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RESEARCH PAPER

Evaluation of Granular Fill Layer Underlain by Soft Clay Soil Using Large Scale Cyclic Plate Loading Tests

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Abstract

In general, granular fill materials are widely used to construct new pavement and rehabilitate old pavement. For pavement design, it is essential to know the basic characteristics, such as the permanent deformation behavior of these materials. Considering this phenomenon, this study aims to explain the performance of granular fill layers in pavement systems using cyclic plate load tests. For this purpose, a large-scale cyclic plate load test facility, also known as pavement model testing (PMT), was developed to investigate the permanent deformation characteristics of the pavement structure. To conduct experiments, a standard pavement structure was built with granular fill layers on top of a soft clay subgrade and a geotextile between the subgrade and the base layer. The PMT was used to apply a 40 kN cyclic load through a steel plate with a 305 mm diameter for up to 10,000 cycles after the pavement structure was built. A total of four tests were carried out to evaluate the effects of the granular fill layer's thickness on the pavement's permanent deformation. Furthermore, an analytical solution was developed for the fill layer thickness using the test results. Additionally, the outcomes of some previous studies in the literature were compared to the ones that were obtained. The results of this study indicate that the permanent deformations of the pavement structure and the subgrade increased with the number of load cycles. The permanent deformations began to limit at 3000 cycles when the fill layer thickness was 20 cm, but it was observed that deformations did not limit at 3000 cycles when the fill layer thickness increased to 45 cm. Also, the permanent deformations decreased by two times when the granular fill layer thickness doubled appropriately.

Keywords Cyclic plate load tests · Permanent deformation · Soft clay · Granular fill · Geotextiles

1 Introduction

The rapid increase in the population has led to an increase in highway or road construction activities on soils with very low bearing capacity. Reinforcement of these problematic soils with a granular fill layer is one of the soil improvement techniques that is widely used. Problematic soil behavior can be improved by totally or partially replacing inadequate soils with granular fill compacted in layers. However, soil behavior can be further improved by placing geosynthetics in granular fill. In this technique, one or more geosynthetics are placed in the granular fill material to form a composite material. This technique is commonly used for unpaved roads, embankments, shallow foundations, and large stabilized areas such as car parks or working platforms for oil drilling [1–10].

Unpaved roads are usually used for low volumes of traffic and serve as access roads. The low-volume roads, which are in an agricultural country, play a very important role in the rural economy and resource industries. Typically, these road structures are constructed from one or more layers with crushed stone aggregate laid on top of the subgrade. When unpaved roads are built on soft soils, large

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permanent deformations can occur, which increase maintenance costs and lead to interruptions in traffic service [8, 11, 12]. The term "rutting" is used to describe these displacements, which are a common form of "failure" on roads [13–16]. Rutting may develop in all individual pavement layers, including the subgrade [17, 18]. It can be caused either by consolidation and/or by lateral movement of materials under moving wheel loading [19]. On the other hand, rutting is problematic for drivers because it increases fuel consumption and increases the possibility of skidding (on ice or water). Rutting also causes problems because it encourages water to soak into the pavement instead of draining off the surface, which leads to rapid pavement deterioration. Water entering the pavement in this way may collect in a "buried" rut in the subgrade and/or reduce the load-carrying capacity of the granular layers [20]. The base aggregate layer is the most important component of unpaved roads against rutting. Especially, resistance to permanent deformation, which is nearly synonymous with shear strength, is an important characteristic for aggregates that are to be used as fill material in the base layer. It is stated that, although the considerable emphasis is being placed on resilient moduli, permanent deformation characteristics are often more important from a practical viewpoint [21]. Studies looking into the permanent deformation of the base layer have therefore gained attention [22]. In recent years, the effect of the base course's thickness on rutting by using plate loading tests has been investigated by Khoueiry et al. [23]. They developed a plate loading test to analyze the performance of unpaved roads. Plate loading tests were carried out in a test tank with a width of 1800 mm, a length of 1900 mm, and a height of 1100 mm. Also, they conducted tests using the developed traffic simulator. In other words, they subjected the road base they prepared to a plate load and a traffic load. Their results showed that road base thickness and loading type were effective in determining the behavior of the road base. On the other hand, some researchers have investigated the effect of geosynthetics in the base layer on rutting by using cyclic plate-loading tests [24–28]. The effectiveness of geosynthetically reinforced quarry wastes using plate loading tests (a test box with a volume of 1 m^3 and a circular foundation with a diameter of 300 mm) was investigated by Sheikh et al. [25]. They reported that reinforcement with the combination of geotextile and geocell increased the bearing capacity by 2.4 times. The effectiveness of the use of geotextiles and geogrids in reducing the required base layer thickness when built on different soft subgrades was examined by Nazeri et al. [26]. In this study, the geosynthetics have been embedded at the interface of the subgrade and the base course. Consequently, it was reported that the geosynthetic prevents the base course layer from penetrating into the subgrade [26]. A group of researchers evaluated the effectiveness of geogrid-reinforced flexible pavements to reduce the thickness of the base course [27]. In the cyclic plate loading test setup, they used a hydraulic actuator at a frequency of 0.77 Hz to provide a cyclic load of 40 kN through a 30.5-cm-diameter circular steel plate. As a result of their work, they reported that this type of test setup can be used efficiently and the base course thickness can be reduced if the base course layer is reinforced. The results of a series of small-scale cyclic plate loading tests evaluating the rutting performance of unpaved roads with and without geogrid reinforcement were presented by Jayalath et al. [28]. By placing the geogrid layer in the granular layer and at the interface of the base and subgrade, they performed cyclic plate loading tests on a granular base of varying thicknesses. According to their test results, they reported that the geogrid placed at the interface can reduce vertical deformation if the granular base thickness is thin. However, the findings of their small-scale tests are useful for planning and designing large-scale cyclic plate loading or field tests by simply optimizing the number of tests [29–32]. For more accurate findings, the literature emphasizes the importance of studying rutting with large-scale cycling loading tests. The accurate prediction of rutting is vital for the design of pavement and management; thus, a systematic monitoring of permanent deformation is required for the mechanistic-empirical design to ensure good performance of pavement under traffic loading and adverse climate conditions. Therefore, in this study, a large-scale cyclic plate load testing facility (Pavement model testing-PMT) was developed to investigate the effects of the base course's thickness and the geotextile, placed on soft clay soil, on the rutting. PMT was made for four different base layer thicknesses. Furthermore, an analytical solution was developed for the base layer thickness using the test results. Based on the test results, the behavior of the composite soil deposits subjected to cyclic loading was interpreted in detail.

2 Laboratory Testing Program

The laboratory testing program was carried out in the research center of Mersin 5th regional office of the General Directorate of Highways. In the PMT facility, the model pavement structure was constructed in a 2.0 × 2.0 × 2.0 m steel tank, and the wheel loading from the vehicle was simulated using a circular steel plate subjected to axial loading through an actuator assembly. A servo-hydraulic actuator, which has a dynamic force rating of 260 kN and a dynamic stroke of 200 mm, was attached between the two I-beams of the crosshead (Fig. 1). A cyclic load was applied through a steel rod that fit into a

hole on the loading plate that sat on the surface of base course layer. The loading plate was a 25.4-mm thick steel plate, 305 mm in diameter.

The maximum 40 kN load was applied in tests, which resulted in a loading pressure of 550 kPa and simulated dual tires under an equivalent 80 kN single-axle load. It is shown in Fig. 2 that the load pulse has a linear load increase from 2.2 to 40 kN in 0.3 s, followed by a 0.2 s period where the load is held constant at 40 kN, followed by a linear load decrease to 2.2 kN over a 0.3 s period and then followed by a 0.5 s resting period of 2.2 kN before the next loading cycle (total of 1.3 s/cycle). This load pulse results in a frequency of 0.77 Hz.

The testing program included four tests with varying layer thicknesses and applied maximum cyclic load. Details of these tests are summarized in Table 1.

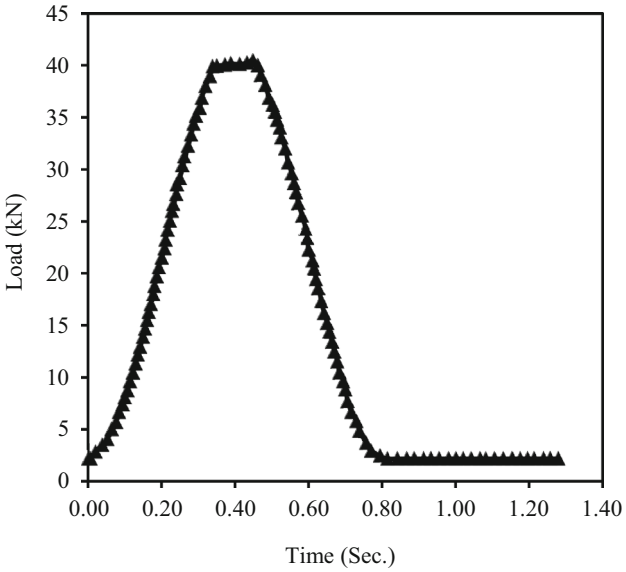


Fig. 2 Load pulse applied in the test

3 Material Properties

3.1 Subgrade Soil

The subgrade soil conditions at the construction site of Karatas Road were determined from a geotechnical site investigation including laboratory tests. Two test pit excavations were carried out to define the soil profile of the test site, and the groundwater level was observed as 1.80 m at the field. Two subsoil layers were clearly identified. The first layer of 0.60 m depth was observed as topsoil and the second layer between the depths of 0.60 and 3.0 m shows silty clay stratum with low plasticity (CL) according to the Unified Soil Classification System (USCS). Laboratory

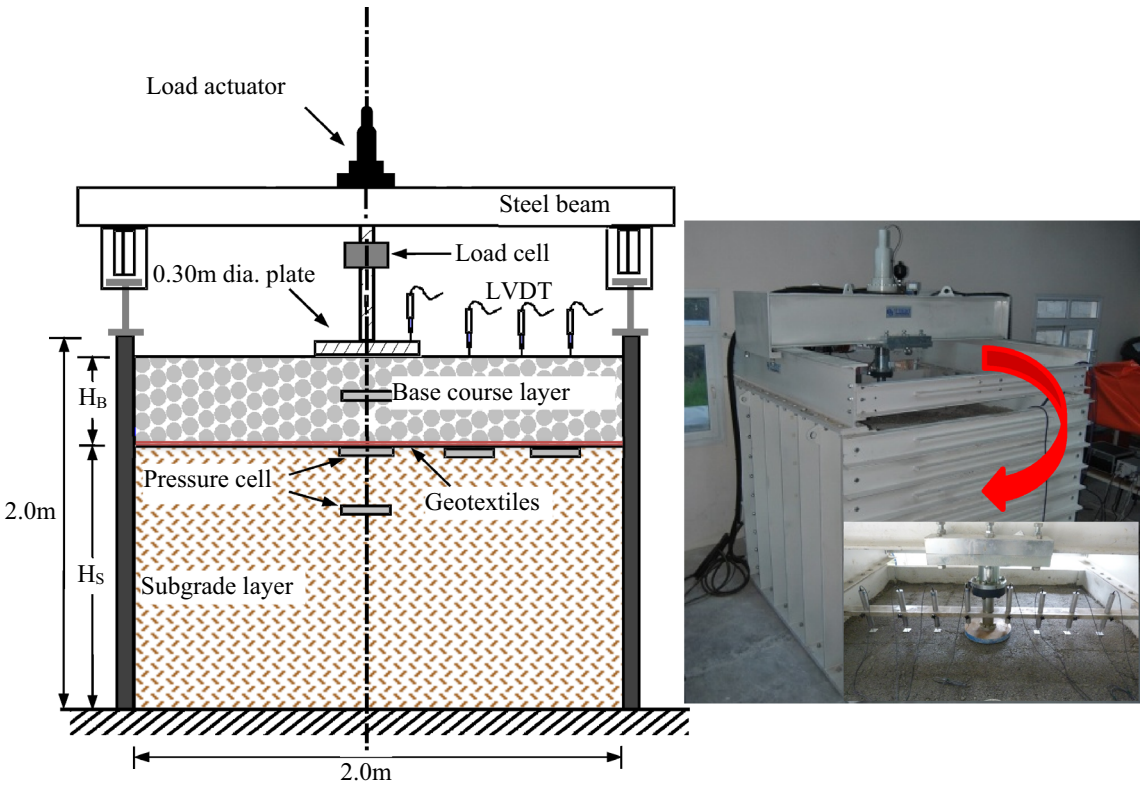


Fig. 1 Schematic view of PMT setup and laboratory test box, hydraulic actuator and reaction system

Table 1 Details of the laboratory test program

Test series	Base thickness (cm)	Subgrade thickness (cm)	Max. cyclic pressure (kPa)
Series I	20	165	551
Series II	30	155	549
Series III	40	145	550
Series IV	45	140	552

tests were conducted on representative subgrade soil samples for gradation, specific gravity, compaction parameters (optimum moisture content-maximum dry density) and California bearing ratio (CBR) value at optimum moisture content. From the laboratory tests, the clay content of the soil layers varies about 20%. The water content of the stratified soil layers varies between 20% and 25% depending on the depth, and is almost the same as or greater than, the plastic limit. Specific gravity values vary from 2.60 to 2.67 along the depths. Large scale direct shear machine (450 × 450 × 200 mm) manufactured by Utest Corporation, TURKEY was also used to perform the shear properties of subgrade and granular fill soils according to the ASTM D3080-98 [33]. These properties are summarized in Table 2. The particle size distribution and the relation between CBR and moisture content of subgrade soil are also shown in Fig. 3.

3.2 Granular Fill Bed

Some laboratory conventional tests to obtain the index and engineering properties were conducted on the granular fill material which was obtained from the Tarsus region situated east of Mersin, Turkey. Granular fill bed was prepared at a value of optimum moisture content of 4.1% and a maximum dry unit weight of 23.0 kN/m^3 obtained from the modified proctor test. The values of critical internal friction angle and the cohesion of granular fill were obtained as 51.12° and 11.0 kN/m^2, respectively from large-scale direct shear tests. The specific gravity of the granular fill was obtained as 2.64. Typical soil characteristics of granular fill material are given in Table 3. From the sieve analysis, granular soil was classified as well graded gravel-silty gravel, GW-GM according to the unified soil classification system. Figure 4 shows the particle size distribution and compaction properties of granular fill material.

Table 2 Properties of subgrade soil

Geotechnical Properties	Units	Value
Maximum dry density (γ_{kmax})	kN/m^3	17.94
Optimum moisture content (ω_{opt})	%	19
Liquid limit (LL)	%	28
Plastic limit (PL)	%	17
Plasticity index (PL)	%	11
Specific gravity (γ_s)		2.67
California bearing ratio (CBR) (for ω = 19%)		3–4
Large scale direct shear test		
Friction angle (°)	Degrees	25.85
Cohesion (c)	kPa	21.90
Resilient modulus (Mr)	MPa	52.94 (ω = 19 ± 0.5%)

3.3 Geosynthetics

The inclusion of geogrid/geotextile layer at the base-subgrade interface will enhance the bearing capacity of the subgrade layer, increases its resistance to shear failure, and help eliminate the differential settlement between the existing and new lanes [22].

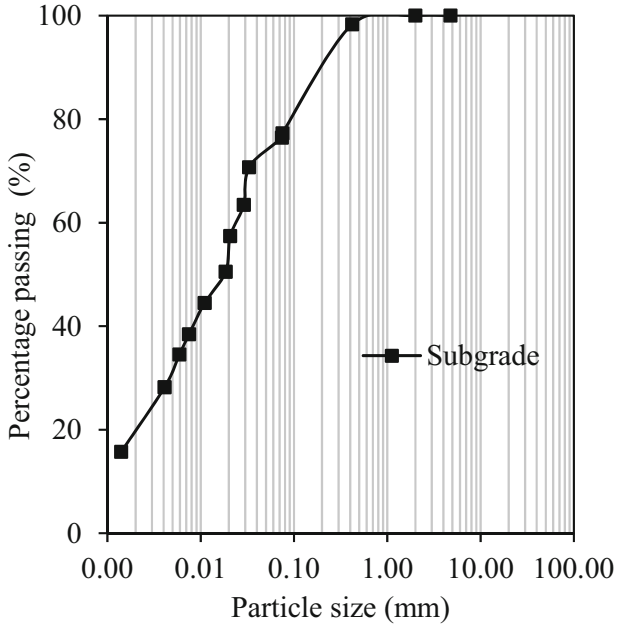
So, one type of geosynthetics was used in this research, a black colored high strength woven geotextile, GT. The physical and mechanical properties of the geosynthetics as provided by the manufacturer (Geoplas comp. from Turkey) are given in Table 4.

3.4 Preparation of Pavement Model Test (PMT)

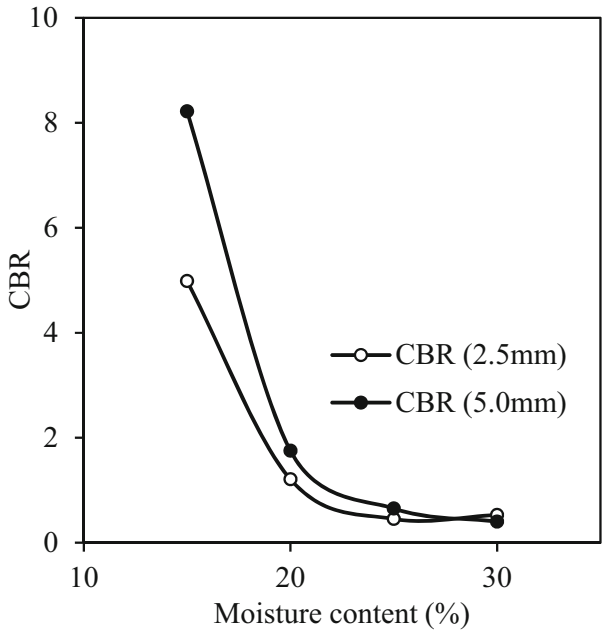
The silty clay subgrade was first placed inside the steel test box. The target dry density and water content of the subgrade were set to 17.00 kN/m^3 and 19 ± 1%, respectively, to achieve a weak subgrade of about CBR = 3–4 (estimated based on the DCP tests). The subgrade was prepared by using a tiller to mix the silty clay and water. Then, the silty clay was raked level and compacted using a 203 × 203 mm plate adapted to a vibratory jack hammer to the predetermined height (The thickness of each lift was 150 mm) to achieve the desired density. After the completion of subgrade preparation, the instrumentations including pressure cells were installed.

The high strength woven geotextile, placed at the base subgrade interface, was used to reinforce sections, which have a base layer thickness of 200–450 mm for all test series, respectively. The preparation details of test sections can be found in [34].

The base course layer was also prepared by placing the crushed limestone in 150 mm thick lifts, mixing with the



(a) Particle size distribution



(b) CBR values for different moisture contents

Fig. 3 Typical soil characteristics of subgrade soil material

desired water, and then compacting to the predetermined height. The target dry density and water content of the base course layer were 22.90 kN/m^3 (i.e. 98% degree of modified proctor compaction) and 4.3%, respectively. The nuclear density gauge and dynamic cone penetrometer (DCP) were deployed to measure the in-place properties of

Table 3 Geotechnical properties of granular fill layer

Geotechnical properties	Units	Value	
		Modified compaction	Vibratory compaction
Maximum dry density (γ_{kmax})	kN/m^3	23.00	23.55
Optimum moisture content (ω_{opt})	%	4.1	4.0
Liquid limit (LL)	%	N.P. (Non-Plastic)	
California bearing ratio (CBR)		252–246	
Los Angeles abrasion loss	%	30	
Water absorption	%	0.82	
Methylene blue test	%	1.25	
Large scale direct shear test			
Friction angle (°)	Degrees	62.07	
Cohesion (c)	kPa	26.46	
Resilient modulus (Mr)	MPa	94.56 ($\omega = 4 \pm 0.5\%$)	

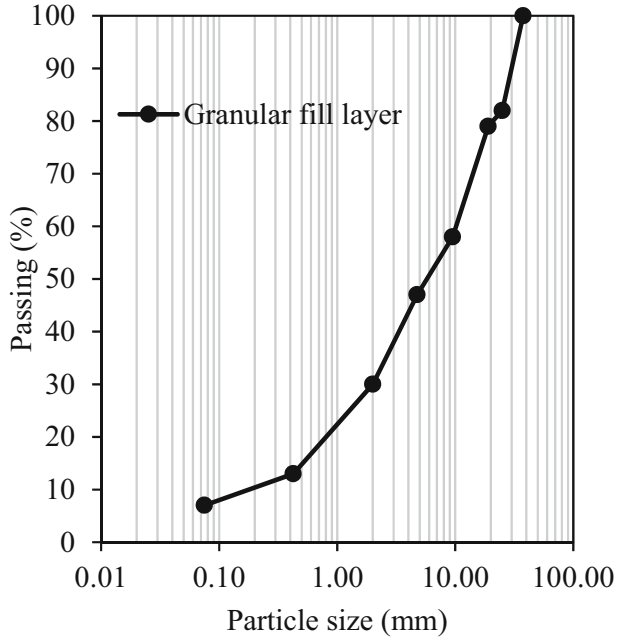
the subgrade layer to ensure quality control. The nuclear density gauge and sand cone tests were used to measure the in-place properties for construction control of the base course layer. At least three measurements were performed for each property. The mean values of these properties are summarized in Table 5 for all test pavement sections.

4 Test Results and Discussion

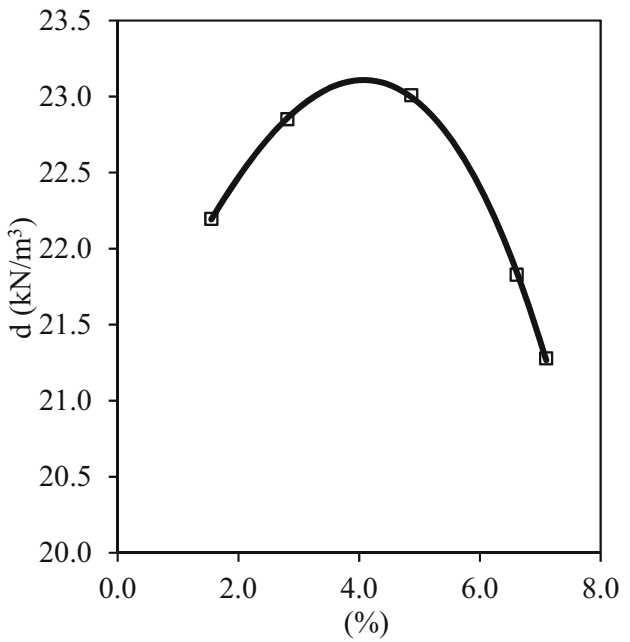
4.1 Interpretation of Test Results

Vertical displacements on the surface of the base course of the unpaved pavement system were measured at eight locations using displacement transducers as shown in Fig. 1. The recorded displacements of the loading plate (averaged from two displacement transducers) developing with the number of loading cycles during all the tests, which included accumulated permanent (plastic) deformation and resilient deformation (elastic rebound) are given in Fig. 5. Developments of permanent deformation at the base course surface level of unpaved pavement system with the number of load cycles for all tests are shown in Fig. 6.

Figure 6 clearly demonstrates that the soft soil behaviour can be improved by totally or partially replacing the inadequate soils with layers of compacted granular fill in terms of the improved sections exhibited a lower level of surface deformation than the unimproved sections. In other



(a) Particle size distribution



(b) Compaction curve

Fig. 4 The gradation and compaction curves of granular fill material

words, as can be seen from the figure, the subgrade layer makes a more significant contribution to the total permanent deformation, when compared to the base layer. Also, the use of geosynthetics resulted in reducing the permanent deformations, when it is placed at the base subgrade interface. This means that the geosynthetic at the base-subgrade interface mostly enhance the performance of the weak subgrade, i.e., it functions more as stabilizing the weak subgrade layer than reinforcing the base aggregate layer [8].

In most cases, the permanent deformation increases strongly with the number of load cycles at the beginning of cyclic loading, then the rate of deformation gradually gets slower. In order to compare with in situ or laboratory test results, there have been seen that the permanent deformation of subsoil was simulated using the some cumulative deformation models proposed by researchers in literature [35–39]. The variation curves of the permanent deformation with the number of load cycles seem close to the hyperbola, as shown in Fig. 7. So the relationship of the

Table 4 Engineering properties of geotextiles

Parameter	Value
Structure	Woven
Dynamical puncture resistance	13 kN
Static puncture resistance	3.5 kN
Unit weight	300 g/m^2
Thickness	0.85 mm
Characteristics opening size	195 µm
Raw material	polypropylene
Elongation at max. load	20%/16% (MD[a]/CD[b])
Tensile strength at 2% elongation	35/35 (MD[a]/CD[b])
Water permeability	16×10^{-3} m/s
Width	5.2 m

[a]Machine direction

[b]Cross machine direction

Table 5 In-place properties of subgrade and base course for different test sections

Test series	Subgrade		Base course		
	Average CBR (from DCP)	Average moisture content (%) (sample)	Average moisture content (%) (nuclear geuge)	Average density (kN/m^3) (nuclear gauge)	Relative compaction (%) (sand cone)
Series I	3.98	18.89	4.1	23.8	96
Series II	3.86	19.27	3.9	23.9	97
Series III	4.03	19.38	4.2	23.8	96
Series IV	3.89	18.96	4.3	24.0	98

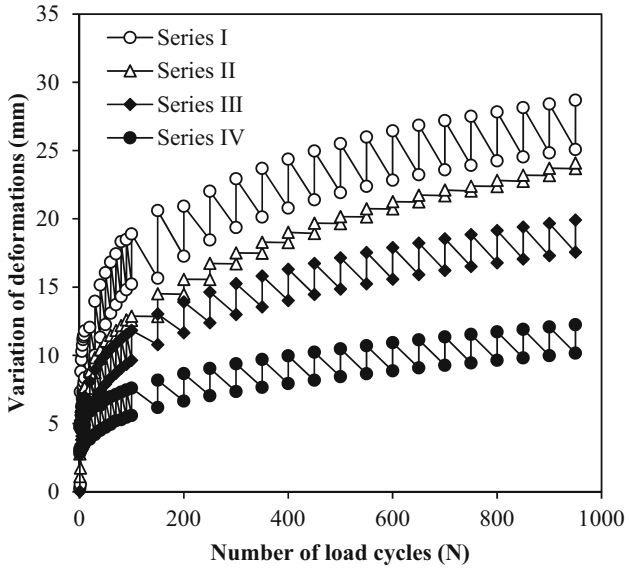


Fig. 5 Variation of deformations versus the number of loading cycles for different base layer thicknesses

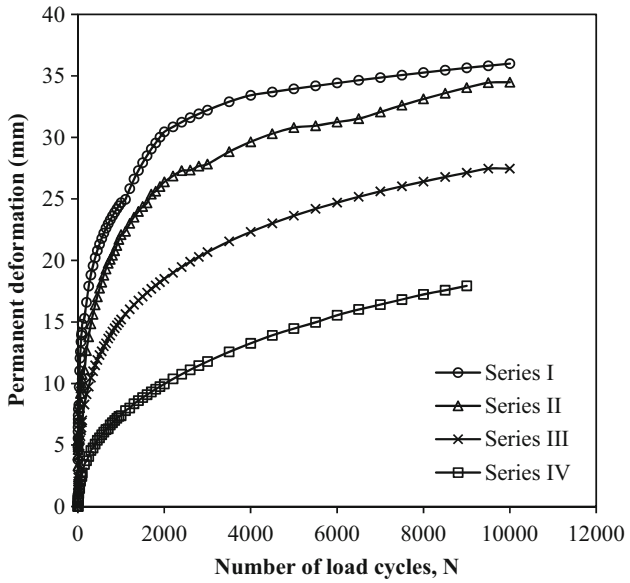


Fig. 6 Development of permanent deformation versus the number of loading cycles for different base layer thicknesses

permanent deformation to the number of load cycles can be fitted with the hyperbolic equation as follows:

$$\mathrm{PD} = \frac{N}{a + b \times N} \tag{1}$$

where PD, permanent deformation; N, number of load cycles; a and b, test parameters depend on soil layers' geotechnical properties (such as water content (%), CBR, unit weight, i.e.)

The permanent deformation generated from the first load cycle PD_1 is equal to the converse of a. If N approaches the

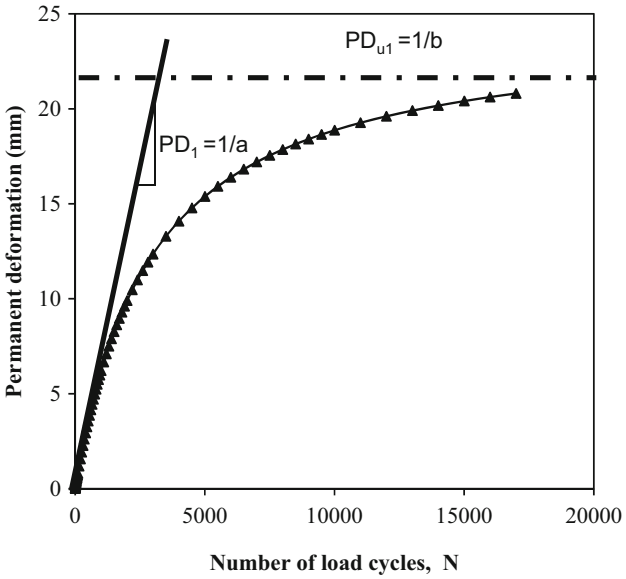


Fig. 7 The behavior shape of the permanent deformation with the number of load cycles

infinity, the deformation tends towards the ultimate value PD_{ul}, and PD_{ul} is equal to the converse of b. For the different thicknesses of the base course, the fitting parameters are shown in Table 6. PD_1 and PD_{ul} decrease with the increase of the base course thickness. The ultimate permanent deformation, PD_{ul} can be used to evaluate the potential of traffic-load-induced cumulative permanent deformation of subsoil.

Figure 8 shows the comparisons of permanent deformation between laboratory large scale tests and empirical models proposed by predecessors (based on Table 6). It can be seen that the trend of tested settlement with the number of load cycles is consistent with the calculated results. In general, the calculated settlements develop faster than the measured ones during the early stage of cyclic loading. Especially, when the number of load cycles increases for Series III and IV, it understood that the differences will be obvious.

The permanent deformation on the base course layer is also calculated by an empirical equation, in which constants are related to the physical and mechanical properties

Table 6 Fitting parameters for different base course thickness

Base course thickness, H_B (cm)	a (cm^{-1})	b (cm^{-1})	PD_1 (cm)	PD_{ul} (cm)
Series I (20)	120	0.265	0.0083	3.80
Series II (30)	200	0.275	0.0050	3.40
Series III (40)	330	0.330	0.0030	2.80
Series IV (45)	1200	0.410	0.0008	2.30

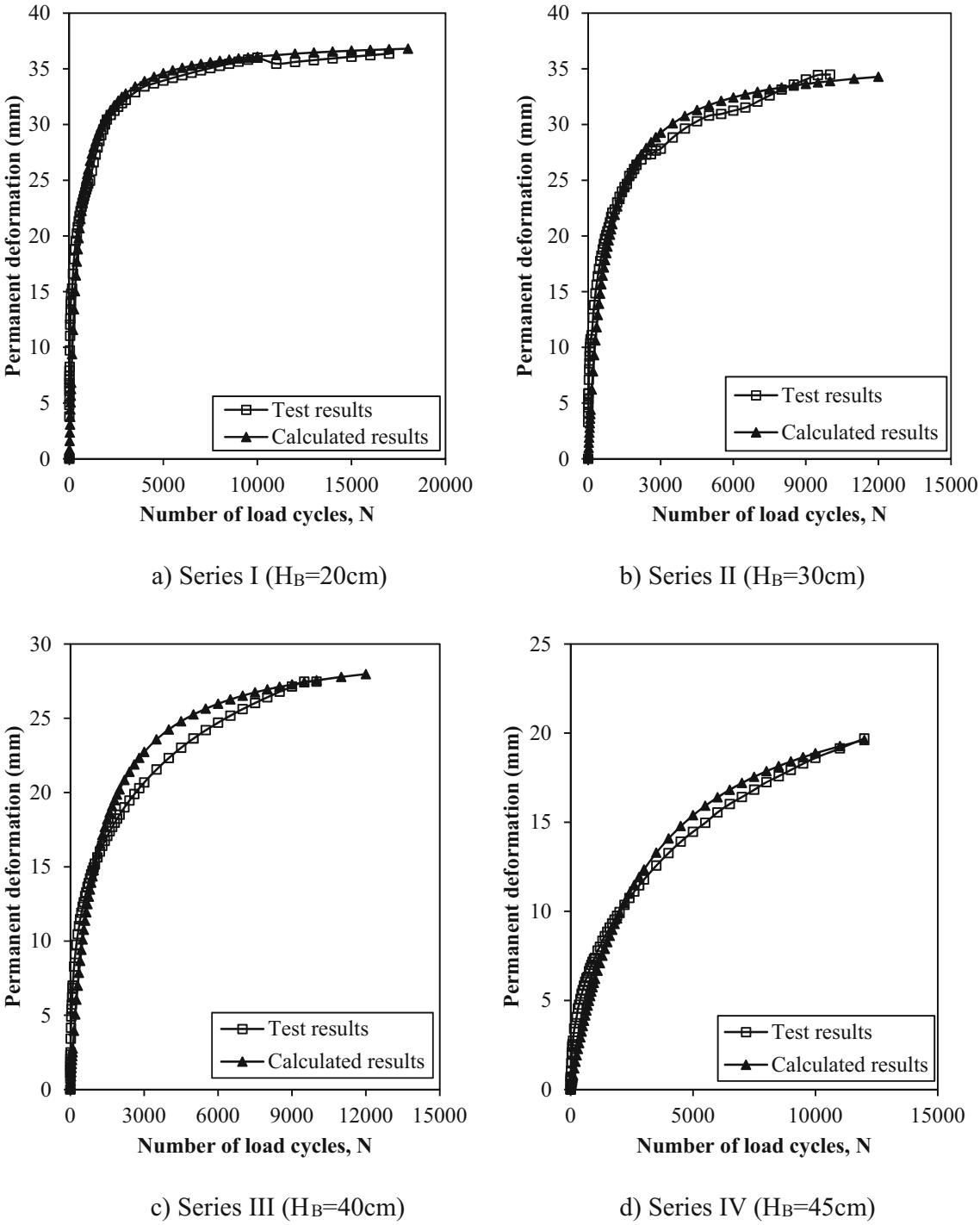


Fig. 8 Comparison of calculation and test permenant deformation results for different base layer thicknesses

of base/subbase soil (based on conventional laboratory tests).

Permanent deformation is generally expressed in terms of the number of load cycles [40]. However, it is suggested that the following general rutting model for the stabilized base layer was derived in terms of stiffness modulus, applied pressure, layer thickness, and the number of load cycles similar to the pavement structure [41].

$$\mathrm{Rut} = d \times (0.5 \times H_B + H_S) \times e^{(3.619 \times P)} \times \left(\frac{E_S \times E_B}{E_S + E_B}\right)^{1.4847} \times N^{(0.310 \times R_T)} \quad (2)$$

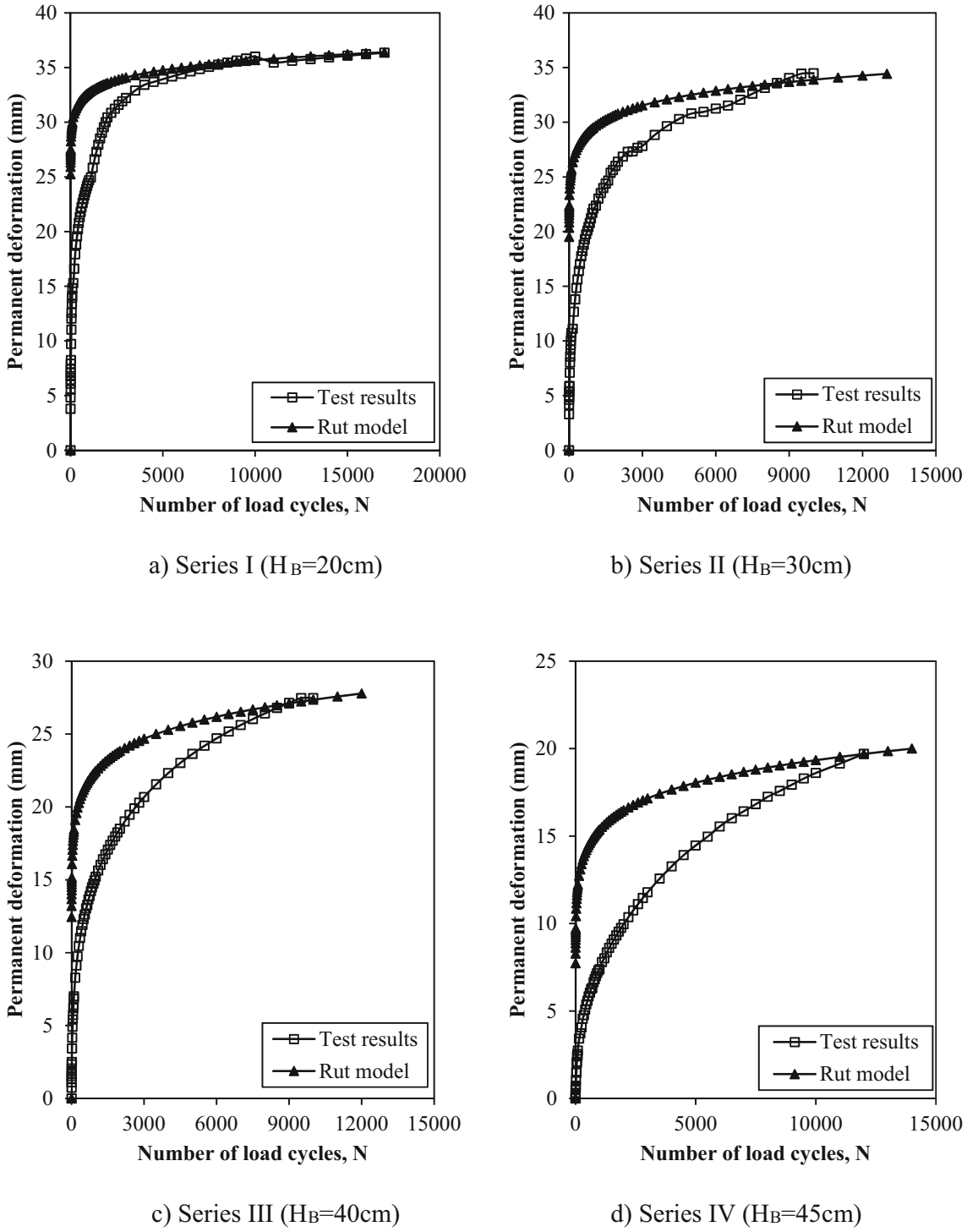


Fig. 9 Comparison of rut model and test permenant deformation results for different base layer thicknesses

where E_B and E_S = vertical stiffness modulus of the base layer and the stiffness modulus of the subgrade respectively; P = applied pressure in GPa; R_T = thickness ratio (i.e., the ratio between the thicknesses of base and subgrade); N = the number of load cycles; and d is a constant.

The results in Fig. 9 show that the calculated permanent deformations from the rut model became a little higher than their measured values until approximately 10,000 load cycles for all test series. In other words, a rapid increase in permanent deformation obtained from rut models was observed during an initial phase, to approximately 1000

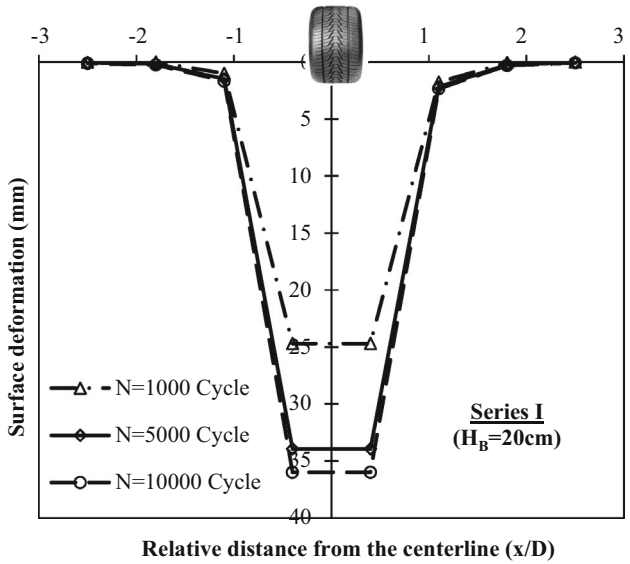


Fig. 10 Profile of surface deformation with the number of load cycles

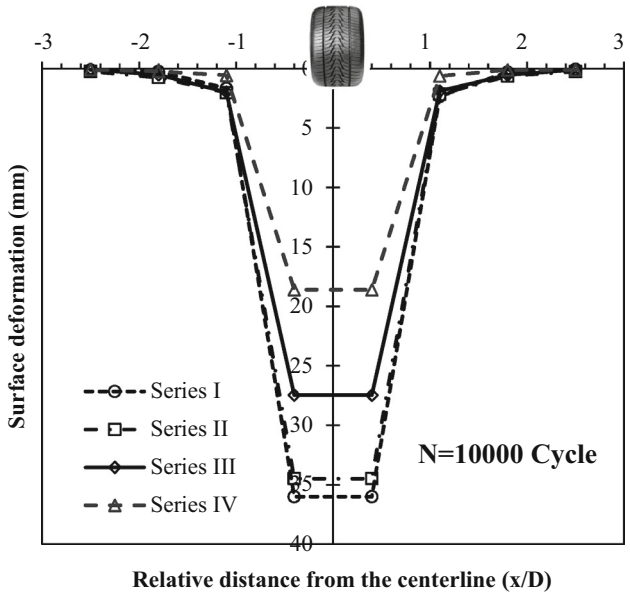


Fig. 11 Profile of surface deformation for different base layer thicknesses

load cycles, and then the rate of increase slowed for all test series.

However, as seen in Fig. 9 that the comparisons of the calculated values with experimental results indicate that the proposed method can generally provide a reasonable prediction of cyclic load-induced permanent settlement of the road on soft subsoil with a low embankment. As seen in Figs. 10, 11 that the improved sections formed by increasing the filling layer exhibited a lower level of surface deformation.

The vertical stress distribution at $z/D = 2$ below the base surface and along the centerline of the loading plate at the

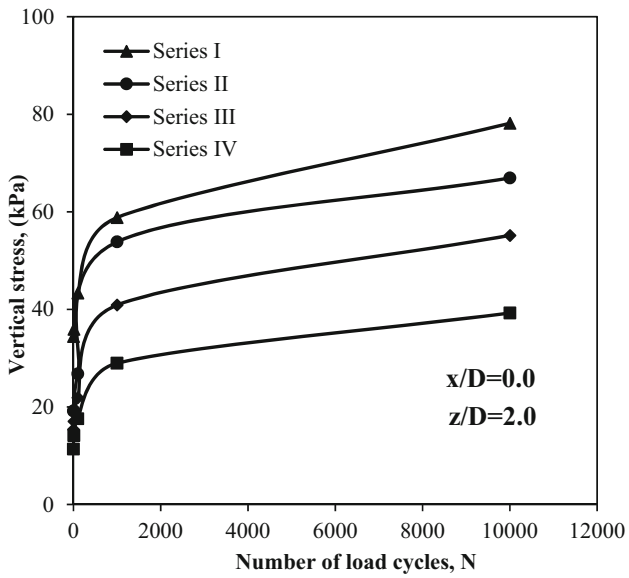


Fig. 12 Vertical stress distribution for different base layer thicknesses

end of 10,000 cycles for different thickness of base layer sections are shown in Fig. 12. The stresses measured were the total vertical stresses that it was obtained during the peak load for each cycle, and the stresses caused by the weight of the soil are not included.

Vertical stress development in relation to the number of load cycles appeared to consist of two phases in all series, a rapid increase in vertical stress was observed during an initial phase, to approximately 2000 load cycles, and then the rate of increase was continued more slowly. However, in Series I, the rate of increase slowed but was still comparatively higher than it was in the other tests. The figure also shows that the load was redistributed to a wider area in the improved test sections, resulting in an improved stress distribution on top of the subgrade layer when geotextiles and the thicker base layer were installed.

It is considered that rutting can occur for a number of reasons [20]. Fundamentally, there are three contributory mechanisms, which are here, labeled as Modes 0, 1 and 2. In the most of tests, the mode of failure can be described as a local shear failure in the subgrade layer (Mode 2) as the base layer is especially thinner. The surface deformation pattern of Mode 2 failure is of a broad rut with slight heave remote from the wheel. In other words, the surface rut has been repeatedly infilled, but rutting at the subgrade surface has continued with the base layer following this. It is considered that the solution to this type of rutting is to improve with geosynthetics or increase the base layer thickness so that the wheel loads are spread better. So, then the stress on the subgrade will be less. Another method is to restrict high axle loads (not tyre stresses) as these are the principal influences on stress in depth.

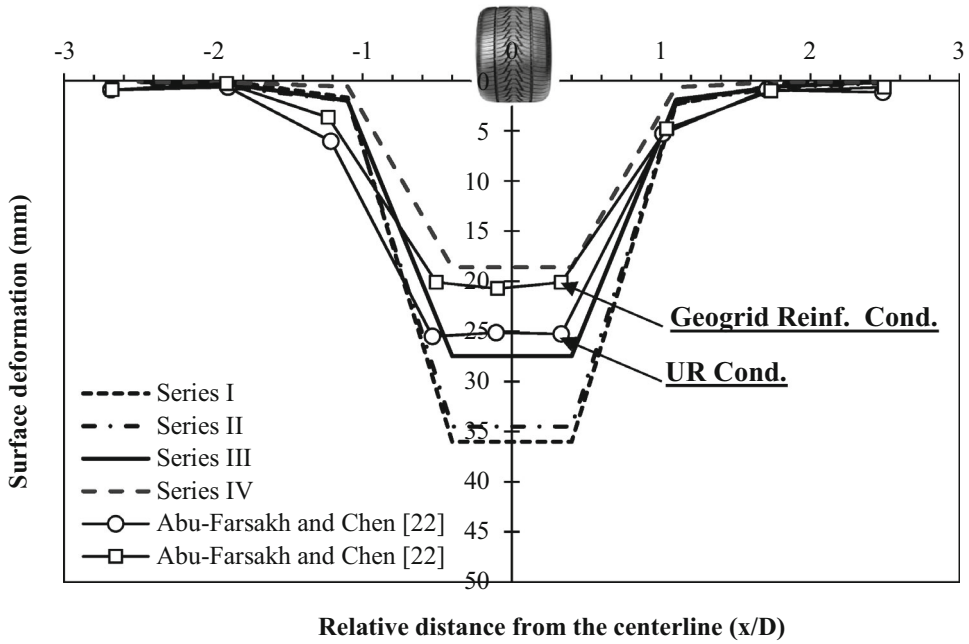


Fig. 13 Comparison of results of test and different studies for surface deformation

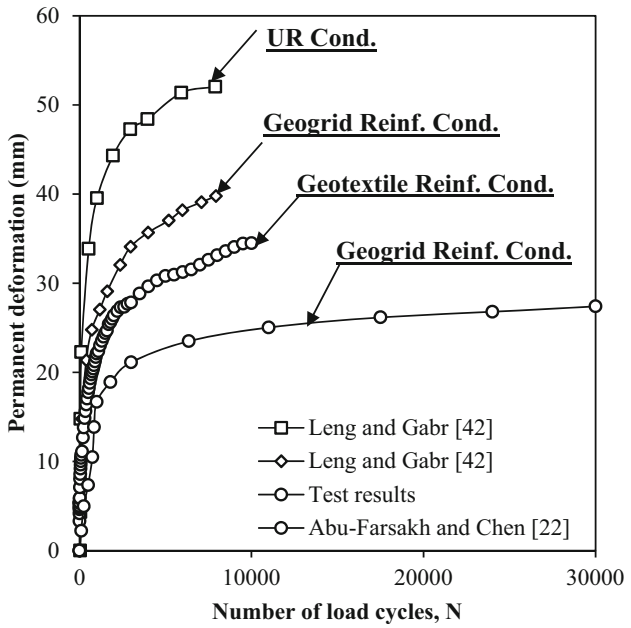


Fig. 14 Relationship between test result and different studies for geosynthetic reinforcement

For permenant settlement condition, experimental results are compared with typical design parameters presented based on a comprehensive study of experimental data in Figs. 13 and 14. As seen from the figures that test results are roughly in agreement with other studies for geosynthetic reinforcements. The benefit of using geosythetic reinforcements to reduce the rut depth of pavement sections has been clearly demonstrated through laboratory cyclic plate load tests and the other studies in the literature [22, 42].

5 Limitations of Research Program

While this study is one of the large-scale load test program on geotextiles reinforced pavement structure to date, there are several limitations that should be mentioned. First, the tests were conducted on only one soil type. The results observed from this test program may be different for other soils. Only one type of geotextiles reinforcement was evaluated; the results are therefore specific to the reinforcement tested. Other geosynthetics (such as geogrid, geotextile, and geocell) may perform very differently. Additionally, only large scale laboratory tests were conducted. As the effect of real conditions is considered, field tests should also be included in future works. The findings obtained from this study will be of use for designing and constructing, low volume roads founded on soft soils, large stabilized areas for parking of vehicles, etc. The investigation is considered to have provided a useful basis for further research leading to an increased understanding of the bearing capacity and subgrade modulus variation of pavement structure resting on geotextiles reinforced granular fill over clay soils.

6 Conclusions

The following are the most significant takeaways from the results of large-scale cyclic plate loading tests, including analytical approaches:

- As the thickness of the compacted granular fill with geotextile increased, the degree of permanent surface deformation (rutting) decreased dramatically. Additionally, the growing number of load cycles demonstrated how rutting considerably decreased as base layer thickness increased. For all tests, the increase in permanent deformations was minimal after 5000 loading cycles.
- For all tests, a rapid increase in vertical stress was observed up to 2000 loading cycles, and then the rate of increase continued more slowly. Besides, when the base layer thickness was at its greatest, the lowest vertical stress values were recorded.
- The local shear failure (Mode 2) was observed in the tests. It is considered that the solution to this type of rutting is to increase the number of layer of geosynthetics or the base layer thickness so that the wheel loads are spread better.
- For the tested pavement systems, the permanent deformations measured in large-scale laboratory tests and those obtained through empirical approaches exhibited similar development trends. Nevertheless, the large-scale laboratory tests, as proposed in this paper, are a meaningful tool for a more accurate prediction of permanent deformations, as there are some limitations to the empirical models.

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Data availability The data presented in this paper can be given by the authors upon request.

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