The mechanical behavior of epoxy asphalt mixture under cyclic loading

Z Zhang 1, Z D Chen 1, L H Guo 2, X F Niu 3, P T Xue 2 and S J Zhang 2

1 Key Laboratory for Special Area Highway Engineering of Ministry of Education, Chang'an University, Xi'an, 710064, China
2 Highway Administration Bureau of Henan communications and transportation department, Zhengzhou, 450000, China
3 Xuchang Huajie Highway Survey and Design Co., Ltd., Xuchang, 461000, China

Corresponding author and e-mail: Z Zhang, 470604245@qq.com

Abstract. In order to investigate the mechanical behavior of epoxy asphalt mixture under cyclic traffic loading, cylindrical samples of the epoxy asphalt mixture were subjected to cyclic loading-unloading tests under varying confining pressures. The accumulation and dissipation of energy were observed in the energy evolutions. It turns out that the epoxy asphalt mixture exhibits elastic-plastic property in the first few cycles, and then the elastic property would be strengthened gradually in the cyclic loading tests. Applying a moderate confining pressure would significantly reduce the dissipated energy. The proportion of dissipated energy is about 25% from the unconfined test, and less than 15% from the confined test. As a result, more energy would be required if to produce equal permanent deformation under higher confining pressures. Therefore, a moderate increase in the confining pressure would be helpful in restraining permanent deformation, such as rutting.

1. Introduction
Epoxy asphalt mixture is commonly used in bridge pavements [1-5]. In practices, the pavement is directly subjected to the vibration and impact of cyclic traffic loadings. The strength, deformation and hysteretic responses of epoxy asphalt mixture under a cyclic traffic loading are therefore quite different from those of a monotonic loading test. It is well known that most materials may become weaker and more brittle under cyclic loading [6, 7]. It is therefore quite important to understand the mechanical behavior of epoxy asphalt mixture under cyclic traffic loadings.

Extensive tests have been applied to understand the mechanical behavior of epoxy asphalt mixture [8-13]. However, the influences of cyclic loading and confining pressure have rarely been considered in the tests. More recent studies indicate that the cyclic loading-unloading tests could better resemble the conditions of actual traffic loading [6, 7, 14-20].

This paper investigated the stress-strain relations and energy evolutions of epoxy asphalt mixture by testing samples under the conditions of cyclic loading that better resemble actual traffic loading. The energy accumulation, evolution, and dissipation of epoxy asphalt mixture under cyclic loadings with varying confining pressures were also being probed into. It may play an important role in the application and design of epoxy asphalt mixture.
2. Materials and testing

The binder used here is the 2910-type domestic epoxy asphalt. In the experimental study, Andesite aggregates with a nominated maximum size of 13 mm were used. Clean, hard, and anti-wearing aggregates were selected to meet the requirements of Technical Specifications for Construction of Highway Pavements (JTG F40-2004), a national standard of China. The aggregate gradation was designed according to the average of the recommended values of JTG F40-2004. The mixture was designed based on a conventional Marshall design with a 4% of target air voids that resulted in a 4.7% of binder content.

The compacted samples (160 mm in height and 100 mm in diameter) were sliced to 100 mm in both height and diameter to smooth the rough surfaces and eliminate test errors. The MTS815 hydraulic servo loading system [7] was used to conduct the controlled-stress cyclic loading tests under varying confining pressures. In the cyclic loading tests, a loading-unloading rate of 15 kN/min was adopted with a constant temperature of 20°C.

The sliced samples were tested respectively under varying confining pressures (0, 0.25, 0.5, 0.75 MPa). The loading amplitude and axial strain were recorded during the tests. Firstly, monotonic loading tests under varying confining pressures were carried out to determine the maximum compressive strength of epoxy asphalt mixture under varying confining pressures. It turns out that the unconfined compressive strength was significantly less than the confined compressive strength (Table 1). In the table, \( \sigma_{uc} \) is the unconfined compressive strength determined in the monotonic loading tests; \( \sigma_{cb} \) is the prescribed confining pressure in the cyclic loading tests. In the cyclic loading tests, the lower bound \( \sigma_{lb} \) was set at 25% of the unconfined compressive strength (10.6 MPa), while the upper bound \( \sigma_{ub} \) was set at 75%, which was not too high to induce significant damages to both unconfined and confined tests [14, 21, 22].

| Material type          | Density (g/cm³) | Void (%) | \( \sigma_{uc} \) (MPa) | \( \sigma_{ub} \) (MPa) | \( \sigma_{lb} \) (MPa) |
|------------------------|-----------------|----------|--------------------------|--------------------------|--------------------------|
| Epoxy asphalt mixture  | 2.6             | 4.09     | 10.6                     | 0                        | 2.6                      |
| Epoxy asphalt mixture  | 2.62            | 3.86     | 12.3                     | 0.25                     | 2.6                      |
| Epoxy asphalt mixture  | 2.61            | 3.99     | 14.1                     | 0.5                      | 2.6                      |
| Epoxy asphalt mixture  | 2.58            | 4.05     | 15.5                     | 0.75                     | 2.6                      |

3. Determination of energy in cyclic loading

The energy of epoxy asphalt mixture would be transformed, accumulated, or dissipated in the process of cyclic loading. Assuming that the total work performed by the testing equipment on the epoxy asphalt mixture is converted to the input energy, as shown in Figure 1, one part of the input energy would be accumulated as the elastic energy when loading, which would be totally released later during unloading. The other part of the input energy would be converted to the dissipated energy which would cause irreversible plastic deformation and internal damage. Therefore the input energy could be assumed as the sum of the elastic energy and the dissipated energy [23, 24].

\[
U_i^0 = U_i^e + U_i^d
\]

where \( U_i^0 \) is the input energy of \( i \)th cyclic loading, in MJ; \( U_i^e \) is the elastic energy of \( i \)th cyclic loading, in MJ; and \( U_i^d \) is the dissipated energy of \( i \)th cyclic loading, in MJ. The input energy \( U_i^0 \) could be determined by the integral of loading stress–strain curve. The elastic energy \( U_i^e \) could be determined by the integral of unloading stress–strain curve. The dissipated energy \( U_i^d \) could be determined by subtracting \( U_i^e \) from \( U_i^0 \), i.e. subtracting the integral of unloading stress–strain curve from the integral of loading stress–strain curve. As a consequence, the dissipated energy would be slightly larger than the hysteresis loop area, rather than being equal to it. Contrast to many other studies and materials [21, 23], the dissipated energy was proved in this case as not being equal to the
The hysteresis loop area. Specifically, the area under the stress-strain curves is divided into several bar blocks [25] to calculate approximate integrals, as shown in Figure 2. Therefore, the equations for the energies could be expressed as follows:

\[
\begin{align*}
U_i^0 &= \sum_{j=1}^{n} \frac{1}{2} \left( \sigma_{i,j} + \sigma_{i,j+1} \right) \left( \varepsilon_{i,j+1} - \varepsilon_{i,j} \right) \\
U_i^e &= \sum_{j=1}^{n} \frac{1}{2} \left( \sigma_{i,j} + \sigma_{i,j+1} \right) \left( \varepsilon_{i,j+1} - \varepsilon_{i,j} \right) \\
U_i^d &= U_i^0 - U_i^e
\end{align*}
\]

where \( \sigma_{i,j} \) is the \( j \)th measured stress at \( i \)th loading, in MPa; \( \varepsilon_{i,j} \) is the \( j \)th measured strain at \( i \)th loading; \( \sigma_{i,j}' \) is the \( j \)th measured stress at \( i \)th unloading, in MPa; \( \varepsilon_{i,j}' \) is the \( j \)th measured strain at \( i \)th unloading.

![Figure 1. The energy conversion.](image)

4. Analysis of test results

4.1. Stress-strain loops

The hysteretic stress-strain loops in the cyclic loading tests under varying confining pressures are presented in Figure 3. Epoxy asphalt mixture is an artificial mix containing joints and microcracks [26-29], which would give rise to inevitable plastic deformation in the cyclic loading tests. Therefore the unloading path deviates from the original place by being slightly lower than the prior loading path, with the residual strain accumulated during the process of cyclic loading. The residual strain is mainly produced over the first few cycles, and then the increment would decrease until become stable for the subsequent cycles.
Figure 2. The integral of stress-strain curve.  

Figure 3. The hysteretic stress-strain loops.

The stress-strain curves slightly go up as the cyclic loading tests proceed. It indicates that the modulus of the latter loading process is always greater than that from the previous one. This is owing to the repeated compression of the original voids in epoxy asphalt mixture. Consequently, the deformation induced in each cycle would gradually decrease.

In the initial stage of cyclic loading, the stress-strain loops shift to the right side quickly, with a significant plastic hysteretic behavior [23]. But later on, the voids in the epoxy asphalt mixture are gradually compressed, and the stress is more likely to be borne by the granular skeleton. Consequently, the plastic hysteretic behavior of asphalt mixture would gradually reduce, yielding a more consistent elastic loading-unloading path.

It seems that the confining pressure has significant effects on the behaviors of epoxy asphalt mixture. Higher confining pressure results in larger modulus, as indicated by the significant change to the curve. At the same time, the epoxy asphalt mixture would exhibit less residual strain under higher confining pressure.

4.2. Input energy

Relationships between the input energy $U^0_i$ and cyclic loading number $i$ of the specimens of epoxy asphalt mixture under different confining pressures are shown in Figure 4. Under each confining pressure, the input energy decrease nonlinearly along with the increase in cyclic loading numbers. This is owing to the repeated compression of the original voids, and the gradual decrease in the deformation induced in each cycle, as shown in Figure 3. Therefore the total work (equivalent to input energy) performed by the testing equipment on the epoxy asphalt mixture decreases gradually each time.

(a) With a confining pressure of 0 MPa  
(b) With a confining pressure of 0.25 MPa
The input energies $U_i^0$ under different confining pressures (0, 0.25, 0.5, 0.75 MPa) were obtained and shown in Figure 5. If the confining pressure increases from 0 MPa to 0.5 MPa, the input energy would decrease significantly in the process. It appears that the voids in the specimen are gradually compacted under confining pressure. As a consequence, both the deformation and the input energy would decrease under higher confining pressure. However, if the confining pressure increases from 0.5 MPa to 0.75 MPa, the input energy would increase slightly. Because excessive confining pressure would cause slight reorientation of the aggregates and changes in the microstructure, they need to absorb more energy to resist the trend of sliding dislocation between the particles, which in turn enhance the ability of absorbing energy.

4.3. Elastic energy

The proportion of elastic energy to input energy ($U_i^e/U_i^0$) and the proportion of plastic dissipated energy to input energy ($U_i^d/U_i^0$) are calculated in Figure 6. As it is shown, a large part of the work done by external load is converted to elastic energy, while the remaining energy would be dissipated gradually while generating a permanent plastic deformation. The proportion of elastic energy increases gradually over the first several cycles and becomes more stable later, while the plastic energy exhibits an opposite trend. It indicates that elastic property of epoxy asphalt mixture would be strengthened gradually after the cyclic loadings.
The proportions of elastic energy and plastic energy.

The proportions of elastic energy under different confining pressures (0, 0.25, 0.5, 0.75 MPa) are obtained and shown in Figure 7. If the confining pressure is controlled below 0.5 MPa, beginning from 0 Mpa, the proportion of elastic energy would increase significantly. It indicates that elastic property of epoxy asphalt mixture would be strengthened under a moderate confining pressure (below 0.5 MPa). However, if the confining pressure increases from 0.5 MPa to 0.75 MPa, the proportion of elastic energy would decrease slightly. It indicates that elastic property of epoxy asphalt mixture would be slightly weakened under an excessive confining pressure (over 0.5 MPa).

4.4. Dissipated energy

Relationships between the dissipated energy $U_i^d$ and cyclic loading number $i$ of epoxy asphalt
mixture are displayed in Figure 8. Initially, the dissipated energy would decrease in inverse proportion to the increase of cyclic loading numbers before coming to a more stable state. Similarly, the stress-strain relations (Figure 3) indicate that the increment in both the permanent deformation and residual strain would significantly decrease in the initial stage and tends to be stable later. Therefore the energy dissipation behavior is consistent with the residual strain behavior revealed in stress-strain relations.

Confining pressure also has an effect on the dissipated energy. The dissipated energy of epoxy asphalt mixture would decrease in inverse proportion to the increase in the confining pressure (below 0.5 Mpa). It indicates that the same work done by vehicles will induce less dissipated energy, and consequently less permanent deformation. Therefore, it would be helpful in restraining permanent deformation, such as rutting by increasing confining pressure moderately (below 0.5 MPa).

![Figure 7.](image1.png) **Figure 7.** The proportions of elastic energy under different confining pressures.  
![Figure 8.](image2.png) **Figure 8.** Relationships between the dissipated energy and cyclic loading number.

5. Conclusions
This paper reports on an investigation into the stress–strain relations and energy evolutions of epoxy asphalt mixture in the cyclic loading tests. The following conclusions can be drawn: (1) The epoxy asphalt mixture exhibits elastic-plastic property in the first few cycles, and then the elastic property would be strengthened gradually, as indicated by the smaller residual strains and the higher elastic energy proportions produced in subsequent cycles. (2) A large part of the external work done is converted to the elastic energy, with the remaining energy dissipated. The proportion of dissipated energy is about 25% from the unconfined test, and less than 15% from the confined test. (3) It appears that the voids in the specimen are gradually compacted under confining pressures. Therefore the elastic property of epoxy asphalt mixture would be strengthened given moderate confining pressures (≤ 0.5 Mpa). However, excessive confining pressures may cause slight reorientation of the aggregates and changes in the microstructure. Therefore, the elastic property of epoxy asphalt mixture may be slightly weakened under excessive confining pressures (> 0.5 MPa). (4) Applying a moderate confining pressure would significantly reduce the dissipated energy. It indicates that a moderate confining pressure will induce less dissipated energy, and consequently less permanent deformation. Therefore it would be helpful in restraining permanent deformation, such as rutting by increasing confining pressure moderately (below 0.5 MPa).

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