bottom each on a side surface of the asphalt mixture, in addition to the bottom of the steel plate. Same asphalt mixture was used for the surface and binder courses in this analysis.

Although primers, corrosion inhibitors, and waterproof layers are often used in the bond between the steel plate and binder course in existing roads, two bond conditions were assumed in this analysis. One was rigid connection condition where the steel plate was completely connected to the binder course, and the other was unbonded condition where no horizontal bond was present between the two.

The solid element analysis was conducted on a one-fourth model of the specimen and loading plate shown in Fig. 2 as described in Fig. 3.

(3) Material constants

Modulus of elasticity of \(2.0 \times 10^5\) MPa and Poisson’s ratio of 0.3 were used for the steel plate.

In order to determine the material constants of the asphalt mixture, uniaxial compression test was carried out by applying creep load ranging from 0.138 to 0.55 MPa in the non-failure region\(^3, 6\). Fig. 4 shows the relationship between strain and time obtained by the test. Four constants for Burger’s model shown in Fig. 1 were determined from the test results using the following procedure developed by Uchida\(^7\):

[1] Determine \(\eta_1\) from residual strain \(\varepsilon_r\), using

\[
\varepsilon_r = \sigma_0 \times t_1 / \eta_1.
\]

[2] Determine \(E_1\) from strain decrease \(\Delta \varepsilon\) immediately after unloading, assuming that \(\Delta \varepsilon = \Delta \sigma / E_1\).

[3] Determine \(E_2\) and \(\eta_2\) from the curve of strain to loading time so that correlation with measurement was maintained, using total strain

\[
\varepsilon(t) = \sigma_0 / E_1 + \sigma_0 t / \eta_1 + \sigma_0 / E_2 \times (1 - e^{-E_2 t / \eta_2}).
\]

The uniaxial compression test was performed at 20° C, 40° C, and 60° C to use the material constants.
obtained for each temperature in the viscoelastic analysis for proper comparison with the results of the previous experiment.

The mixture used in the test was dense-graded asphalt mixture containing straight asphalt 60/80. Table 1 shows the mix proportions and major properties.

Table 2 shows the four constants for each temperature obtained by the uniaxial compression test. Almost no residual strain was found during the uniaxial compression test because load was applied in the linear viscoelastic region, which was sufficiently remote from the failure of the asphalt mixture. Since residual strain was only about 20 μm/m at all test temperatures with load stress $\sigma_0 = 0.138$ MPa and loading time $t_1 = 3$ seconds, $\eta_1$ was fixed to 20700 N∙s/mm² for all test temperatures in this study.

The decrease in stress immediately after unloading $\Delta \sigma$ is a part of spring component $E_1$ and, theoretically, is an instantaneously changing component of stress. However, the actual measurement revealed that this process of decrease in stress required some time to complete as shown in Fig. 4. The authors made preliminary calculation of coefficients using the value of stress change $\Delta \sigma$ for different time periods from unloading: 0.01 second and 0.02 seconds. The comparison of the analysis results with the different coefficients against the measurement results under dynamic loading in the uniaxial compression test revealed a better reproducibility with $\Delta \sigma$ for 0.02 seconds. Therefore, $E_1$ calculated from $\Delta \sigma$ for 0.02 seconds was adopted in this study.

(4) Loading method

Load was applied by simulating the haversine wave for a loading time of 0.05 seconds or 0.1 second in the viscoelastic analysis.

3. VISCOELASTIC ANALYSIS RESULTS

(1) Analysis results for 20ºC

Figs. 5 and 6 show the viscoelastic analysis results with the asphalt mixture material constants determined for 20ºC.

Under the condition where the steel plate was rigidly connected to the surface of asphalt mixture (hereinafter referred to as “rigid connection condition”), tensile strain in the steel plate reached its maximum level almost simultaneously with the peak of the applied load. Compressive strain in the asphalt mixture reached its maximum level slightly after the peak of the applied load, showing larger maximum values closer to the surface of the asphalt mixture. Although there was a time difference between the maximum load and the maximum strain, the asphalt mixture showed a mostly elastic behavior until around the maximum strain.

Under the condition where the steel plate was not bonded to the asphalt mixture surface (hereinafter referred to as “unbonded condition”), tensile strain occurred in both the steel plate and binder course. According to elastic theory, neutral axis should occur in both the steel plate and asphalt mixture under this condition due to the absence of bond between the two. The viscoelastic analysis results showed a similar tendency, with compressive strain

<table>
<thead>
<tr>
<th>Combined gradation</th>
<th>Percentage passing by mass, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 mm</td>
<td>100</td>
</tr>
<tr>
<td>13.2 mm</td>
<td>98.3</td>
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<tr>
<td>4.75 mm</td>
<td>62.9</td>
</tr>
<tr>
<td>2.36 mm</td>
<td>42.8</td>
</tr>
<tr>
<td>0.6 mm</td>
<td>26.3</td>
</tr>
<tr>
<td>0.3 mm</td>
<td>15.7</td>
</tr>
<tr>
<td>0.15 mm</td>
<td>9.0</td>
</tr>
<tr>
<td>0.075 mm</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Table 1 Mix proportions and properties of the asphalt mixture used.

<table>
<thead>
<tr>
<th>Asphalt content, %</th>
<th>5.5</th>
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</thead>
<tbody>
<tr>
<td>Asphalt type</td>
<td>Straight asphalt 60/80</td>
</tr>
<tr>
<td>Porosity, %</td>
<td>3.8</td>
</tr>
<tr>
<td>Dynamic stability (mm/times)</td>
<td>390</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constants</th>
<th>20ºC</th>
<th>40ºC</th>
<th>60ºC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_1$ (N·s/mm²)</td>
<td>20700</td>
<td>20700</td>
<td>20700</td>
</tr>
<tr>
<td>$\eta_2$ (N·s/mm²)</td>
<td>433</td>
<td>22</td>
<td>10</td>
</tr>
<tr>
<td>$E_1$ (N/mm²)</td>
<td>8297</td>
<td>1545</td>
<td>551</td>
</tr>
<tr>
<td>$E_2$ (N/mm²)</td>
<td>512</td>
<td>147</td>
<td>145</td>
</tr>
</tbody>
</table>

Table 2 Constants of the asphalt mixture.
occurring in the surface course and tensile strain occurring in the binder course within the asphalt mixture, suggesting elastic behavior of the asphalt mixture to the time around the maximum strain.

Elastic theory predicts that strain will decrease proportionally to the decrease in load after reaching the maximum level. However, strain in the viscoelastic analysis showed a tendency toward slow decrease during that period, without any sudden change.

These tendencies were consistent between the different loading times, except for the increase in strain values with the increase in loading time.

It was revealed in the previous study that the composite body of steel plate and asphalt mixture had a tendency toward elastic behavior at 20ºC, especially in the time range where maximum load and maximum strain were reached, and that the strain behavior until the maximum strain was satisfactorily reproducible by static linear elastic analysis. The current viscoelastic analysis results support these findings.

(2) Analysis results for 40ºC

Figs. 7 and 8 show the viscoelastic analysis results with the asphalt mixture material constants determined for 40ºC.

Under the rigid connection condition, tensile strain occurred in the steel plate, and compressive strain occurred in the asphalt mixture, only slightly after the peak of the applied load. The analysis results until this time point can be adequately explained by elastic theory like in the case of 20ºC.

However, strain in the asphalt mixture changed from compressive to tensile during the decrease in tensile strain in the steel plate as the applied load decreased to near zero. The tensile strain in the asphalt mixture reached its maximum level at around the time when the decrease of strain in the steel plate converged. The tensile strain was larger in the top of the binder course and in the bottom of the surface course than in the bottom of the binder course.

Similar results were obtained in the previous dynamic bending test with the specimens with a mastic asphalt binder course, which were assumed to provide adequate bonding with the steel plate (Fig. 9). Although these behaviors were not reproducible by linear elastic analysis, viscoelastic analysis successfully reproduced the change from compressive to tensile strain in the asphalt mixture.
Under the unbonded condition, strain in the asphalt mixture remained generally tensile, except for the compressive strain temporarily induced in the bottom of the surface course during loading. The time at which maximum tensile strain was reached varied depending on the location within the asphalt mixture, being delayed closer to the surface of the asphalt mixture.

This time delay was also observed in the previous experiment with the specimens with a stone mastic asphalt (SMA) binder course. However, there were significant discrepancies between the viscoelastic analysis results and the measured strain values in the asphalt mixture as shown in Fig. 10. These were likely because the SMA binder course in the test specimens was not completely unbonded from the steel plate. It is expected that the discrepancies between the viscoelastic analysis and the experimental

Fig. 7 Viscoelastic analysis results under 0.05-second loading at 40ºC.

Fig. 8 Viscoelastic analysis results under 0.1-second loading at 40ºC.

Fig. 9 An example from the experiment with the specimens with mastic asphalt binder course.

Fig. 10 An example from the experiment with the specimens with SMA binder course.
values will be made smaller by simulating the bond conditions in the experiment more closely in the analysis.

(3) Analysis results for 60ºC

Figs. 11 and 12 show the viscoelastic analysis results with the asphalt mixture material constants determined for 60ºC.

Under the rigid connection condition, strain in the asphalt mixture changed from compressive to tensile as shown in the case of 40ºC. The maximum values of tensile strain were larger than those at 40ºC, probably because of the stiffness or viscoelastic properties of the asphalt mixture due to the temperature.

Under the unbonded condition, tensile strain occurred in the asphalt mixture immediately after the start of loading. The time to the maximum tensile strain varied depending on the location, being longer closer to the surface of the asphalt mixture like in the case at 40ºC.

The strain behaviors observed in the specimens with mastic asphalt or SMA binder courses during the previous experiment[1] were found to fall between the analysis results under the rigid connection condition and those under the unbonded condition, due to the influence of primers, corrosion inhibitors, or waterproof coating. The major cause of such results was considered to be the bond condition between the binder course and the steel plate in these specimens, which was intermediate between the two conditions in the analysis.

(4) Discussion on the strain distribution

The change from compressive to tensile strain observed in the asphalt mixture was successfully reproduced by the viscoelastic analysis using the asphalt mixture material constants for 40ºC or 60ºC. It is also necessary to understand the strain distribution within the entire asphalt mixture. Fig. 13 shows contour diagrams of horizontal (X-axial direction) strain distribution under 0.05-second loading at 40ºC.

The contour diagrams show the one-fourth model, with symmetry conditions on the right-side and back-side boundary surfaces. The convex on the right top is the loading plate. Tensile strain in the steel plate reached the maximum level at 0.06 seconds from the start of loading.
where compressive strain in the asphalt mixture was also almost at the maximum level. The compressive strain was found to be distributed across the entire asphalt mixture at this time point.

However, tensile strain occurred in the side surfaces near the top of the binder course and the bottom of the surface course at 0.1 second and was distributed across the entire layer immediately below the loading plate at 0.2 seconds. The range of distribution was found to be larger at 0.4 seconds, although the maximum tensile strain values were smaller.

In summary, it was revealed that with the analysis model used in this study, horizontal tensile strain in the asphalt mixture occurred immediately below the loading plate, and the tensile strain region continued to be larger at 0.4 seconds, although the maximum tensile strain values were smaller.

Although the maximum tensile strain values appeared in the side surfaces of the asphalt mixture, tensile strain was also found inside the asphalt mixture, revealing that tensile strain could occur even in confined areas. This suggests that the change from compressive to tensile strain in the asphalt mixture confirmed in the current analysis is likely to occur in existing roads or under other confined conditions, even though the values of tensile stress vary.

4. SUMMARY

The findings of this study are summarized below:

(1) Viscoelastic analysis was performed by modeling the previous dynamic bending test on composite specimens of asphalt mixture and a steel plate, using material constants calculated for Burger’s model of the asphalt mixture from uniaxial compression test results. Although there were some influences of the differences in asphalt mixture types or others, the relationship between strain and time was almost consistent between the experiment and the analysis.

(2) The composite body of steel plate and asphalt mixture exhibited elastic behavior in the viscoelastic analysis at 20°C, which was consistent with the previous experiment results.

(3) It was found in the previous experiment at 40°C that strain in the asphalt mixture changed from compressive to tensile. This phenomenon, which was irreproducible by linear elastic analysis, was successfully reproduced by the viscoelastic analysis in this study.

(4) In the previous experiment at 60°C, tensile strain in the asphalt mixture occurred when loading was started. The time to the maximum strain was longer closer to the surface of the asphalt mixture. These behaviors were successfully reproduced by the viscoelastic analysis in
5. CONCLUSIONS

The current study analytically verified that there could be many cases where tensile strain was induced even under positive bending condition in the asphalt mixture laid on steel plate deck. It is well known that elastic analysis based on multi-layer elastic theory is adequately applicable to strain or fatigue analysis on earthwork pavement. However, the authors verified both experimentally and analytically in the previous and current studies that strain behavior of asphalt mixture on steel plate deck could not be fully explained by elastic theory and need to be analyzed on the basis of viscoelastic theory.

The strain behavior the laboratory test specimens exhibited was generally successfully reproduced by the current study, with a few future tasks left, especially in setting of boundary conditions between the steel plate and asphalt mixture. Future research will also include simulation of existing roads under moving wheels and measurement on existing roads, for better understanding of characteristic strain behaviors of the asphalt pavement on steel plate deck.

REFERENCES


(Received June 5, 2014)