Determination of Resilient Modulus of Subgrade Using Cyclic Plate Loading Tests

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ABSTRACT

Resilient modulus of subgrade is often necessary for pavement design and determined by cyclic triaxial tests or correlation with other laboratory or insitu test results (such as CBR and DCP data). Cyclic plate loading tests were conducted in this study to determine the resilient modulus of a weak subgrade. The weak subgrade was made of 75% Kansas River sand and 25% kaolin and compacted at wet of optimum in a large geotechnical testing box (2m x 2.2m x 2m). This subgrade was first evaluated by DCP tests and then tested under a 30-cm diameter rigid plate at four different magnitudes of cyclic loading. During the tests, the deformations of the plate and the subgrade surface were monitored. The test results showed that the plate deformation increased with the number of cycles. An elastic solution was used based on the rebound deformation of the plate to calculate the resilient modulus of the subgrade. The calculated resilient modulus of the subgrade decreased and approached a stable value with the number of cycles under different magnitudes of cyclic loading. The calculated resilient modulus from the cyclic plate loading tests was compared with that determined based on the correlation with the CBR value of the subgrade.

INTRODUCTION

Resilient modulus is an elastic modulus under cyclic loading and defined as a repeated deviatoric stress divided by the corresponding recoverable axial strain of a specimen in a cyclic triaxial test. Resilient modulus is one of the most important properties of pavement materials and it is essential to predict recoverable stress, strain, and permanent deformation. In order to obtain the resilient moduli of different pavement materials, several test methods were introduced in the past few decades, such as: (1) triaxial test, (2) torsional shear test, (3) simple shear test, (4) hollow cylinder test, (5) FWD test, and (6) cyclic plate loading test, etc. Several correlations were also developed with simple laboratory and field test data, such as California Bearing Ratio (CBR) and Dynamic Cone Penetration (DCP), to estimate the resilient modulus.

Cyclic plate loading test is more appropriate to determine the overall resilient modulus of the pavement material when the material is not easily sampled, anisotropic, layered, and composite with other materials, such as geosynthetics. A research project was completed at the University of Kansas to investigate the behavior of triangular aperture geogrid-reinforced bases under cyclic loading over weak subgrade. In order to obtain the ratio of the resilient modulus of the reinforced base over that of the subgrade, four cyclic plate loading tests at different magnitudes of applied loads were conducted to determine the resilient modulus of the weak subgrade.

MATERIALS

The weak subgrade was an artificial soil composed of a mixture of 75% Kansas River sand and 25% kaolinite by weight. The grain size distribution of Kansas River sand is presented in Figure 1. Compaction tests were performed to obtain the compaction curve for this subgrade as shown in Figure 2. The maximum dry density is 2.01g/cm^3, which corresponds to the optimum moisture content of 10.8%. A series of laboratory un-soaked CBR tests (ASTM D 1188) for this subgrade were performed at different water contents. The CBR vs. moisture content curve is presented in Figure 3. The subgrade soil was compacted at a water content of 11.4% for the box tests to achieve its CBR at approximately 2%, which was verified by vane shear tests and DCP tests.

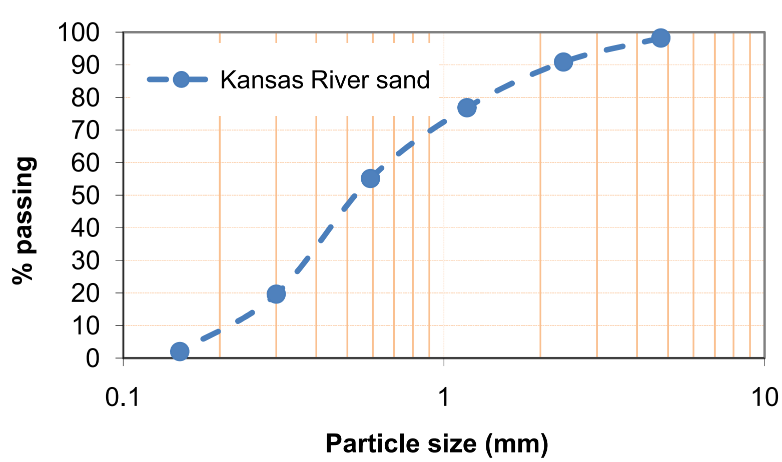

Figure 1. Grain size distribution curve of Kansas River sand (Han et al. 2008)

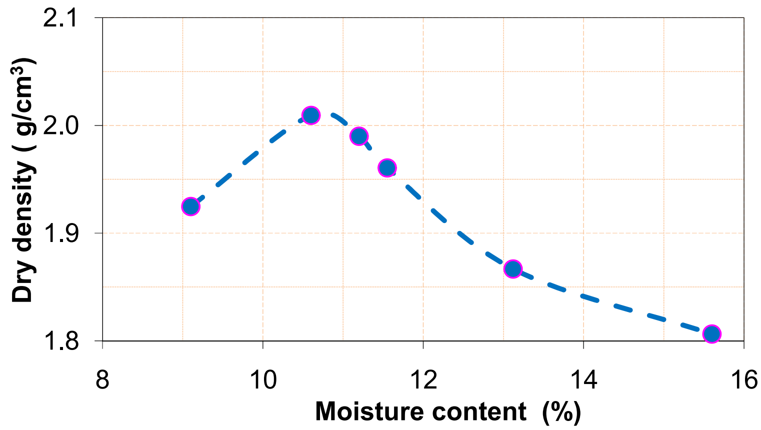

Figure 2. Compaction curve of the subgrade (Qian et al. 2010)

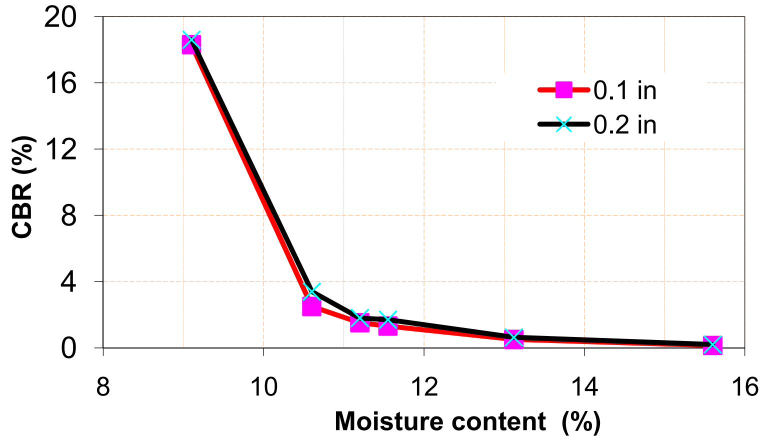

Figure 3. CBR vs. moisture content of the subgrade (Qian et al. 2010)

TEST SETUP

Cyclic plate loading tests were conducted in a large test box system in the geotechnical laboratory at the Department of Civil, Environmental, and Architectural Engineering at the University of Kansas. This system includes a loading actuator, a data acquisition system, and a steel box (2 m x 2.2 m x 2 m high).

The loading system was an MTS hydraulic loading system. The steel loading plate had a diameter of 0.3 m and thickness of 0.018 m with several stiffeners. The cyclic loading wave was generated with a peak force at four magnitudes: 4, 8, 12, and 16 kN, respectively, and a trough force of 0.5 kN as shown in Figure 4. The frequency of this wave was 0.77 Hz.

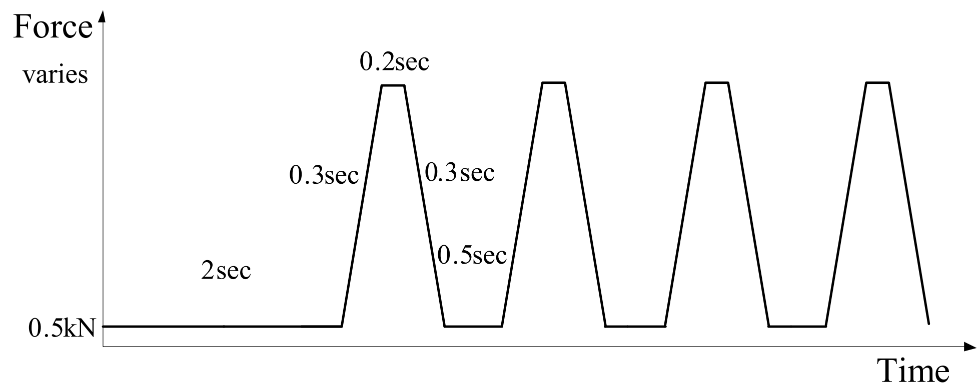

Figure 4. Cyclic loading wave

The instrumentation and data acquisition system included one earth pressure placed under the loading plate covered by a thin layer of soil and two displacement transducers set on the loading plate. Details of the test box system are illustrated in Figure 5 as an example.

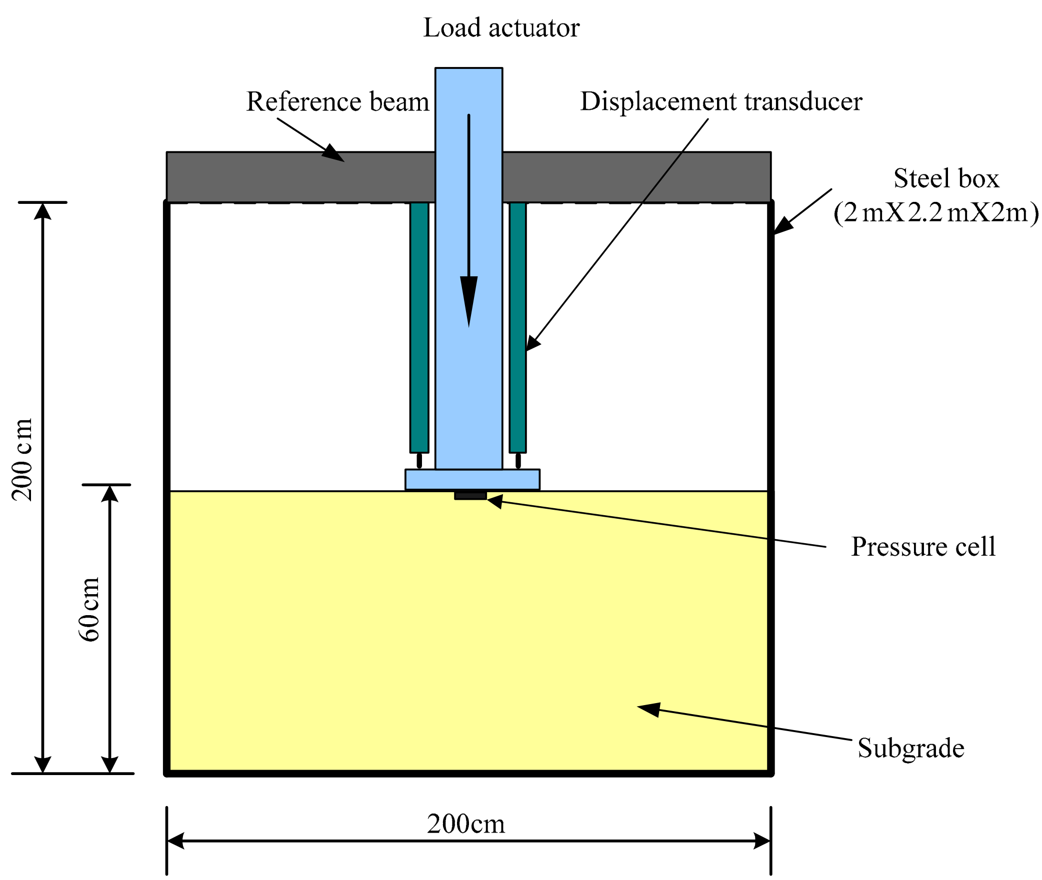

Figure 5. Setup of a cyclic plate loading test

The subgrade was placed and compacted in four layers (150 mm thick for each layer) at the moisture content of 11.4% for the 600-mm thick subgrade.

RESULTS AND DISCUSSION

Four cyclic plate loading tests were conducted in this study to determine the resilient modulus of a weak subgrade. DCP and vane shear tests were conducted after the preparation of the subgrade to ensure the CBR value of the subgrade at approximately 2% achieved and then the subgrade was tested under a 30-cm diameter rigid plate at one of four magnitudes of cyclic loading. During each the test, the deformations of the plate were monitored. Figure 6 shows the measured displacements versus the number of cycles under the peak loads of 4 kN. The magnitudes of the loads were selected based on the measured stresses at the interface between geogrid-reinforced bases and subgrade.

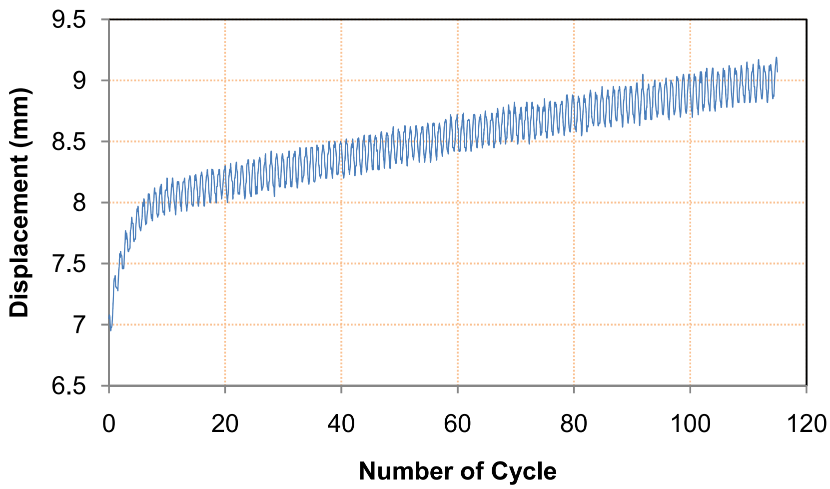

Figure 6. Displacement versus number of cycles under a peak load of 4 kN

The test results showed that the plate deformation increased with the number of cycles. The elastic solution presented in Harr (1966) as shown in Equation (1) was used to calculate the resilient modulus of the subgrade based on the rebound deformation of the plate.

$$\delta = \frac{p_i B I (1 - \nu^2)}{E_{sg}} \quad (1)$$

where, δ = the elastic displacement, i.e., the rebound in each load cycle (m); p_i = the vertical stress applied on the subgrade (kPa); ν = Poisson's ratio of the subgrade (0.5 used in this study considering the fact that the subgrade was undrained under cyclic loading); B = the diameter of the loading plate (m); I = the displacement influence factor; and E_{sg} = the resilient modulus of the subgrade.

Each test was cyclically loaded until the modulus reached the constant. The calculated resilient modulus of the subgrade first increased and then decreased and approached to a stable value with the number of cycles under different magnitudes of cyclic loading as showed in Figures 7, 8, 9, and 10, respectively.

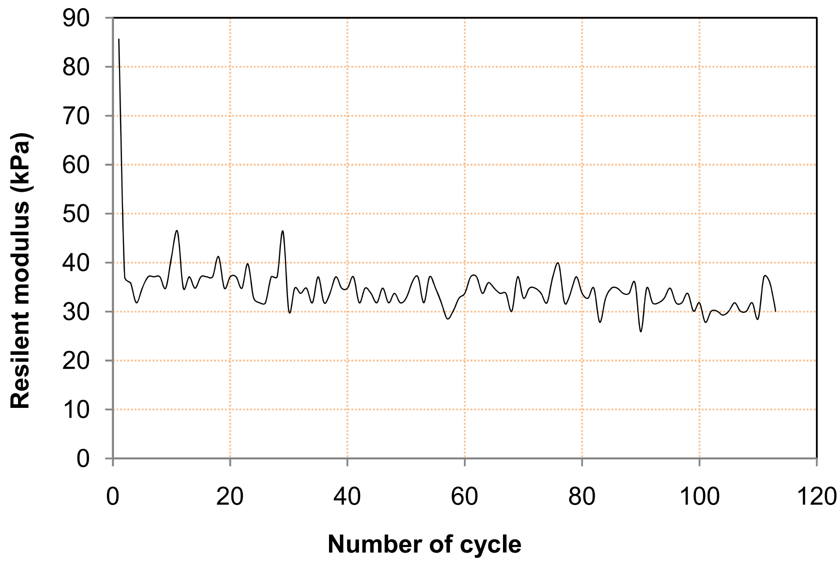

Figure 7. Resilient modulus versus number of cycles under 4-kN peak loading

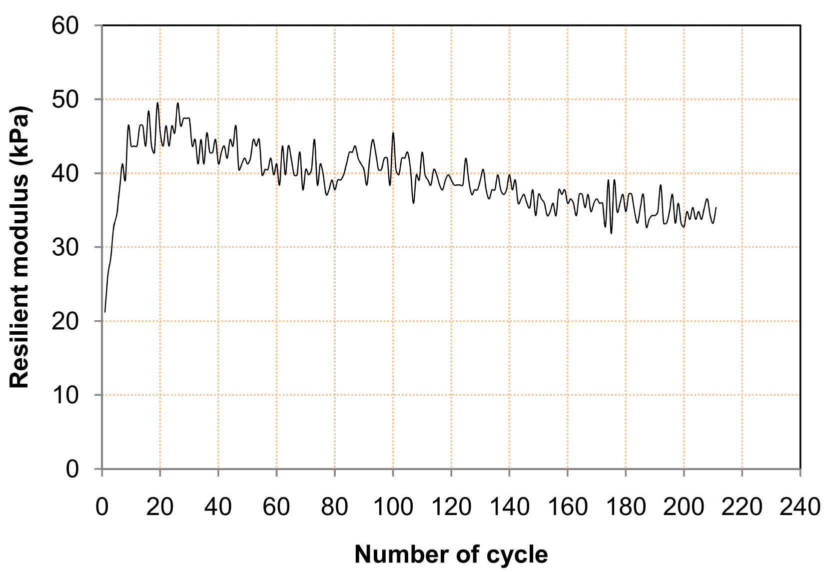

Figure 8. Resilient modulus versus number of cycles under 8-kN peak loading

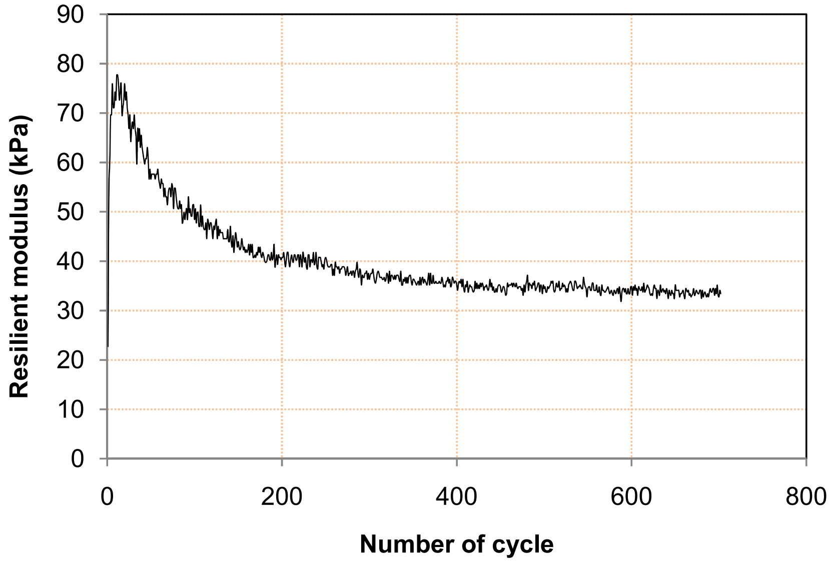

Figure 8. Resilient modulus versus number of cycles under 12-kN peak loading

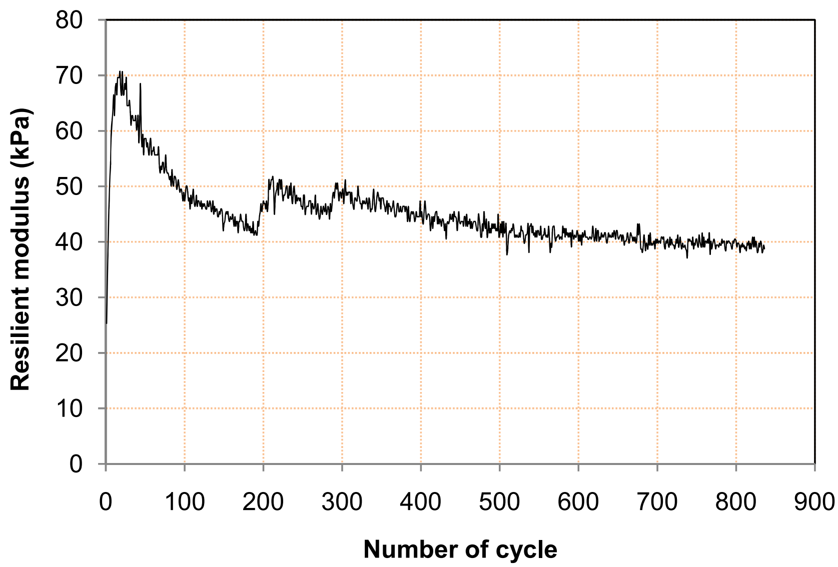

Figure 8. Resilient modulus versus number of cycles under 16-kN peak loading

According to all four tests, the resilient moduli of the subgrade ranged from 30.0 to 40.0 MPa with an average value of 37.2 MPa. Since the load was applied by a rigid plate, the resilient modulus under flexible loading should be modified by multiplying a factor of 0.79, as indicated by Yoder and Witczak (1975). Thus, the corrected resilient modulus of the subgrade was 29.4 MPa.

The AASHTO design guide (1993) suggested that the resilient modulus of fine-grained soils can be estimated using Equation (2) (Heukelom and Klomp, 1962) based on the correlation with the CBR value of the subgrade as follows：

$$Mr = 1500\ CBR \tag{2}$$

The calculated resilient modulus based on the correlation with the CBR value of the subgrade was 20.7 MPa.

The Transportation and Road Research Laboratory (TRRL) suggested using the correlation based on NCHRP 1-37A Design Guide (2002) as shown in Equation (3).

$$Mr = 2555\ (CBR)^{0.64} \tag{3}$$

The calculated resilient modulus using the above equation was 27.48 MPa.

Similar to the correlation recommended by the TRRL, the South African Council on Scientific and Industrial Research (CSIR) suggested using the following correlation to estimate the resilient modulus:

$$Mr = 3000\ (CBR)^{0.65} \tag{4}$$

The calculated resilient modulus using Eq. (4) was 32.5 MPa.

Therefore, the calculated resilient moduli using the three correlations from Equations (2) to (4) ranged from 20.7 to 32.5, which are close to those measured from the cyclic plate loading tests.

CONCLUSIONS

This paper presents an experimental study of using cyclic plate loading tests to determine the resilient modulus of a weak subgrade. The following conclusions can be drawn from this study:

1. The vertical permanent deformation of the subgrade increased with the number of cyclic loading.
2. The calculated resilient modulus of the subgrade using the elastic solution first increased, and then decreased and reached a stable value after a certain number of cyclic loading.
3. The average resilient modulus of the weak subgrade determined form the cyclic plate loading tests in this study was 29.4 MPa, which is close to that calculated using three correlations with the CBR value of the subgrade.

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