DEFORMATION CHARACTERISTICS OF SUBGRADE SOILS UNDER REPEATED LOADING

Y. Qiu[1], N.D. Dennis[2], and R.P. Elliott[3]

ABSTRACT

A Mechanistic-Empirical (M-E) design method will be the key feature of the next version of the *AASHTO Guide for the Design of Pavement Structures*. One of the requirements for M-E design procedures is the direct estimation of rutting by summarizing the permanent deformation of component pavement layers including subgrade. This paper reports an extensive research effort relating to permanent deformation of subgrade soils. Repeated load testing was conducted on an Arkansas subgrade soil. While most soil specimens were subjected to 10,000 to 100,000 load repetitions, one specimen was loaded to over 1 million applications to verify the general trend of deformation accumulation. Various factors including moisture content, density, deviator stress, confining pressure, load frequency, freeze-thaw and aging were investigated to determine their individual contributions to deformation accumulation. A test protocol was developed to effectively evaluate deformation parameters of subgrade soils. Data analysis from the repeated load testing also provided useful information for refinement of philosophies regarding design, construction, and operation of highway systems.

INTRODUCTION

The performance of highway pavements depends upon an appropriate design criteria and proper construction procedures. An appropriate design philosophy should account for the physical behavior of the pavement structure under moving vehicle loads. To achieve this philosophy, design criteria should directly relate pavement distresses to all components that directly contribute to distress. The goal is to contain overall pavement distresses by controlling the contribution of individual components through proper material selection and quality construction. One of the two major flexible pavement distress modes is rutting. According to current M-E pavement design methods such as Asphalt Institute design method and Shell design method, rutting is related to the elastic compressive strain at the top of the subgrade. Even in some purely mechanistic analyses, the prediction of permanent deformation is based on elastic response (Huang, 1993; and Owusu-Antwi, et al., 1998). Rutting is a result of the permanent deflection of the pavement surface that is caused by the gradual compaction and accumulated plastic deformation of all pavement layers, including subgrade. As a result, it is doubtful that a design postulation based on elastic response is realistic or even mechanistically sound. In cases where subgrade stresses are high, a linear relationship between elastic and permanent deformation does not exist. This brings the mechanistic soundness of the M-E methods into question. Even though these methods are not mechanistically pure, their use for high volume roads may be practical because stresses at the top of the subgrade are low. However, for low volume rural roads, stresses in the subgrade may be quite high. The high stress results in large vertical permanent deformation in the subgrade that may not be reliably predicted using elastic methods. A more rational approach requires rutting to be estimated by summation of the permanent deformation of component layers, including subgrade.

Early research on permanent deformation of subgrade soils dates back to the 1950s (Seed, et al., 1955). Comprehensive research projects include the research on a Vicksburg clay (Liquid Limit, *LL* = 37, Plasticity Index. *PI* = 14) at University of California at Berkeley and an investigation on a Keuper Marl (*LL* = 32, *PI* = 14) at the University of Nottingham. Succeeding research efforts have been reported by others over time (Seed, et al., 1958;

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1 Assistant Professor, School of Civil Engineering, Southwest Jiaotong University, Chengdu, 610031, P. R. China, Former Doctoral Candidate in the Department of Civil Engineering at University of Arkansas.
2 Associate Professor, 4190 Bell Engineering Center, Department of Civil Engineering, University of Arkansas, Fayetteville, AR72701, USA.
3 Professor and Head, 4190 Bell Engineering Center, Department of Civil Engineering, University of Arkansas, Fayetteville, AR72701, USA.
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Larew and Leonards, 1962; Monismith, et al., 1975; Thom, 1988; Muhanna, 1994; and Behzadi and Yandell, 1996). However, most of the research efforts relating to subgrade soils have been directed to the resilient modulus, especially since resilient modulus was incorporated into routine design methods (AASHTO, 1986). There are two primary reasons that the investigation of permanent deformation has been limited: One is the time-consuming and costly nature of repeated load testing such that there exists no well-accepted testing methodology so far. The other is the accepted use of elastic compressive strain at the top of the subgrade in current design methods to contain the permanent deformation of the entire pavement structure. This elastic compressive strain is estimated based on elastic layer theory or finite element analyses, which only requires elastic properties of all component materials. Vertical permanent strain is then assumed to be proportional to the predicted vertical elastic strain. The pavement structure is then designed such that permanent deformation can be limited by limiting the elastic strain at the top of subgrade. A more rational approach to analyze pavement structures requires direct prediction of permanent deformation and a test protocol should be established first.

This paper reports a concerted research effort on permanent deformation of subgrade soils through laboratory investigation. Based on extensive literature review, comprehensive series of repeated load tests were conducted and various factors influencing deformation accumulation were investigated. A testing protocol for predicting permanent deformation of subgrade soils under repeated loading was prepared. The test protocol specifies a methodology for repeated load testing for subgrade soils. It can serve as a basis for a standard and can be used to evaluate material properties needed to perform an M-E design of flexible pavement structures. The lessons learned during the laboratory investigation and analyses of test results provide some insights that are useful in refining pavement design philosophy and upgrading construction quality control.

SOIL DESCRIPTION AND TESTING PROGRAM

The soil was taken from the east shoulder of Highway 365, Section 12, T13N, R14W, in the southeast corner of Faulkner County, Arkansas. The soil at this location is mapped as Gallion in the Faulkner County soils report (USDOA, 1979). The liquid limit and plastic limit of this soil are 27 and 17 as determined by AASHTO T-265, respectively. The moisture-density relationship demonstrated in Fig. 1 indicates that this soil has an optimum moisture content of 14.6% and a maximum dry density of 18.22 kNm^{-3} (AASHTO T-99). The specific gravity is 2.67 (AASHTO T-100). According to the gradation curve as illustrated in Fig. 2 (AASHTO T-88), the soil has an AASTHO classification of A-4 and Unified Classification of CL, which is a low plastic silty soil.

A kneading compactor was used to fabricate soil specimens at various moisture contents and dry densities to simulate the range of field conditions expected in highway subgrades. The mold used for soil compaction has a diameter of 100 mm and a height of 125 mm. A lubricated portion of Shelby tube with a diameter of 73 mm was used to cut a test specimen from the compacted soil in the mold. After extrusion of the soil from the Shelby tube, a test specimen was created with a diameter of 73 mm and a height of 120 mm. This specimen size is the same as that used for resilient modulus testing in a previous research (Elliott, et al., 1988).

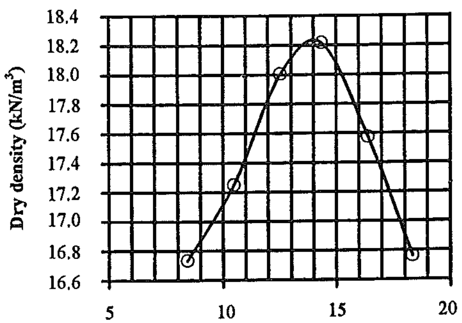

Fig. 1 Compaction Curve

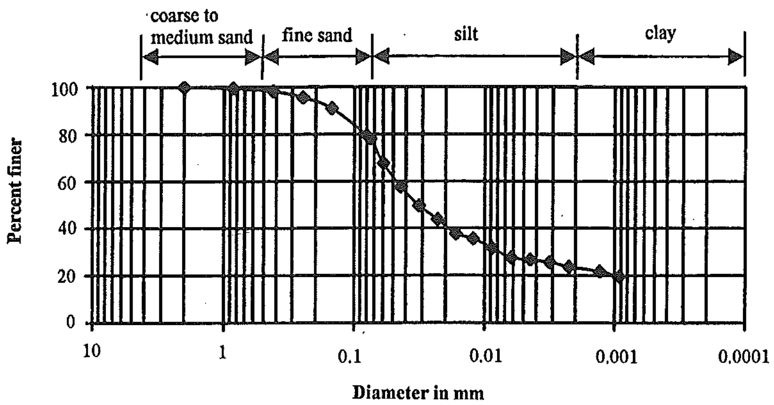

Fig. 2 Soil Gradation Curve

A comprehensive literature review by Elliott et al. (1998) indicated that factors contributing to the accumulation of permanent deformation under repeated loading include: load frequency, load duration, rest period, confining pressure, stress history, first load application, number of repetitions, moisture content, density, deviator stress, freeze-thaw, etc. These factors were formally incorporated into the repeated load testing program in order to determine their contributions to deformation accumulation. All specimens were subjected to 10,000 to 100,000 load repetitions except one specimen which was subjected to 1,600,000 repetitions to verify the general trend of the development of permanent deformation over a high number of load applications. The load duration was set to 0.1 second to represent a great range of load pulses that subgrade soils are subjected to under moving traffic conditions (Barksdale, 1971).

All repeated load testing was conducted using an MTS 810 servo-hydraulic universal testing machine. A HP-VEE visual program was written to acquire load and deformation data at user-defined intervals, which could be readily exported to spreadsheets for data analysis. Figure 3 presents the MTS set-up and the data acquisition console. A detailed description about the apparatus configuration and data acquisition is documented elsewhere (Elliott, et al., 1998).

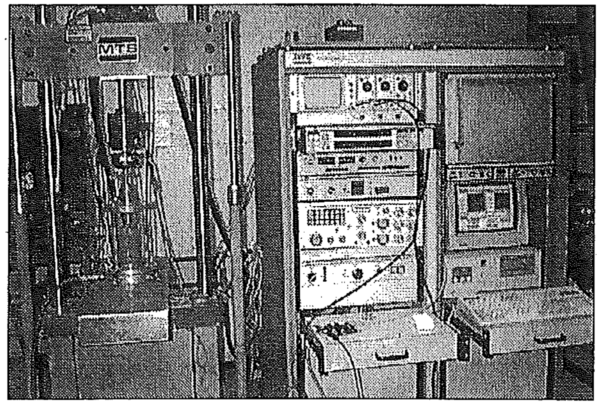

Fig. 3 MTS Set-up and Data Acquisition

TEST RESULTS AND DATA ANALYSIS

General Deformation Behavior

Data from one of the first load tests is presented in several different scales in Figs. 4(a), 4(b) and 4(c). For this particular test, the load frequency was set to be 2 Hz with a rest period of 0.4 second. Load repetitions were continued to 1,600,000 cycles. Confining pressure was 41kPa and the deviator stress was 62 kPa. As indicated most clearly in Fig. 4, a large part of the total deformation was developed during the first 100 cycles of the test. It was also noted that the general relationship between axial strain and the number of load applications is more or less linear when represented on log-log scale as shown in Fig. 4(b). The log-log representation of the data is consistent with the power model proposed by Monismith, et al. (1975). This model links permanent strain e_p and load repetition N with two parameters A and b, $e_p = AN^b$. From the data presented in Fig. 4(b), it is apparent that the linearity of this relationship improves if the first 100 data points are excluded, resulting in R^2 value to jump from 0.9593 to 0.9880. Inspection of Fig. 4(b) reveals that the permanent deformation under the first load application for the load test reported constituted 64% of total permanent deformation that was accumulated after 1,600,000 applications. The accumulated permanent deformation, expressed as a percentage of the total permanent deformation at 1,600,000 cycles of load, for the first 100; 500; 1,000; and 10,000 load applications, was 75, 83, 85, and 90, respectively.

First-Cycle Deformation

Because permanent deformation under the first several load applications makes up a large portion of potential permanent deformation, it is essential that the deformation data under first few repeated loads be captured. Unfortunately, it is not easy to accurately capture and isolate these data, especially at high load frequencies. Previous researchers have used manual loading to get the first cycle data (Diyaljee and Raymond, 1982) or collect data after several cycles (Muhanna, et. al, 1998). Even with the advanced technology for data acquisition, it still remains a problem to identify and collect the exact first-cycle data because the initiation of GUI (Graphical User Interface) data acquisition application takes several seconds and the phase difference between deformation and loading may also affect the precision of early data points.

A practical way to eliminate any unreasonable data generated under the first few load applications is to remove these data points from the analysis and extrapolate them from the regression equation generated by the remaining data points. In this research, only data after 100 applications have been used in developing regression coefficients. The deformation data for load applications between 1 to 100 are then extrapolated using the regression equations.

Number of Load Applications

Permanent deformation testing is usually time-consuming. If the number of load applications can be reduced to a point where usable information about permanent deformation can be extracted from a limited data set, the expense and time associated with testing can be reduced greatly. As shown in Fig. 4, the measured permanent deformation at 1,600,000 load applications is 3.29% axial strain. The testing time required to produce 1,600,000 load repetitions is over 200 hours. If the test had been concluded after 10,000 repetitions (less than 2 hours), the extrapolated strain using regression parameters ($R^2 = 0.9626$) for 1,600,000 repetitions would have been 3.52%. This represents only a 7% deviation between measured and predicted vertical strain. The strong linearity between axial strain and load applications in all tests conducted during this study supports the contention that repeated load testing can be concluded in 10,000 repetitions.

Load Frequency and Rest Period

Figures 5(a) through 5(d) present the results of a series of tests conducted at different load frequencies. Three different rest periods, 0.4 second, 0.9 second, and 1.9 seconds, were used during the testing. These rest periods, coupled with the 0.1 second load pulse, resulted in load frequencies of 2 Hz, 1 Hz and 0.5 Hz, respectively. A review of the literature revealed that a frequency of 0.5 Hz was used often. It would be more economical and much less time-consuming if the rest period could be reduced to a smaller value while still achieving reasonable results. Figures 5(a) and 5(b) present results with deviator stress set to 41 kPa using different rest periods. The confining pressures are 21 kPa and 41 kPa, respectively. The data in these figures present strong evidence that the difference among the data sets under different rest periods is not large enough to make clear a claim that rest period affects strain accumulation. Therefore, it is a reasonable postulation that the load frequency in the range used for these tests does not affect the permanent deformation response of soils under repeated loads. Figures 5(c) and 5(d) present data for tests where the

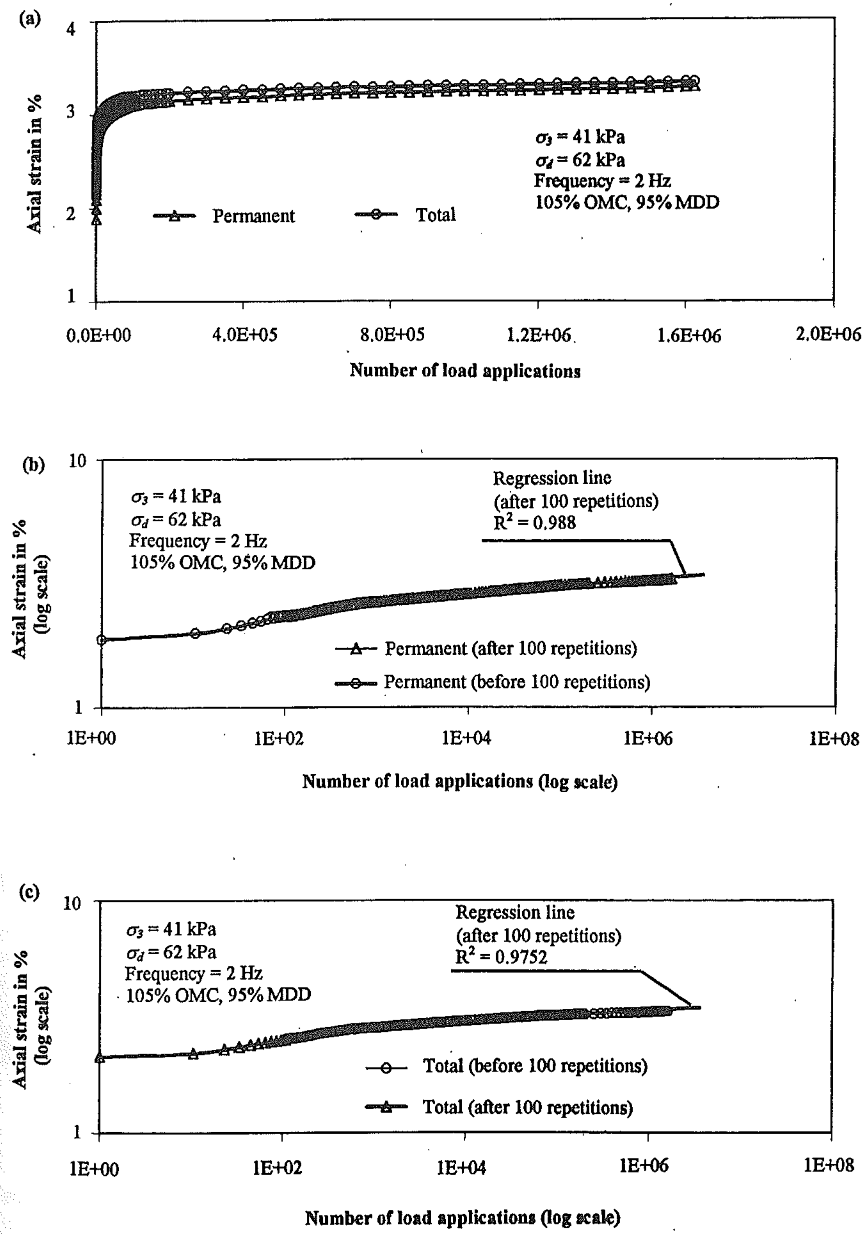

Fig. 4 Development of Total and Permanent Deformation Versus Load Repetition

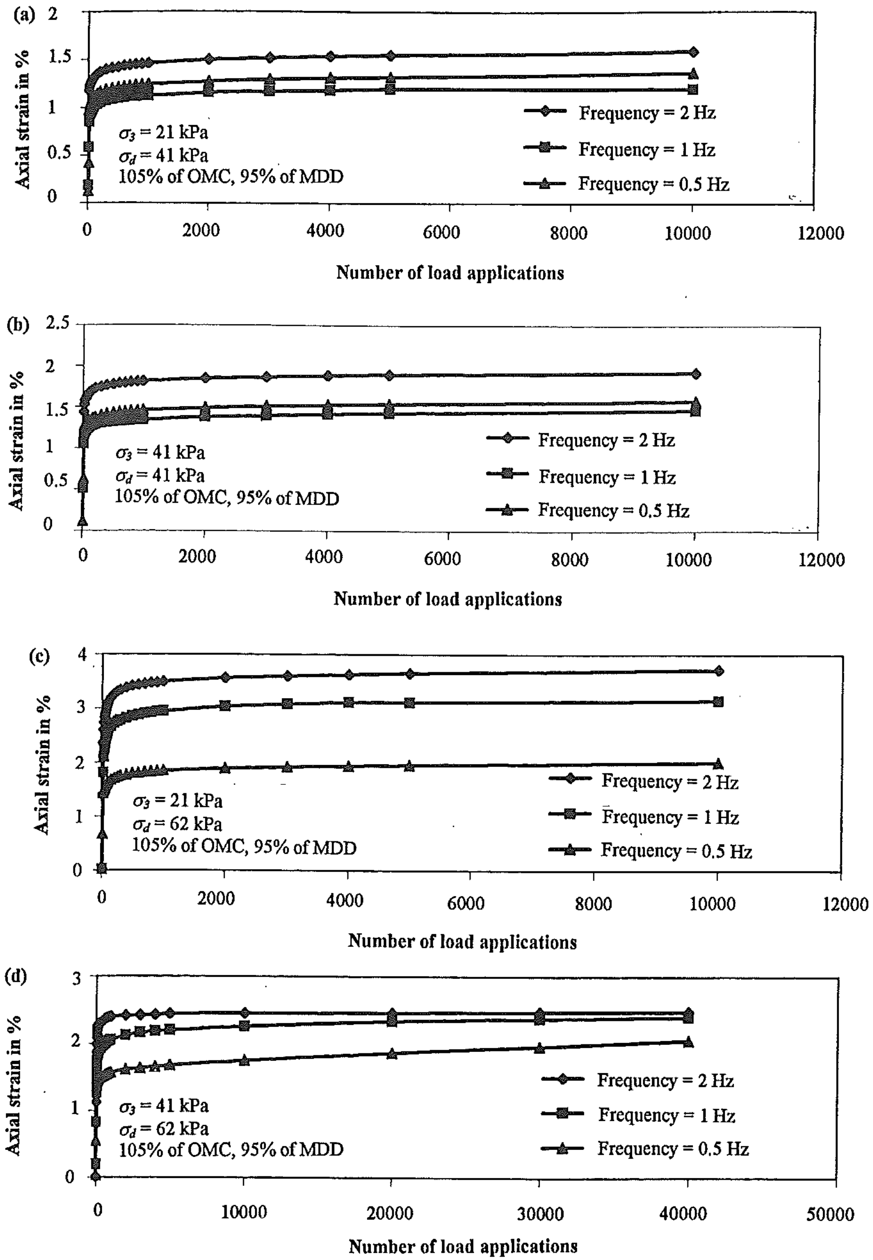

Fig. 5 Effect of Load Frequency on Permanent Deformation

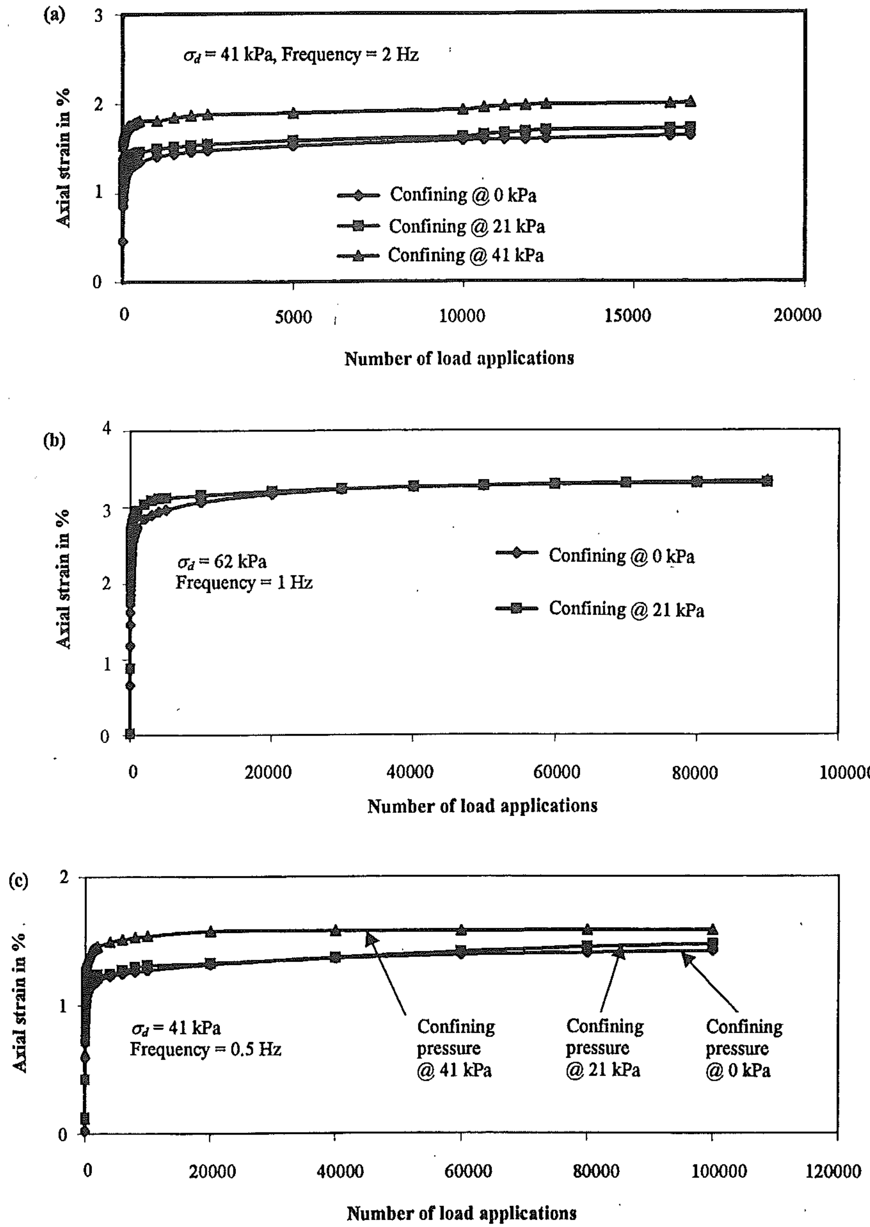

Fig. 6 Effect of Confining Presure on Permanent Deformation

confining pressures are 21 kPa and 41 kPa, respectively, and the deviator stress is 62 kPa. For this higher deviator stress, the difference in deformation is great enough to assume that a higher frequency causes greater deformation. It is believed that an interactive effect between deviator stress and load frequency on the deformation accumulation might exist. Since the test specification for resilient modulus testing requires a rest period of 0.9 second (AASHTO T 292-92), it is recommended that a frequency of 1 Hz be used in repeated load testing for permanent deformation research such that both resilient as well as residual deformation data can be acquired simultaneously.

Confining Pressure

The effects of varying confining pressure are illustrated in Fig. 6(a) to Fig. 6(c). The deviator stress was 41 kPa and 62 kPa while the confining pressure was 0, 21 kPa or 41 kPa. Each figure demonstrates the effects of differing confining pressure for a particular deviator stress. Generally, the contribution of confining pressure appears to be an insignificant factor in the accumulation of permanent deformation. A small increase of permanent deformation is observed in Fig. 6(a) and Fig. 6(c) when the confining pressure is increased from 21 kPa to 41 kPa. This increase in axial strain might be caused by the gradual consolidation of the test specimens at the high chamber pressure. Based on the data presented in Fig. 6, a fixed confining pressure of 21 kPa, which is representative in highway subgrades, could be used in repeated load testing.

Deviator Stress and Dynamic Strength

Test results illustrating the effect of varying deviator stresses under constant confining pressures are presented in Fig. 7. The results clearly demonstrate that deviator stress plays a critical role in the development of permanent deformation. Higher deviator stress results in earlier and more rapid accumulation of permanent deformation. Although the general trend of deformation accumulation remains the same over the applied range of deviator stresses used in this study, the initial deformation under the first couple of load applications significantly increases with an increase of deviator stress. Figure 7 also demonstrates that with increasing deviator stress, the strain accumulation rate tends to stay the same until the applied deviator stress approaches the dynamic strength of the soil. For the tested soil, the dynamic strength was found to be about 67.5% of its static strength. When the applied deviator stress reaches dynamic strength, the specimen fails after only a couple of load applications, as illustrated in the curve for σ_d = 172 kPa in Fig. 7. While the exact number of repetitions to cause failure is not easy to identify, it is within the first 100 load cycles.

Stress History

The investigation of stress history is summarized in Fig. 8(a) to Fig. 8(c). These figures illustrate the effects of previous loading history on the permanent deformation of the test specimen. One virgin specimen and another specimen subjected to previous loading history were tested under the same deviator stress and the results are plotted in the same figure. As an example, the data presented in Fig. 8(a) represents one unique test specimen that was subjected to a deviator stress of 62 kPa and a confining pressure of 41 kPa. The second specimen was subjected to the same

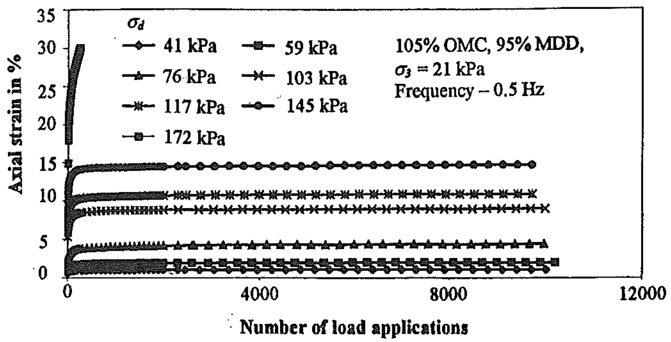

Fig. 7 Effect of Deviator Stress on Permanent Deformation

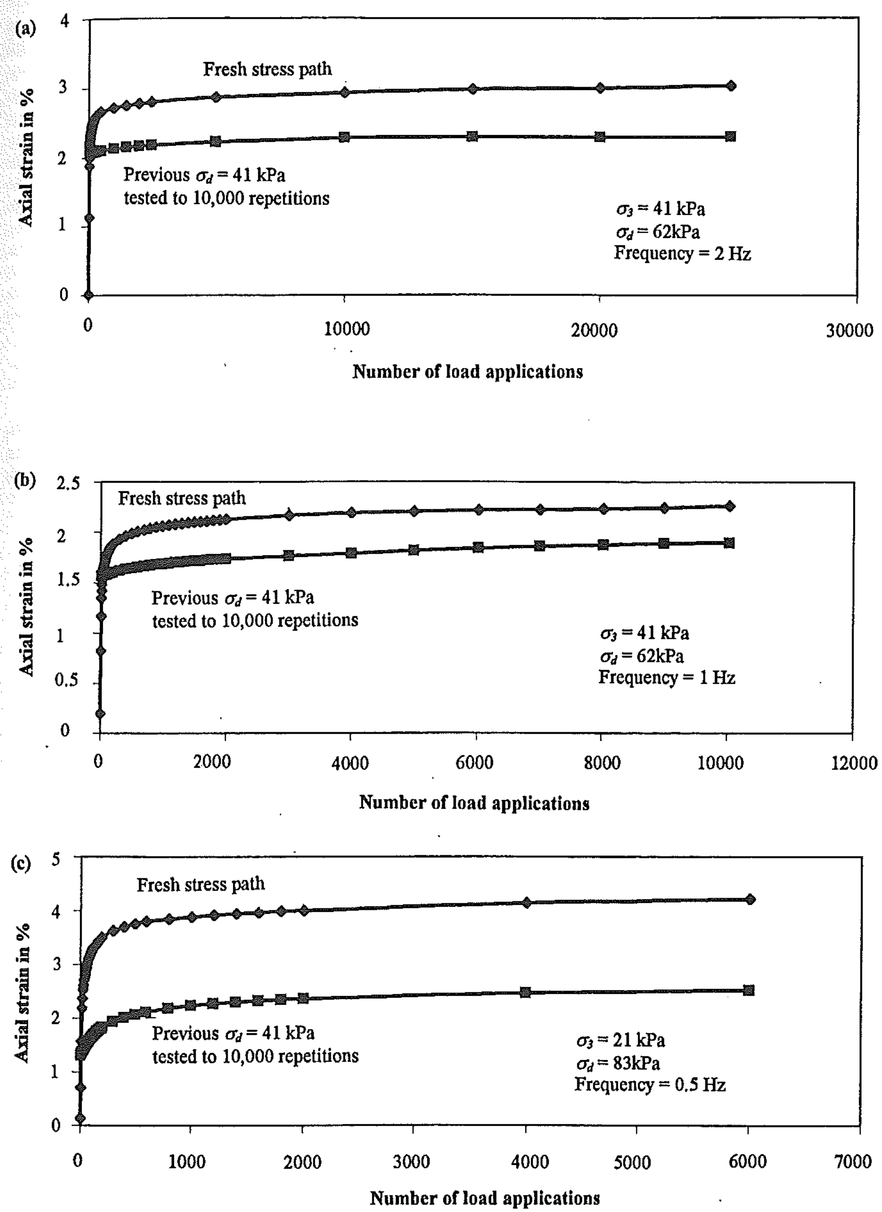

Fig. 8 Effect of Stress History on Permanent Deformation

deviator and confining pressures but it had been previously tested to 10,000 load cycles at a deviator stress of 41 kPa. Previous loading at lower deviator stresses increased the soil's resistance to deformation under repeated loads at high deviator stress as suggested by Seed, et al. (1955). The work hardening of previous load application made the specimen stiffer and less prone to permanent deformation. Based on this observation, it is concluded that sequential testing with increasing deviator stresses applied on the same specimen is not appropriate for permanent deformation testing.

Moisture Content

Figure 9 illustrates the effect of moisture content on the accumulation of permanent deformation. Three different moisture contents: 105%, 110%, and 120% of OMC, were used to demonstrate the critical role of moisture content on the accumulation of permanent deformation. Figure 9 clearly illustrates that moisture content is a significant factor contributing to the accumulation of deformation. Increasing moisture contents appears to soften the soil leading to a substantial increase of the accumulated strain. Comparing the data in Fig. 7 and Fig. 9, it can be seen that the specimen having a moisture content of 120% of OMC and subjected $\sigma_d = 41$ kPa developed more deformation than a specimen having a moisture content of 105% of OMC and subjected to $\sigma_d = 76$ kPa. Different moisture contents expected in service conditions should be used in the preparation of specimens to evaluate the effect of moisture content on permanent deformation.

Density

All specimens were compacted with a target dry density of 95% of maximum dry density (AASHTO T-99). In reality, the density of the prepared specimens ranged from 94% to 96%. This variation in density had little effect on permanent deformation as illustrated in Fig. 10. It is concluded that density can be set to a fixed magnitude, e.g., 95% of maximum dry density which is representative of the post-construction quality of highway subgrades in accordance with compaction specification.

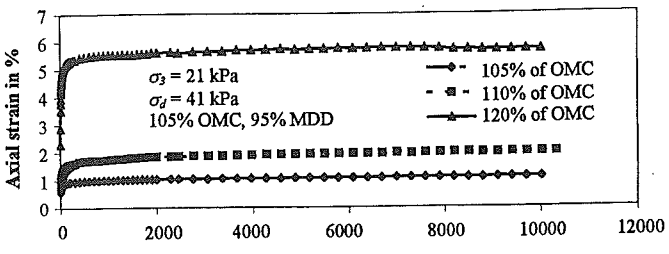

Fig. 9 Effect of Moisture Content on Permanent Deformation

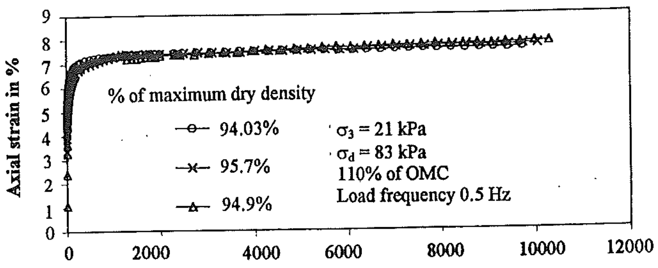

Fig. 10 Effect of Dry Density on Permanent Deformation

Freeze-thaw

The damaging effect of freeze-thaw on pavement performance is a great concern for pavement engineers in cold regions. Load-limit program has been the first option to control freeze-thaw damage to pavement structures although some operational controversy may occur due to the different climatic regions for long distance, cross-region delivery. Figure 11 demonstrates the effects of freeze-thaw on permanent deformation. One cycle of freeze-thaw increased permanent deformation by nearly 100%. No significant additional increase in deformation was observed for additional cycles of freeze-thaw as shown in Fig. 10 (slight decrease of permanent deformation was observed in some cases which might be a resul of phase change and migration of moisture).

Aging Period

The thixotropy of soils has a significant effect on the deformation behavior. In order to investigate the thixotropic effect on permanent deformation and estimate conditioning period required for thixotropic soils, several identical specimens were subjected to the same testing conditions with different aging periods. The data series in Fig. 12 illustrates the dramatic thixotropic effect on deformation accumulation. The deformation of the specimen tested immediately after extrusion nearly was double that of specimens tested 72 hours after extrusion. Figure 12 also suggests that a 72 hour rest period is a practical upper limit on the rest period for thixotropic soil specimens since the 96 hour rest period resulted in almost identical deformation behavior.

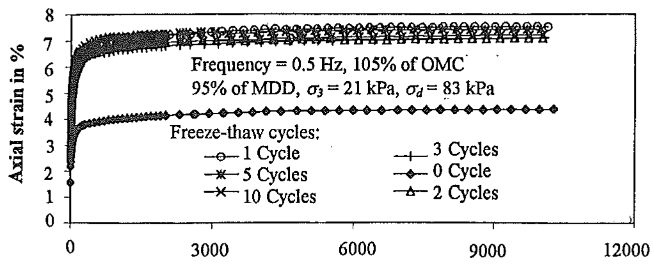

Fig. 11 Effect of Freeze-Thaw on Permanent Deformation

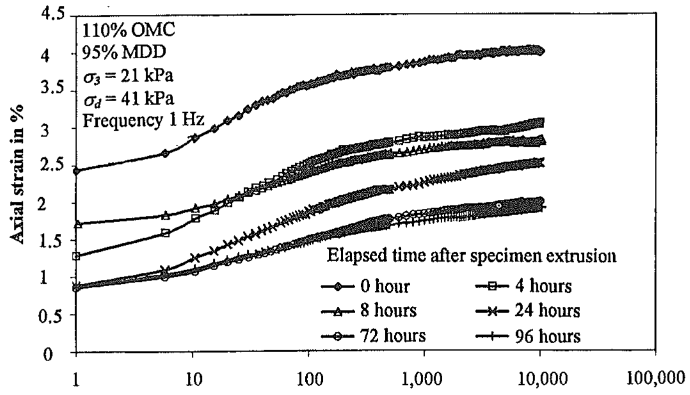

Fig. 12 Effect of Aging Period on Permanent Deformation

CONCLUSIONS AND RECOMMENDATIONS

Extensive repeated load tests have been conducted in this research. The analyses of test results indicate that a strong log-linear relationship exists between accumulated permanent strain of subgrade soils and load repetitions. This relationship suggests that good prediction of permanent deformation of subgrade soils can be made using data from laboratory tests of short duration. Test results also suggest that the main contributors to the accumulation of permanent deformation of subgrades include moisture content, deviator stress, first-cycle freeze-thaw, and aging period for thixotropic soils. To keep the time-consuming repeated load tests practical, it is appropriate to fix minor factors such as confining pressure, load frequency and density in the testing protocol.

Based on the results of this investigation, a practical test protocol for permanent deformation was prepared. The basic set-up of proposed protocol includes the following configurations:

1. Use a virgin soil specimen for each deviator stress (sequential testing is not recommended).
2. Compact soil specimens to 95% of maximum dry density.
3. Testing variables include moisture content, deviator stress, one cycle of freeze-thaw if needed and 72 hour of aging for thixotropic soils.
4. Confining pressure can be set to 21 kPa.
5. Load frequency can be set to 1 Hz with the rest period to 0.9 second.
6. Test can be concluded at 10,000 load repetitions.
7. Limit the deviator stress to dynamic strength when quick failure is expected after several repetitions.

Since deviator stress, moisture content, and the first-cycle freeze-thaw are major contributors to the accumulation of permanent deformation, it is crucial to keep out over-weighted trucks to avoid premature failure of pavements, especially during springtime. A load-limit program could minimize the potential damage. Permanent deformation accumulated over the first 10 repetitions accounts for about 70% of the deformation developed after 10,000 applications. Heavy construction vehicles during the compaction, hauling, leveling of succeeding layers could improve the quality performance of pavements. On the other hand, over-weighted vehicles should be removed form newly constructed or rehabilitated pavements.

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