Typical asphalt pavement dynamic response simulation at the action of dynamic load with multi-steps loading method

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Abstract. The dynamic response of a typical pavement subjected to a dynamic load is important. Dynamic moduli of asphalt mixtures, cement treated crushed stone and lime treated soil are tested in the lab. The finite element model is established based on the dynamic modulus. The dynamic load is applied to the pavement structure by the loading steps method and then the pavement response is calculated. The pavement structure model was built in the lab and pavement structure responses are tested under the action of dynamic load which was applied by large size MTS. Compared with the results in the lab, simulation results are verified. By analysis of the simulation results show that: the tensile strain at the bottom of the surface and base under the action of the dynamic load is obviously smaller than the strain under the action of static load, deflection also follows that. In some special cases, the tensile strain at the bottom of the surface and base under the action of the dynamic load may exceed that under the action of static load.

1. Introduction
Many studies on pavement response to loading have been conducted by using the multilayered elastic approach. A stationary, circular wheel load is assumed in this approach, whereas the pavement is actually subjected to dynamic wheel loading which is a kind of randomly varied load (1; 2). The pavement responses under the dynamic load are studied by many scholars, in which most of them focus on simulation by finite element (FE)(3-8). Alireza Bayat built a 3D FE model to analyze the response of asphalt pavement structure in which dynamic modulus and static force are combined to calculate the response (9). It is feasible to simulate the viscoelastic properties of HMA with FE, but it is difficult to simulate the dynamic load caused by pavement roughness at the same time. The researches have a deep insight into the response of pavement under the action of dynamic load, but most of them are not verified by testing in site or in the lab and the dynamic load loading frequency is also not considered. In this paper, a 3-D FE model was built and dynamic moduli are adopted which are obtained in lab. Based on the results the strain and deflection are analyzed and verified by large (material testing system) MTS in the lab.

2. Pavement materials dynamic modulus

2.1 Definition of dynamic modulus
The dynamic modulus is a fundamental property that defines the relationship between stress and strain under sinusoidal loading at various temperatures and loading frequencies for linear viscoelastic
materials such as asphalt concrete(10). It is the ratio of stress to strain under vibratory conditions which can be calculated from data obtained from either free or forced vibration tests, in shear, compression. The dynamic modulus reflects the ability of materials to resist deformation.

For viscoelastic material, when an oscillatory force (stress) is applied to it, the strain will lag behind stress, the dynamic modulus can be expressed as the formula (1) or formula (2):

$$E^* = \frac{\sigma}{\epsilon} = \frac{\sigma_0 e^{i\omega t}}{\epsilon_0 e^{i(\omega t - \phi)}}$$  \hspace{1cm} (1)

$$E^* = \frac{\sigma_0}{\epsilon_0} \cos \phi + i \frac{\sigma_0}{\epsilon_0} \sin \phi$$  \hspace{1cm} (2)

Where: $\sigma_0$ is stress; $\epsilon_0$ is strain; $\phi$ is phase lag between stress and strain.

The dynamic modulus can be calculated as the following equation:

$$|E^*| = \sqrt{\left(\frac{\sigma_0}{\epsilon_0} \cos \phi\right)^2 + \left(\frac{\sigma_0}{\epsilon_0} \sin \phi\right)^2} = \frac{\sigma_0}{\epsilon_0}$$  \hspace{1cm} (3)

By equation(3), uniaxial compressive test can be carried out in the lab and dynamic modulus can be expressed as:

$$|E^*| = \frac{P/A}{\Delta/l_0}$$  \hspace{1cm} (4)

Where: $p$ is loading size, $\Delta$ is deformation, $A$ is the cross section area in radial direction, $l_0$ is measured distance of the sample.

### 2.2 Dynamic modulus of asphalt concrete mixture

Some scholars have studied the dynamic modulus of asphalt mixtures. Nader Solatifar thinks that the basic input information for pavement design is dynamic modulus(11), You Huang studied dynamic mechanical properties of asphalt mix under two-point bend load, and the impact of load level to dynamic modulus, trapezoid beam method is employed to conduct dynamic modulus tests on asphalt mix SAC13 (Stone Asphalt Concrete with nominal maximum aggregate size 13 mm)(12). Liqiang used (simple performance testing) SPT to test the dynamic modulus of (stone matrix asphalt) SMA and Superpave at different temperature and loading frequencies, and analyze the influence of loading frequency to the dynamic modulus and phase angle(13).

In this paper, SPT is adopted as an asphalt mixture dynamic modulus test method to measure the dynamic modulus of (Stone Matrix Asphalt-13)SMA-13 asphalt mixture. The test results are shown in Table 1.

| Table 1. SMA-13 Asphalt mixture dynamic modulus/MPa |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Temp. (℃)      | 25              | 20              | 10              | 5               | 2               | 1               | 0.5             |
| Frequency (Hz) |                 |                 |                 |                 |                 |                 |                 |
| 21              | 12240           | 11570           | 9860            | 8420            | 6510            | 5330            | 4210            |

### 2.3 Dynamic modulus of base and subbase

Dynamic moduli of cement-stabilized crushed-stone samples and lime treated soil were measured referring to the dynamic modulus testing method for SMA-13. The half sine wave load was applied to the test samples according to the methods above. The dynamic modulus was measured at frequencies of 0.5, 1, 2, 5, 10, 20 and 25 Hz. The test results are shown in Table 2 and Table 3.
Table 2. Dynamic Resilient Modulus/MPa

| Strain (με) | Frequency (Hz) |
|------------|----------------|
|            | 0.5 Hz | 1 Hz | 2 Hz | 5 Hz | 10 Hz | 20 Hz | 25 Hz |
| 10         | 21870  | 22070| 22310| 22510| 22640 | 22770 | 22390 |
| 20         | 20960  | 21110| 21140| 21170| 21400 | 21450 | 21430 |
| 30         | 20510  | 20620| 20680| 20710| 20810 | 20950 | 20980 |
| 40         | 20320  | 20270| 20310| 20380| 20450 | 20560 | 20650 |
| 50         | 20040  | 20120| 20170| 20210| 20310 | 20380 | 20490 |

Table 3. Lime improved soil resilient modulus (MPa)

| Strain (με) | Loading Frequency (Hz) |
|------------|------------------------|
|            | 0.5 | 1 | 2 | 5 | 10 | 20 | 25 |
| 20με       | 2810 | 2840| 2870| 2920| 2950| 2990| 2960 |
| 40με       | 2740 | 2750| 2783| 2830| 2860| 2910| 2810 |
| 80με       | 2550 | 2570| 2600| 2640| 2670| 2710| 2720 |
| 100με      | 2510 | 2530| 2560| 2600| 2630| 2670| 2690 |

From Table 2 and Table 3, it can be seen that loading frequency has little influence on the semi-rigid base materials. In this paper, dynamic modulus of cement stabilized crushed stone and lime treated soil are seen as an invariable, they are 10000MPa and 2800MPa, respectively.

3. Asphalt pavement structure responses

Large MTS can be used to simulate vehicle load and it can be applied to the pavement model to execute the rapid fatigue of pavement materials. Large size MTS is more commonly used for structure testing. In this paper, it’s used for the pavement structure testing shown in Figure 1. The pavement model size is 2 m×1.5 m×2.5 m. The structure of the model is: 6 cm SMA-13 surface, 20cm cement treated crushed stone base, 20cm lime treated soil subbase, 200cm subgrade. The strain sensors are installed at the bottom of the surface and base.

Through a large MTS testing system, dynamic load testing is carried out, tensile strain at bottom of asphalt pavement surface and base at different loading frequencies are obtained.

4. Finite element model and results verification

4.1. Finite element (FE) model and loading area

The structure of the FE model is same as the pavement model in the lab. Boundary conditions: bottom and sides are fixed which means displacement is zero, the top surface is free. Three-dimensional hexahedron eight-node isoparametric element (solid 185) is adopted for the analysis. During the meshing for the model, computational accuracy and computing scale should be considered at the same time. The 3-D model is shown in Figure 2.

Load applying area: tire –pavement contact area can be seen as rectangular. In this paper, the loading area is 324 cm². For the 1/4 model, loading area is 81 cm².

4.2. Executions of dynamic analysis

One method to realize dynamic loading is through loading steps. In this paper, the loading form is seen as a half-sin wave. The half-sin wave is divided into a number of steps. For each step, loading lasts a very short time, and during the short time, it’s seen as invariant. Taking loading frequency 2 HZ for example, the loading process is shown in Figure 3.
4.3. Dynamic modulus of materials
In order to analyze the dynamic response of pavement structure, dynamic moduli are needed for the input of the FE model. According to the analysis in the paper and related documents(11-13), the modulus of asphalt mixture SMA-13 is taken by Table 1-Table 3, cement treated crushed stone is 10000MPa, lime treated soil is 2600MPa, the subgrade soil modulus is 90MPa.

4.4. Simulation results verification
According to the parameters above, the model is simulated, the tensile strain at the bottom of the surface and base are obtained. The strain of simulation and MTS testing results are shown in Figure 4 and Figure 5. The testing at 21℃, loading pressure is 0.7 MPa and loading frequency is shown in Figure 8.

From Figure 4 and Figure 5, it can be seen that the simulation results and testing data are very close. This shows that the parameters adopted in the FE model and the loading method are right. The FE model can be used to analyze the dynamic response of the pavement structure.

5. Pavement dynamic response analysis

5.1. vehicle axle vertical vibration acceleration testing in field

5.1.1. Testing road. A highway and a low volume highway near Jinan city are chosen as the testing roads and the design speed is 100km/h and 60km/h respectively.

5.1.2. Testing vehicle. A light truck and a heavy truck are chosen as the testing vehicle. The Axle Vibration Acceleration Testing Apparatus are mounted on the rear axle. When the trucks run on the two highways, the vertical vibration acceleration is obtained. During the testing process, the trucks are tested by two cases: fully loaded and empty loaded.
5.1.3. Relationship between vertical acceleration and dynamic load. Some documents have already studied the theory of dynamic load (1; 14-16) and have verified that dynamic load is related to acceleration of vehicle mass directly. After the acceleration of vehicle body is tested, dynamic load can be calculated directly. The vehicle vertical acceleration root mean square are shown in Table 4.

| Highway class          | Vehicle speed/(km·h⁻¹) | Empty loaded heavy truck | Fully loaded heavy truck | Empty loaded light truck | Fully loaded light truck |
|------------------------|------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Low volume highway     | 70                     | 2.15                     | 1.73                     | 1.97                     | 1.33                     |
|                        | 60                     | 1.83                     | 1.52                     | 1.66                     | 1.25                     |
|                        | 50                     | 1.56                     | 1.23                     | 1.32                     | 0.99                     |
|                        | 40                     | 1.23                     | 0.98                     | 1.17                     | 0.86                     |
| Highway                | 100                    | 1.89                     | /                        | 1.90                     | 0.86                     |
|                        | 80                     | 1.59                     | 1.42                     | 1.67                     | 0.81                     |
|                        | 60                     | 1.51                     | 1.06                     | 1.26                     | 0.70                     |

5.2. Loading cases combination
The mean value of vehicle vertical acceleration is mostly distributed in the scope of 1~2 m²/s² by Table 3. In this paper, 2 m²/s² is taken as the average value. When the tire pressure is 0.7MPa caused by static load, the average tire pressure value caused by the dynamic load is 0.14 MPa. When the vehicle travels along the pavement, the total peak tire load applied to the pavement is 0.84 MPa. The loading pressure for different cases are listed in Table 5.

| Case No. | Loading cases    | Static load/MPa | Loading frequency/Hz | Dynamic load/MPa | Total peak tire load/MPa |
|----------|------------------|-----------------|----------------------|------------------|--------------------------|
| Case 1   | Static           | 0.7             | /                    | /                | 0.7                      |
| Case 2   | Static + dynamic load | 0.7           | 5                    | 0.14             | 0.84                     |
| Case 3   | Static + dynamic load | 0.7           | 10                   | 0.14             | 0.84                     |
| Case 4   | Static + dynamic load | 0.7           | 5                    | 0.42             | 1.12                     |

5.2.1. Deflection.
By computing with the FE model, the deflections of the 3 cases are shown in Figure 6. From that Figure, it can be seen that the deflection of pavement under the dynamic load is much smaller than that under the action of static load. The deflection of pavement under the action of static load+ 5Hz dynamic load is only a little bigger than the static load+ 10Hz dynamic load.

Beckman beam and falling weight deflection (FWD) is the most commonly used apparatus to test the pavement deflection. During the process of testing deflection using the Beckman beam, the vehicle moves slowly, the load applied to the pavement can be seen as a static load. While the FWD uses the impact load of falling weight, the load duration is very short and it can be seen as a dynamic load. Traditionally, the relationship between the two methods needs to be verified by testing in the field, but it will take a long time and a lot of money to do that. The FE model in this paper can provide the relationship between the two deflections.

5.2.2. Tensile strain at bottom of base.
Tensile strain at the bottom of base is computed with the FE model, the results are shown in Figure 7.
Figure 6. Deflection for different cases

From Figure 7, it can be seen that tensile strain at the bottom of the base is much smaller when the dynamic load is applied to the pavement than the static load. Loading frequency has a certain influence on the tensile strain. The strain under the action of the 10HZ dynamic load is a little smaller than 5HZ.

5.2.3. Tensile strain at bottom of surface.

By the same model and principle, the strain at the bottom of the surface is computed for the 3 cases and the results are sown in Figure 8.

The tensile strain at the bottom of the surface under the dynamic load is also smaller than that under the action of static load. The frequency has a certain influence on the tensile strain at the bottom of the surface. From the Figure, it can be seen tensile strain under the action of 5HZ dynamic load is smaller than the 10HZ dynamic load.

In this paper, the response of pavement is computed with the average dynamic load. For some times, the dynamic load is much bigger than the average which can apply a big instant force to the pavement. For example, when the pavement roughness decreases seriously, it can cause large vertical vibration acceleration. Here, when the peak dynamic load is taken as 0.42MPa. The strain at the bottom of the surface is computed. The results are shown in Figure 9.

From the results, it can be seen that the tensile strain at the bottom of the surface under the action of peak dynamic load is bigger than that under the action of dynamic load. This means that the dynamic load can cause bigger tensile strain than the static load some times.

6. Conclusions

By building a 3-D FE model that adopts dynamic modulus for the pavements materials, the dynamic load is applied with the step loading method and then the results are analyzed. The following conclusions for the typical asphalt pavement structure are obtained:
(1) Generally, tensile strain at the bottom of the base and subbase of pavement under the action of the dynamic load is less than that under the action of static load.

(2) The deflection of pavement under the dynamic load is generally less than that under the action of static load.

(3) In some special cases, the tensile strain at the bottom of the surface and base under the action of the dynamic load may exceed that under the action of static load.

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