The Prediction of Permanent Deformation of Fine-Grained Soils Using Multiple Linear Regression: Dummy Variables

Mohammad Ali Khasawneh
Civil Engineering, Prince Mohammad Bin Fahd University, Al Azeziya, Eastern Province, Kingdom of Saudi Arabia
Email: mkhasawneh@pmu.edu.sa

Rabea Saleh AL-Jarazi
Civil Engineering Department, Jordan University of Science and Technology, Irbid, Jordan
Email: aarabea14@eng.just.edu.jo

***Abstract*—Under repeated traffic loading, knowledge and understanding of cumulative permanent deformation and failure mechanisms for subgrade soils (fine-grained soils) are crucial for the proper design and maintenance planning of pavement structures. In other words, considering the great contribution of subgrade soils to the overall performance of pavement structures, it is crucial to provide the best prediction of permanent deformation behavior. This paper presents a new predictive equation for the permanent deformation of fine-grained soils (A-4a and A-6a soils) utilizing the dummy-variable multiple linear regression technique. The permanent deformation (PD) results revealed that A-4a at OMC exhibited the least plastic deformation versus the highest plastic deformation assigned to A-6a compacted at 2% wet of OMC. The results obtained could be used to help engineers in characterizing fine-grained materials. As per the statistical analysis carried out in this study, the dummy regression for permanent deformation did not greatly improve the prediction power of the model.**

***Index Terms*—pavements, fine-grained soils, permanent deformation, dummy regression**

I. Introduction and Background

In pavement structure, one very important cause of failure lies in the pavement materials. Subgrade soil, which represents the pavement foundation, is of key importance in the pavement structure. How strong, stiff, and saturated this layer is will control the overall pavement performance. The main function of subgrade soils is to provide support to pavement structures. Under heavy traffic loads, subgrade soils contribute to permanent deformation (rutting) and fatigue cracking, the two major distress modes in flexible pavements (Fig. 1).

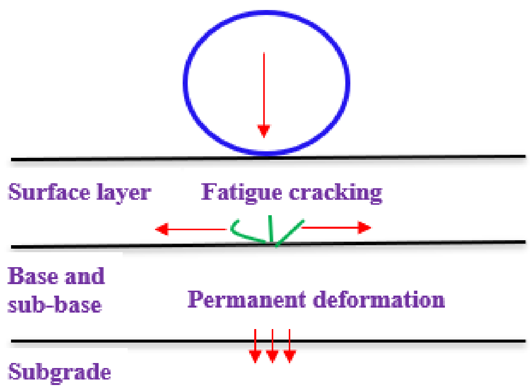

Figure 1. Schematic of a typical pavement structure

Permanent deformation and cracking are accumulated damages done to the pavement structure over load repetitions and are non-recoverable in nature, hence, leads to reducing the service life of pavements, and affecting the durability, stability and safety of pavement structures. Furthermore, traffic loading in pavement analysis is conventionally simplified as a cyclic deviator stress (σ_d). The repeated application of the σ_d results in permanent strain (ε_p) and resilient strain (ε_r) within pavement materials, as shown in Fig. 2.

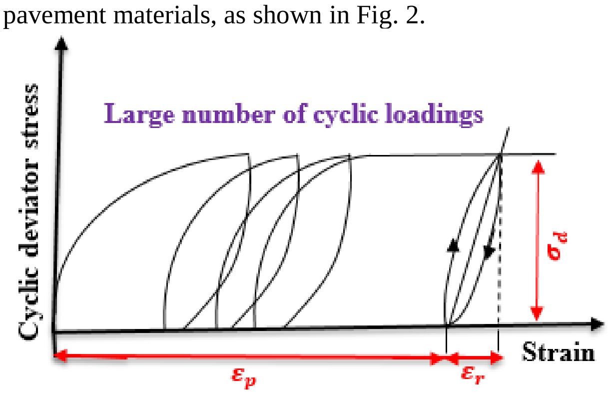

Figure 2. Response of soils to cyclic deviator stress

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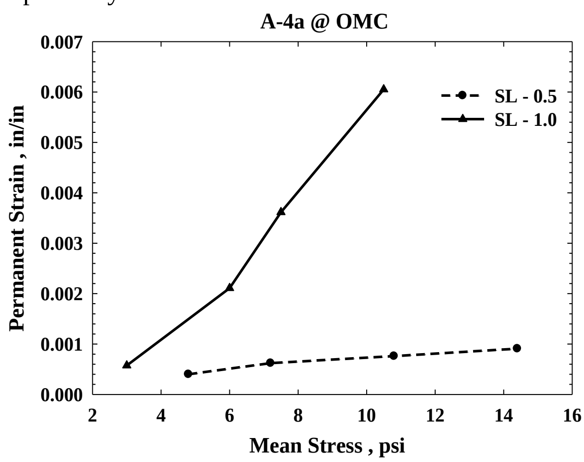
As per the Mechanistic-Empirical Pavement Design Guide (MEPDG) and the American Association of State Highway and Transportation Officials (AASHTO), the resilient modulus (M_R) and the permanent deformation (PD) of subgrade material have the most significant effect on designing pavement structures [1-4]. Therefore, studying the permanent strain characteristics of subgrade soils (fine-grained soils) under repeated vehicular loading is important for the effective and economical design of flexible pavements.

Literature has shown that the amount of PD in each load repetition is dependent on the stress level. This is also influenced by various factors such as grain size distribution, degree of compaction, moisture content, stress history and aggregate type [2,4-7]. For instance, Ishikawa et al. concluded that the accumulated PD increased due to saturation and water content significantly affects mechanical behavior of soils [8]. Rodgers et al. reported that more rutting occurred in sandstone aggregates when a 10 mm rainfall was simulated compared to the dry state [7]. Van Niekerk reported that higher axial stresses are required to produce the same amount of permanent axial strain in samples with 103% degree of compaction versus 97% [9]. Further, it was found that the resistance of soils to permanent deformation under repeated wheel loading is generally improved with increasing density [10]. Mishra et al. concluded that fines content directly related to amount of PD produced in granular materials [11]. In addition, Anupam, et al. studied the effect of admixing fly ash and rice husk ash on permanent deformation behavior of subgrade soils A-7-6 under cyclic triaxial loading [12]. For predicting PD of pavement materials, several researchers have proposed different models, such as Erlingsson and Rahman model [13], Rahman and Erlingsson model [14], Joseph model [15] and Korkiala model [16].

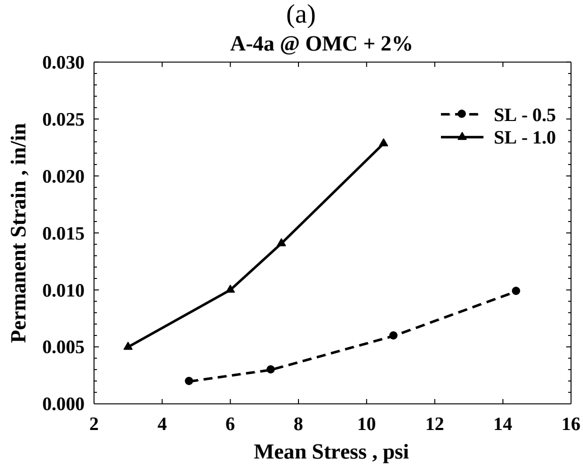
Although all pavement layers contribute to the overall permanent deformation of the pavement system. Yet, subgrade, where cohesive or fine-grained soils are used, does not attract as much attention as do the asphalt surface and granular base. Therefore, the purpose of this study is to investigate some of the factors (different levels of moisture content and stresses) that affect the PD of fine-grained soils (such as A-4a and A-6a) and develop statistical models to predict the PD of fine-grained soils. The experimental results of permanent deformation were obtained using triaxial tests following the AASHTO T307-99 procedures [17].

II. Results and Discussion

Permanent deformation of fine-grained soils under repeated loading is characterized by a rapid increase in deformation during the first cycle, followed by gradual stabilization. The amount of deformation depends on the characteristics of the material and the applied load. Fig. 3a shows the accumulated permanent deformation of A-4a soil at optimum moisture content (OMC) and at different stages of loading for two stress level ratios of 0.5 and 1, respectively. Similar plots were developed for the A-4a at 2 % wet of optimum, A-6a at OMC, and A-6a at 2 % wet of OMC, respectively. Fig. 3b shows the permanent deformation behavior of A-4a compacted at 2 % on the wet-side of OMC at different stress levels. At higher stress ratio, a rapid increase in strain is observed. Likewise, Fig. 4a shows plots of A-6a at OMC and Fig. 4b show plots of A-6a soil compacted at 2 % wet of optimum for permanent deformation versus mean stress, respectively.

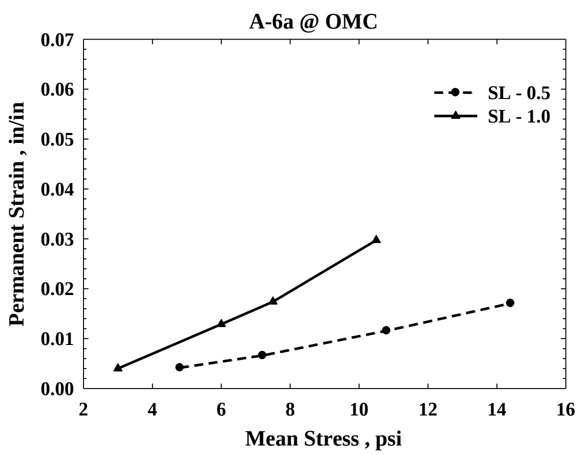


(a)

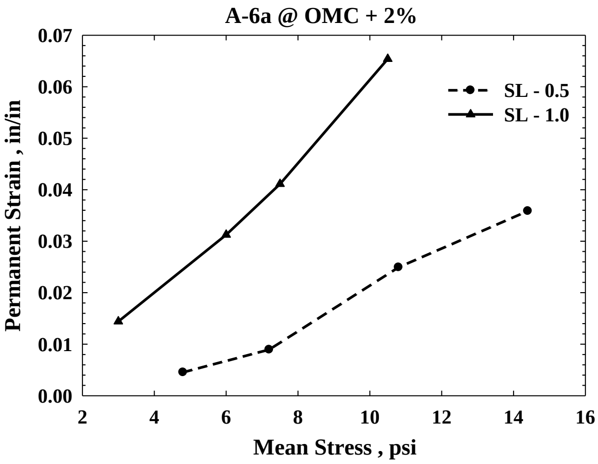


(b)

Figure 3. Permanent strains versus mean stress for A-4a soil at optimum moisture content (a) and for A-4a soil at 2% wet of optimum (b)



(a)



(b)

Figure 4. Permanent strains versus mean stress for A-6a soil at optimum moisture content (a) and for A-6a soil at 2% wet of optimum (b)

From Figs. 3 and 4, it can be seen that at lower stress level ratio there is gradual stabilization, particularly for A-4a materials, while at higher stress level ratio the deformation increases rapidly for both soils used in this study indicating the possibility of rutting accumulation over time.

The results of permanent deformation modeling for all types of soil show good models to predict the permanent deformation with R^2 varying from 67% to 91% with linear model but with less normality when the log inverse function is used to represent the data. When log inverse function is used to represent data, normality is increased; Durbin-Watson values increase from 0.64 to 1.25 with relatively high coefficient of determination (R^2) values ranging from 76% to 85%. The results show no improvement when dummy variable multiple linear regression is used and thus not presented in the paper. Table I shows the permanent deformation modeling results.

TABLE I. PERMANENT DEFORMATION MODELING RESULTS

Type of soil	Mathematical Model	R^2	Sig	F	Durbin Watson
With linear modeling					
A-4a @ OMC	PD=-0.002+0.003SL	0.67	0.062	5.1	0.64
A-4a 2% wet of OMC	PD=-0.01+0.002P+0.13SL	0.76	0.027	8.1	0.94
A-6a @ OMC	PD=-0.01+0.002P+0.11SL	0.84	0.010	13.6	0.76
A-6a @ 2% wet of OMC	PD=-0.024+0.005P+0.031SL	0.91	0.002	26.5	0.86
With inverse log mean stress P'					
A-4a @ OMC	PD=0.004-0.003P'+0.003SL	0.80	0.010	9.7	1.25
A-4a 2% wet of OMC	PD=0.02-0.015P'+0.03SL	0.76	0.020	7	1.74
A-6a @ OMC	PD=0.031-0.019P'+0.011SL	0.83	0.010	12.4	1.82
A-6a @ 2% wet of OMC	PD=0.064-0.041P'+0.03SL	0.85	0.009	14.1	1.83
PD: Permanent Deformation; P: mean stress; SL: Stress Level					

III. CONCLUSIONS

Permanent deformation properties of fine-grained subgrade materials are of key importance in evaluating the entire pavement structure performance. Permanent deformation tests were conducted at different stress levels with large number of load repetitions. The permanent deformation results showed that A-4a at OMC exhibited the least plastic deformation versus the highest plastic deformation assigned to A-6a compacted at 2% wet of OMC.

The degree of moisture content along with the deviatoric stress had a significant effect on the fine-grained materials; with the increase in one of these factors or both, an increase in permanent deformation is highly expected.

As per the statistical analysis carried out in this study, the results for all types of soil showed good models to predict the permanent deformation with high enough coefficient of determination values. The dummy regression for permanent deformation did not improve the model's predictive power and therefore was ignored.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

MAK conducted the experimental work and data compilation, literature review, set the study layout and reviewed and wrote the final version of the paper; RSA analyzed the data and helped write the draft version of the paper; … all authors had approved the final version.

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Mohammad Ali Khasawneh was born in Jordan on August 17th 1980. Dr. Khasawneh has M.Sc. and Ph.D. degrees in civil engineering from the University of Akron, Ohio, USA in the years 2005 and 2008, respectively, and B.Sc. degree in civil engineering from Jordan University of Science and Technology (JUST) in 2003. He is an Associate Professor of civil engineering at Prince Mohammad Bin Fahd University (PMU), Kingdom of Saudi Arabia. His research interests include highway materials and he is interested in educational technology research and development. Dr. Khasawneh is a graduate of the Excellence in Civil Engineering Education (ExCEEd) program. He is a member of the American Society of Civil Engineers (ASCE), Institute of Transportation Engineers (ITE), American Society of Engineering Education (ASEE) and Jordan Engineers Association (JEA).

Rabea Saleh AL-Jarazi was born in Yemen on January 1st 1986. Eng. Rabea has B.Sc. in civil engineering: highway and bridge engineering from Al-Balqa' Applied University (BAU), Amman, Jordan, in 2013, and M.Sc. degrees in civil engineering from Jordan University of Science and Technology (JUST) in 2018. Currently, he is pursuing his Ph.D. degree at Southwest Jiaotong University, Chengdu, China. He is interested in studying pavement materials and design.