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Mechanistic-empirical approach to characterizing permanent deformation of reinforced soft soil subgrade

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A B S T R A C T

This study focuses on characterizing the permanent deformation of geogrid-reinforced soft soil subgrade by using the mechanistic-empirical (ME) approach based on both experimental measurements and results of numerical modeling. Two sets of small-scale pavement sections were built over two types of soft soil subgrade and subjected to cyclic moving loads by means of a reduced-scale accelerated pavement testing (APT) device. Each set of pavement sections included one control section and three sections reinforced by different geogrids placed at the base–subgrade interface. The pavement sections were instrumented to measure vertical deformation and vertical stresses at the top of the subgrade. Strains developed in the geogrids were also measured by strain gauges throughout the construction and accelerated testing. Simplified finite element (FE) models were created to simulate both the control and geogrid-reinforced pavement sections and to compute the pavement mechanistic responses. With the experimental measurements from the first set of tests and results of FE analysis, the permanent deformation model in NCHRP 1-37A for unbound layers was adapted and calibrated to model the permanent deformation of the geogrid-modified subgrade. The effects of geogrids on the subgrade permanent deformation were integrated into the ME performance model through both the mechanistic response modeling and the empirical calibration. Predictions from the permanent deformation model were then compared with the second set of measurements and found to underestimate the permanent deformation of the geogrid-modified subgrade. However, the model was able to distinguish the difference in performance among the sections, i.e. the predicted rank of the performance was consistent with the measurements.

1. Introduction

A weak subgrade has been a major concern to pavement design engineers due to its potential contribution to permanent deformation in flexible pavements, particularly in low-volume thin pavements. Soils with high fines contents are generally not desirable to be used for constructing pavement subgrade due to their moisture-sensitive nature and the consequent loss of subgrade strength particularly in rainy seasons. Typical approaches adopted to avoid or minimize the problem have focused on: (1) increasing the thicknesses of the pavement layers, both unbound and asphalt concrete; (2) removing a top layer of the subgrade and backfilling it with a soil of higher bearing capacity and better properties to resist frost/heave and other load and environmental factors; and (3) stabilizing the subgrade through a variety of techniques such as adding lime or cement. While these methods of treating soft soil subgrade usually provide an adequate load bearing capacity of the subgrade for the pavement foundation, the costly expenses associated with excavation, transportation, and construction materials can be a drawback due to budgetary constraints.

Since the early 1970s, geogrids have been increasingly used in flexible pavements, especially for reinforcing the base layer or improving weak subgrade (Perkins et al., 2005). Through both laboratory and field studies, it has been shown that the inclusion of geogrids at the interface between the base course and subgrade in flexible pavements can improve the performance of flexible pavements by extending the service life or reducing pavement

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structural thickness while maintaining equivalent performance (Haas, 1984; Love, 1984; Barksdale et al., 1989; Al-Qadi et al., 1994; Kinney et al., 1998; Perkins, 2002; Wu et al., 2015). However, most available design methods or design models for geosynthetic-modified pavements are empirically-based, product-specific, and limited to the experimental conditions from which the design methods were developed (Carroll et al., 1987; Webster, 1993; Montanelli et al., 1997). As a result, there is no widely accepted approach for designing flexible pavements modified with geosynthetics. On the other hand, the mechanistic-empirical (ME) approach for analysis and design of conventional pavements, i.e. without the inclusion of geosynthetics, has received wide recognition because of its many advantages over the empirical approach including more reliable performance prediction by integrating the pavement mechanistic responses into the empirical performance models (NCHRP, 2004). The ME approach is now becoming routine practice for pavement design engineers, especially since the release of the pavement design software, AASHTOWare® Pavement ME Design (previously DARWin-ME) by AASHTO (AASHTO, 2008). However, only a limited number of studies were found that attempted to develop ME methods or models for flexible pavements reinforced with geosynthetics, including geogrids.

Perkins et al. (2004, 2009) conducted a series of large-scale triaxial tests on base aggregate with a single layer of geogrid installed at mid-height of the sample to develop ME permanent deformation models for the base layer modified by geogrids. A zone of influence of the geogrid reinforcement was identified, and the ME permanent deformation model for a reinforced base layer was incorporated only into the influence zone. The critical pavement responses needed in the ME models were generated from nonlinear finite element models that account for residual stresses in geogrids due to compaction and traffic loads. The ME models for the base layer were then simultaneously calibrated along with the permanent deformation models for the asphalt layer and subgrade based on measurements of the surface rutting/total permanent deformation from large-scale box testing and full-scale accelerated pavement testing. Henry et al. (2009) modified the ME permanent deformation models found in NCHRP 1-37A (2004) to accommodate the development of permanent deformation models for geogrid-modified flexible pavements. The effects of geogrid reinforcements were accounted for both in the mechanistic modeling and through the addition of a factor in the permanent deformation models. The permanent deformation models for the asphalt layer, base layer, and subgrade were calibrated from either surface rutting or individual layer deformation measurements depending on the availability of measurements in the full-scale accelerated pavement testing. While it is important to understand the impact of geogrids directly on subgrade permanent deformation, there is limited quantified information since it is relatively more difficult to measure the subgrade deformation in a pavement system under cyclic moving wheel load. Furthermore, incorporating the effects of geogrids into the ME models is often challenging because of the lack of reliable measurements of geogrids strains under the moving wheel load. This study focuses on characterizing the permanent deformation of the geogrid-reinforced soft soil subgrade by adapting and calibrating the mechanistic-empirical (ME) models. A testing program was undertaken to evaluate the effectiveness of three different geogrid products in improving performance of flexible pavements built over soft soil subgrade. The geogrids were tested within scaled pavement sections using a reduced-scale accelerated pavement testing (APT) device that applies unidirectional cyclic moving wheel loads. It is worth pointing out that the resilient and permanent deformation behavior of pavement unbound materials is often investigated and characterized by using the laboratory triaxial testing that currently do not take into consideration of effects of principal stress rotation due to moving wheel loads (Chen and Abu-Farsakh, 2010; Gräbe and Clayton, 2014; Inam et al., 2012). During the accelerated testing in this study, both elastic and permanent deformations at the top of the subgrade, vertical stress on top of the subgrade, and strains developed in the geogrids were measured at different stages of the load applications. The NCHRP ME permanent deformation model was modified and calibrated based on both the numerical modeling and the experimental measurements. The mechanistic inputs in the model were obtained from finite element analysis that accounts for the addition of the geogrids in the pavement. The direct measurements of the subgrade permanent deformation along with repetitions of the cyclic loads were used to calibrate the empirical factors in the ME models. Predictions from the ME models were then compared with an additional test set of measurements of subgrade permanent deformation.

2. Instrumented reduced-scale accelerated pavement testing

Two sets of reduced-scale accelerated pavement testing (APT) were carried out using a one-third scale mobile model load simulator (MMLS3). In each of the two instrumented accelerated tests, there were four pavement sections, among which one was a control and the other three were reinforced by different geogrid products designated as Grid A, Grid B, and Grid C, respectively. The two instrumented accelerated tests are designated as APT I and APT II, respectively. The pavement sections materials, layout, and thicknesses were the same for these two sets of instrumented accelerated testing, except for the subgrade soil types.

2.1. Test section and materials

The test pavement sections were constructed in a concrete pit with available space of 364 cm (144 in) long, 206 cm (81 in) wide, and 127 cm (50 in) deep to the backfill surface. The structural thickness of pavement layers were scaled down according to the scale of MMLS3 load and existing Pennsylvania Department of Transportation (PennDOT) design specifications for low-volume roads (PennDOT, 2010). The structural layer thickness was determined for a one-third scale model pavement as follows: 4 cm (1.5 inches) AC layer and 10 cm (4 inches) base layer. Fig. 1 shows the plan view and cross section view of the pavement sections. A sensitivity analysis using FE models was carried out to investigate the potential boundary effects on the pavement with the four-section layout in the existing concrete pit. In the FE models, the distance from the loading center to the nearest boundary was varied from 25 cm (10 inches) to 102 cm (40 inches) to observe the boundary effects on vertical stress on top of the subgrade. As can be seen in Fig. 2, the change of vertical stress on top of subgrade becomes minimal when the distance from the load center to the boundary reaches 51 cm (20 inches). It is noticed that the boundary distance is 46 cm (18 inches) for the four-section layout as shown in Fig. 1, which is 5 cm less than the ideal boundary distance. However, the vertical stresses on top of subgrade for sections with boundary distance of 51 cm (20 inches) and 46 cm (18 inches) are 15.7 kPa (2.27 psi) and 15.4 kPa (2.24 psi), respectively. The percentage difference in vertical stress atop subgrade between the two cases is about 1.9%. It is, therefore, expected that the boundary effects due to the side walls with distance of 46 cm to the load center are negligible.

The asphalt layer was constructed using surface mix with a maximum nominal aggregate size of 9.5 mm. The asphalt mixture had a theoretical maximum specific gravity of 2.532, which was used to check the air void percentage for the subsequent compactions of asphalt concrete. The base layer was constructed using a