EVALUATION OF THE EFFECTIVENESS OF GEOTEXTILE SEPARATION AND FILTRATION IN MITIGATING PUMPING OF SUBGRADE PARTICLES INTO OVERLYING GRANULAR LAYERS IN PAVEMENT SYSTEMS

B. Kermani [1, 2], M. Xiao [1], S. M. Stoffels [1]
Institution: [1] The Pennsylvania State University – [2] The Transtec Group, Inc.

ABSTRACT

Subgrade fines migration, also known as pumping, negatively affects the performance of pavements due to decreased drainage capability, reduced pavement stability, increased permanent deformation, and gradual creation of nonuniform foundation support conditions. The issue of infiltration of fines and the resulting base course contamination have become even more problematic considering the age of the roadways and the increasing levels and magnitude of traffic. Therefore, pumping is considered an important failure mechanism of pavements and should be taken into consideration when designing the pavement or monitoring it during its service life. This paper presents the results and findings from research studies undertaken to determine magnitude and rate of migration of subgrade soil particles into subbase and to evaluate the effectiveness of geotextiles separation and filtration in reducing such migration, in both flexible and rigid pavement systems. A one-third scale Model Mobile Load Simulator (MMLS3), an Accelerated Pavement Testing (APT), was used to apply simulated traffic loading on pavement sections. Analyses were conducted to identify the thickness of stress-equivalent scaled pavement sections, such that the vertical compressive stress at the top of the subgrade (i.e., subgrade and subbase interface) under the wheelpath of MMLS3 were equivalent to the stress in corresponding full-scale pavement sections. Pavement sections were constructed on a bed of non-plastic saturated silt as subgrade and partially saturated aggregate subbase. Earth pressure cells and dynamic pore water pressure cells were installed at different locations of the pavements to measure total stress and excess pore water pressure generated by cyclic traffic loadings and to validate the stress equivalency. A total of six sets of MMLS3 tests were carried out to quantify the magnitude and rate of pumping for flexible and rigid pavement on typical collector roads and interstate highways. The experiments were repeated by using a geotextile separator and filter layer at the interface between subgrade soil and aggregate subbase. The results revealed that due to cyclic traffic loading, considerable subgrade fines migrated into subbase. The migration was affected by the traffic-induced downward pressure at the interface, which varied in different pavement types (flexible, rigid) and classes of roadways (collector and interstate). Pumping was also affected by the number of traffic cycles. It was observed that geotextile effectively reduced pumping in pavements. This is because of a significant decrease in the pore water pressure (a key erosional force) developed at the subgrade-subbase interface due to presence of geotextile. This study was supported by Geosynthetic Institute (GSI), PennDOT, and FHWA. The outcomes are anticipated to lead to revised policies for the use of geotextiles for subgrade-subbase separation, leading to improved performances and service life of pavement systems.

Keyword: Geotextile, Pumping, Pavement, Subgrade Fines Migration, MMLS3

1. INTRODUCTION

To properly design and rehabilitate pavement systems, it is necessary to consider possible failure mechanisms that may occur over their life span. Pumping of subgrade fines is an undesirable mechanism in a pavement system, which can lead to its failure (Christopher et al. 2006). Pumping is defined as the infiltration of subgrade fines into the overlying granular layers of pavements under cyclic traffic loads (Alobaidi and Hoare 1994). Development of pore water pressure at the subgrade-subbase interface, due to cyclic traffic loading, is known as the key contributor to this phenomenon (Alobaidi and Hoare 1996, 1999). Only a few experimental studies have been conducted to investigate subgrade pumping (Alobaidi and Hoare 1994; Henry et al. 2013; Kermani et al. 2019a; Trani and Indraratna 2010). In rigid pavement specifically, in addition to vertical pumping, horizontal pumping occurs, which may cause loss of slab support as a result of formation of voids underneath the slab and leads to a loss of joint stiffness or load transfer (Jung et al. 2009). Due to pumping and the resulting gradual clogging of granular layers of pavements, their drainage capacity and stability are reduced, which in turn may cause their failure (Holtz et al. 2008).

Separator layers can improve performance of a pavement by preventing subgrade fines from infiltrating into the overlying permeable subbase, thus maintaining the permeability of this layer (Al-Qadi and Appea 2003; Christopher et al. 2006). A separator layer may respectively decrease rut and fault formation in flexible and rigid pavements, and reduce the required thickness of granular layers, which has significant economic advantages (Hufenus et al. 2006). Throughout the history of pavement design, increasing the thickness of subbase and using material such as sand between subgrade and subbase have been found effective in controlling subgrade pumping. However, those methods were found to be relatively cost prohibitive (Guram et al. 1994). As an alternative to granular filter layers, a properly selected geotextile, due to its high apparent opening size and clog resistance, can provide effective and economical means of separation and filtration. Alobaidi and Hoare (1994) indicated that little effort had been made to investigate the preventive capability of geotextile against pumping as a result of filtration and separation together. Koerner and Koerner (2015) discussed several case histories of clogging of inappropriately selected geotextile in contact with fine-grained soils. Brosson and Eriksson (1996) suggested that a certain type of geotextile, might be effective in controlling subgrade pumping under cyclic traffic loading. Zornberg and Thompson (2012) indicated that a geotextile placed between the aggregate and the subgrade acts as a separator can minimize contamination of the aggregate base by the subgrade. This paper presents results and findings from research studies carried out to quantify magnitude and rate of migration of subgrade soil particles into subbase and to evaluate the effectiveness of geotextiles in reducing such migration. A one-third scale Model Mobile Load Simulator (MMLS3), a small-scale accelerated pavement testing (APT), was used to apply simulated traffic load on pavement sections. Pavement systems were designed such that the stresses generated at the subgrade-subbase interface in the lab and in the field were equivalent. Pavement sections were constructed on a bed of non-plastic saturated silt as subgrade and partially saturated subbase. Earth pressure cells and dynamic pore water pressure cells were installed at different locations of the pavement to measure total stress and excess pore water pressure caused by dynamic traffic loadings and to validate the stress equivalency. A total of five sets of MMLS3 tests were conducted to determine the magnitude and rate of pumping for flexible and rigid pavement on a typical collector road and interstate highway. The tests simulating rigid interstate highway and flexible collector road were repeated with a geotextile separation and filtration layer that was placed at the interface between subgrade soil and aggregate subbase to evaluate the efficacy of geotextiles in reducing pavement pumping. In this paper, a summary of the material used and test preparation followed by discussion of the results are presented.

2. MATERIALS AND METHODOLOGY

2.1 Materials

The subgrade material consisted of a non-plastic silt with 56.0% (by mass) of particles passing from No. 200 (0.075-mm) sieve, 95% passing from No. 10 (2.00-mm) sieve, and 100% passing from 3/8-inch (9.5-mm) sieve. Maximum dry density and optimum moisture content of the soil were determined to be 1877 kg/m3 and 11%, respectively, based on the standard Proctor test. This subgrade soil was selected to represent an in situ fine-grained subgrade soil. No. 2A aggregate that was approved by the Pennsylvania Department of Transportation (PennDOT) (PennDOT Publication 408 2016) was used as the subbase layer. This material was selected as it represents a typical coarse aggregate used in pavement construction. The coefficient of uniformity (C_u) and the coefficient of curvature (C_c) were respectively 18.5 and 2.5, per AASHTO Test Method T11 and T27 (AASHTO 2012). The percentage of the aggregate finer than No. 200 sieve was determined to be 6.5%, per AASHTO T11. A comprehensive description of the materials was reported in Kermani et al. (2018a). Grain size distributions (GSDs) of subgrade and subbase are provided in Figure 1.

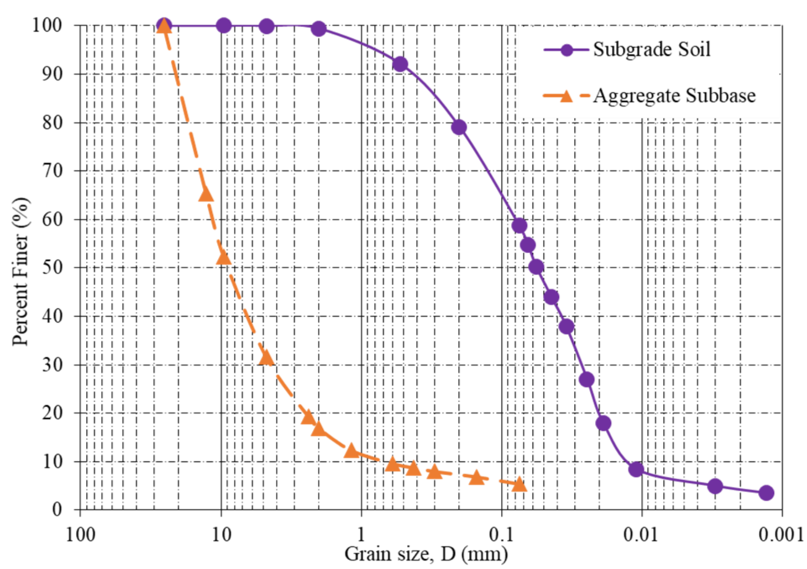


Figure. 1. Grain size distributions of subgrade soil and aggregate subbase used in the tests

A nonwoven, needle-punched geotextile made of 100% polypropylene staple fibers was chosen as the filter and separation layer. A description of the geotextile used in this study is detailed in Kermani et al. (2018b). The ability of a geotextile to retain fines is controlled by its opening size. The geotextile's apparent opening size (AOS) met the required filtration criteria on non-plastic silty soil under a cyclic loading condition (Christopher et al. 2006; Koerner 2012; Narejo 2003):

$$\mathrm{AOS} \leq 0.5\mathrm{D}_{85} \qquad [1]$$

$$\mathrm{AOS} < \frac{18}{\mathrm{c_u}}\mathrm{D}_{50} \qquad [2]$$

where: D_{85} is the soil particle size in mm for which 85% of the soil is finer than 0.075 mm; D_{50} is the soil particle size in mm for which 50% of the soil is finer than 0.075 mm; and C_u is the coefficient of uniformity of the subgrade soil.

2.2 Methodology

Analyses were conducted to determine the thickness of pavement layers for scaled pavement sections based on stress equivalency so that the vertical compressive stress at the top of the subgrade directly under the wheelpath equals to the stress in the corresponding full-scale pavement section. To achieve stress equivalency at the interface, Kenlayer and Kenslabs programs (Huang 2004) were respectively used to determine the interface stress generated by the most frequently used truck in typical flexible and rigid pavements. Since the migration of fines in rigid pavement is most significant at the joints. the stress generated at the subgrade-subbase interface under the joint was considered in the Kenslabs analysis. Description of stress equivalency analyses are detailed in Kermani et al. (2019a) and Kermani et al. (2018a). Layer thicknesses of scaled pavements sections are presented in Table 1.

Table 1. Layer thicknesses of scaled laboratory pavement sections

Pavement Layer	Flexible Pavement		Rigid Pavement
	Simulated collector road	Simulated interstate highway	Simulated interstate highway
Flexible surface	3.8 cm	7 cm	-
Rigid surface	-	-	7.6 cm
Aggregate subbase	10.2 cm	15.2 cm	10.2 cm
Subgrade soil	91.4 cm	91.4 cm	91.4 cm

The test specimen was constructed in a steel container. Four inlets were installed at the bottom of the container to introduce water into the specimen, as needed. Four outlets were installed at 1.27 cm above the subgrade-subbase interface; this configuration allowed water to circulate and exit throughout the pavement subgrade thus bring air out of the specimen. From bottom to top, the model pavement sections were constructed of the subgrade layer of non-plastic silt, the geotextile layer (for the tests with geotextile), the aggregate subbase layer, and the pavement surface (flexible or rigid). The subgrade soil was placed and compacted to a relative compaction of 100% based on the standard Proctor test until the pre-determined thickness was reached. The subbase layer was then placed and compacted uniformly to meet the required thickness based on the analysis. Sand cone tests were conducted to verify the compacted density of the layers. Finally, pavement surface was placed on top of the subbase layer. For the tests with geotextile, after the subgrade was constructed, the geotextile layer was carefully laid on top of the subgrade to separate subgrade and subbase. Water was introduced from the four inlets at the bottom of the container into the specimen at a low pressure and allowed to permeate upward to achieve the saturated condition of a subgrade layer to simulate field conditions. The degree of saturation was determined to be approximately 98.5% for the test. Two earth pressure cells were installed to measure the interface stress and to verify the stress equivalency of the model test condition to the intended field condition. Seven piezometers at various elevations of the model (one at the bottom of the subgrade, four at 2.54 cm down into the subgrade, and two at 2.54 cm into the subbase) were installed to verify and record the generation of dynamic pore water pressure caused by cyclic traffic loading and to examine the saturation process of the model. Figure 2 depicts plan-view locations of the top six piezometers (P2-P7) and two earth pressure cells (P1 and P2) used in flexible (Figure 2a) and rigid (Figure 2b) pavement models. Note that circles in the figures represent sampling locations.

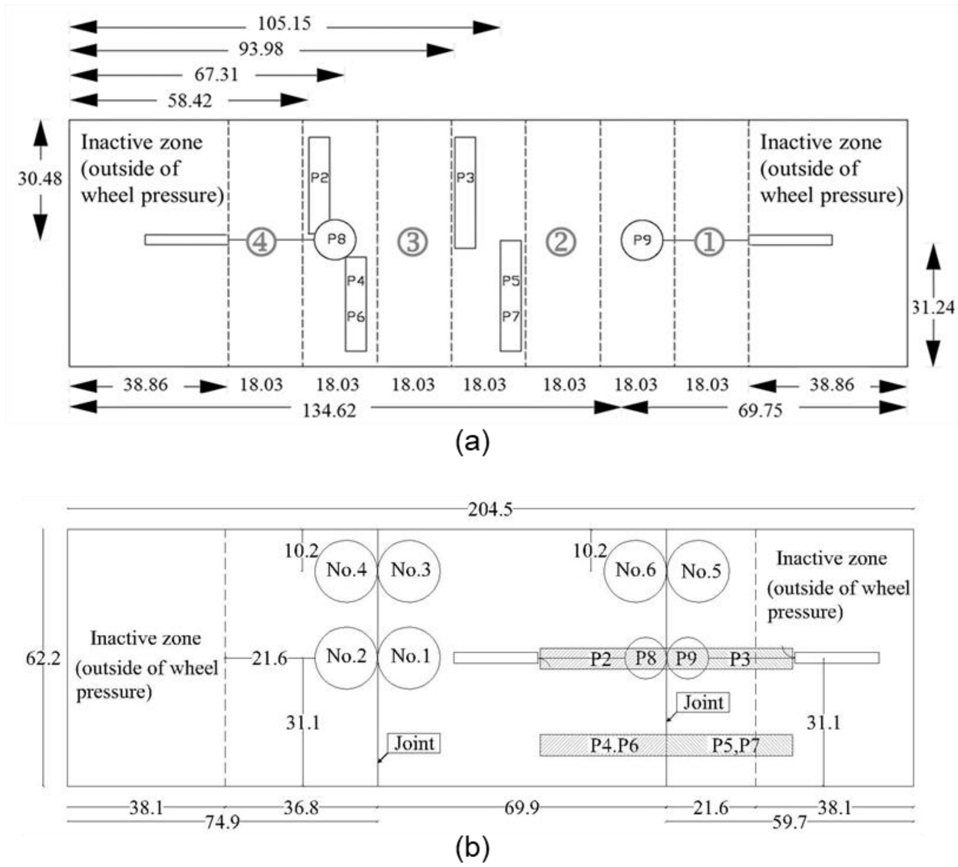


Figure 2. Instrumentation plan view and sampling locations (units in cm)

A snapshot of the MMLS3 testing on the scaled flexible pavement simulating collector roads is shown in Figure 3. MMLS3 applied a wheel load of 2.7 kN with a contact pressure of 700 kPa between the MMLS3 tire and the pavement. The traffic speed was set to 7200 axles (wheels) per hour (two axles per second). The test simulating flexible interstate highway was ended after 1,600,000 cycles, the test simulated flexible collector road was ended after 432,000 cycles, and the test simulating rigid interstate highway was ended after 1,000,000 cycles. The tests for rigid interstate highway and flexible collector road were performed again using geotextile at the subgrade-subbase interface. The result then compared to the corresponding tests without geotextile to assess the capability of geotextile in reducing pumping. Subbase and geotextile's (for the test with geotextile) sampling was conducted at pre-determined number of cycles and at the end of the tests. A set of sieve tests (both wet and dry) was then conducted on retrieved samples of aggregate subbase to quantify magnitude and rate of pumping. For rigid pavement tests, samples were retrieved from under both the approach and leave slabs. For the tests with geotextile, a sample of geotextile underneath the sampled subbase was gently cut and retrieved. After removing the geotextile sample, particles attached to the downside of the sample were separated. Sieve analysis was then conducted on the detached soil particles to measure the amount of particles attached to the downside face of the geotextile to characterize the composition of the filter cake forming at the face of the geotextile. Moreover, fine particles entrapped inside of the geotextile were removed through thorough washing and underwent sieve analysis testing to determine the amount of soil particles inside of the geotextile. Photographs of the sampling process on the pavement model are presented in Figure 4.

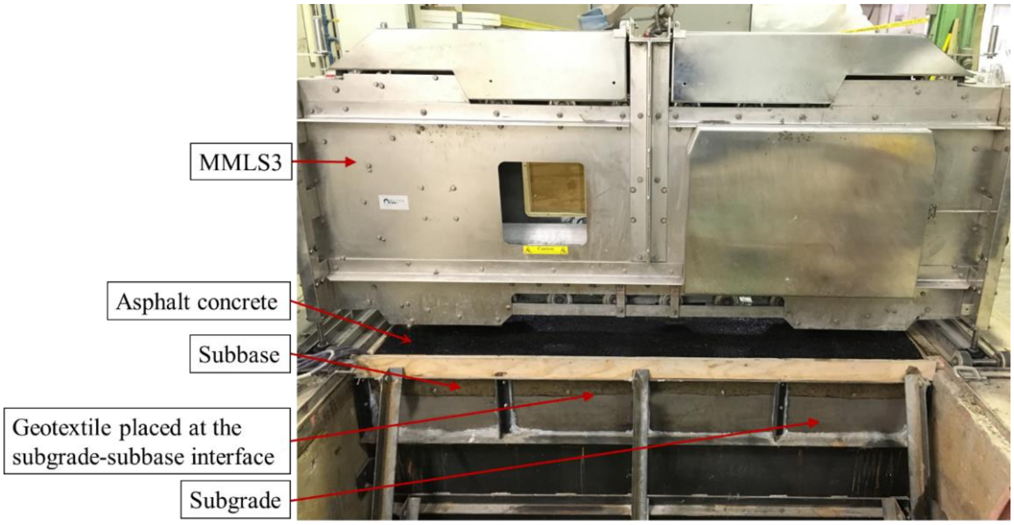
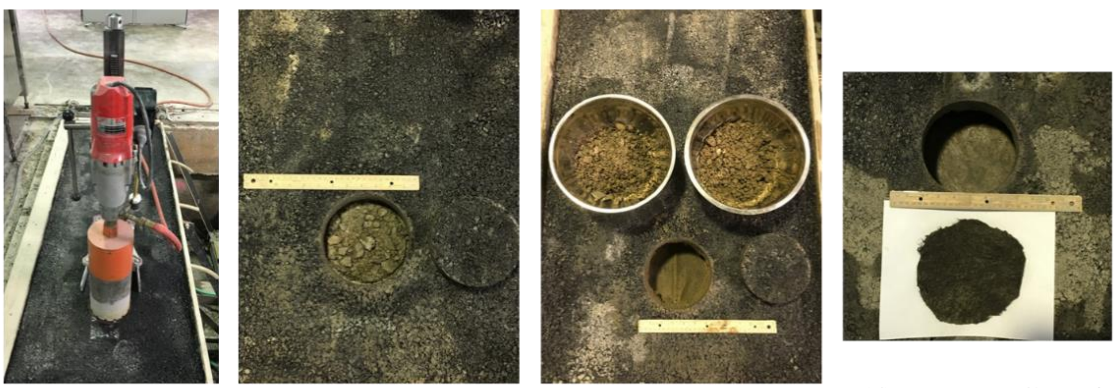


Figure 3. MMLS3 testing on the scaled pavement with geotextile separation layer (Test 3) (from Kermani et al. 2018b)



(a) Drilling into the asphalt concrete pavement

(b) Coring of the asphalt concrete

(c) Retrieving aggregate subbase

(d) Post-sampling of geotextile layer

Figure 4. Sampling process of the subbase and geotextile layers on flexible pavement simulating collector (from Kermani et al. (2018b)

3. RESULTS AND DISCUSSION

3.1 Quantification and Analysis of Subgrade Particles Migrated into the Aggregate Subbase

In this section, results of the tests with and without geotextile are presented and compared. The total mass percentages (% mass of subbase) of migrated subgrade soil into the top half, bottom half, and full depth of subbase beneath the wheelpath in the flexible collector road and rigid interstate highway tests are summarized in Tables 2 and 3, respectively. The total mass percentages of subgrade pumping into the full thickness of subbase versus the number of load cycles for the tests with and without geotextile are shown in Figure 5 for the simulated flexible pavement test and in Figure 6 for the simulated rigid pavement test. The percentage values reported are the net mass percentages of migrated particles from the subgrade into the subbase.

Table 2. Total amount of subgrade migration (% mass of subbase) in top half, bottom half, and full depth of each sample of subbase for scaled flexible pavement simulating collector road (with and without geotextile)

Number of Cycles	Total Migration (%)					
	Without geotextile			With geotextile		
	Top	Bottom	Full	Top	Bottom	Full
100,000	0.54	2.72	1.64	0.12	0.97	0.53
200,000	1.40	4.18	2.80	0.31	1.65	0.99
300,000	4.12	2.37	5.91	0.69	2.22	1.44
432,000	3.99	8.69	6.39	0.98	2.62	1.81

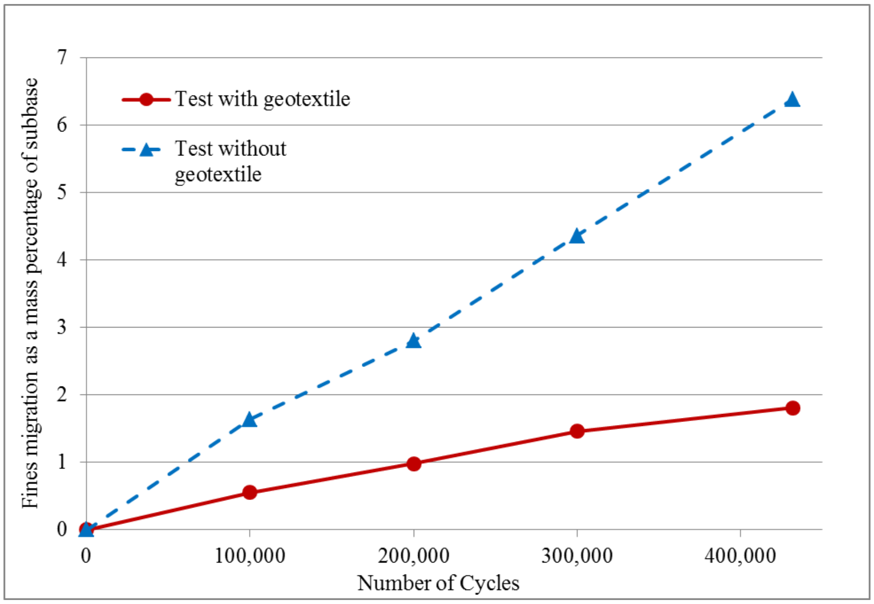


Figure 5. Total mass percentages of subgrade (based on mass of contaminated subbase) pumping into subbase with the number of loading cycles for simulated flexible pavement tests with and without geotextile

Table 3. Total amount of subgrade migration (% mass of subbase) in the top half, bottom half, and full depth of each sample of subbase for rigid simulating interstate highway (with and without geotextile)

Number of Cycles	Total Migration (%)											
	Without geotextile						With geotextile					
	Approach slab			Leave slab			Approach slab			Leave slab		
	Top	Bottom	Full	Top	Bottom	Full	Top	Bottom	Full	Top	Bottom	Full
200,000	2.29	5.85	4.10	2.05	5.35	3.72	0.54	1.63	1.11	0.48	1.50	1.01
1,000,000	6.46	12.54	9.60	5.92	11.73	8.91	1.57	3.95	2.81	1.23	3.15	2.25

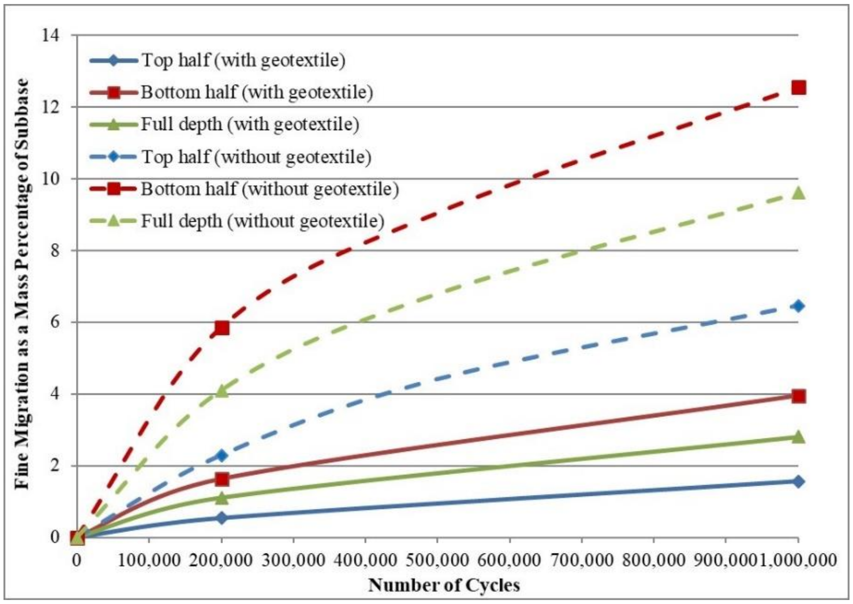


Figure 6. Total mass percentages of subgrade (based on mass of contaminated subbase) pumping into subbase with the number of loading cycles for the simulated rigid pavement tests with and without geotextile

As presented in Tables 2 and 3, the mass of subgrade soil that migrated in the subbase increased by increasing number of traffic cycles. More migration occurred in the bottom half than in the top half of the subbase, this indicates that the migration of subgrade into subbase varied with depth. The rate of migration was faster at the beginning and became slower as the test continued. As the cyclic traffic loads continued, the fines not only accumulated across the interface and in the subbase layer, but also on the bottom surface and inside of the geotextile. Moreover, the increase in viscosity may result in a gradual decrease in the velocity of slurry flow (Kermani et al. 2018c). These conditions occurred simultaneously and lead to a gradual reduction in the rate of pumping. The comparison presented in Tables 2 and 3 reveals that using a geotextile at the subgrade-subbase interface significantly reduced the subgrade pumping.

In addition, significant rutting (3.81 cm) and faulting (3.79 mm) were observed in the simulated flexible and rigid pavement sections, respectively. The observed rutting and faulting decreased to 2.66 cm (30% reduction) and 1.81 mm (52% reduction) respectively, when using geotextile at the interface of subgrade and subbase, which is another evidence of the effectiveness of geotextile.

Figures 5 shows that the fines migration was only 1.81% at the end of the simulated flexible pavement test with geotextile, while this amount was 6.39% in the same test without geotextile. Similarly, Figure 6 shows that for the simulated rigid pavement test, pumping was 9.60% at pavement joint when geotextile was not used. This amount was reduced to 2.81% when geotextile was used at the subgrade-subbase interface. Such reductions in pumping under pavements indicate that geotextile was effective in reducing fines migration in pavements.

3.2 Quantification and Analysis of Subgrade Particles Migrated into the geotextile

The geotextile beneath the sampled subbase sections was cut and analyzed. The fines migrations to the geotextile due to the filter cake effect were quantifies. Table 4 compares total amounts of fines migration to the sampled geotextile and subbase in the test that simulated flexible collector road and the amounts of migrated fines into the sampled subbase in the simulated flexible collector road test without geotextile. Similarly, Table 5 compares total amounts of fines migration to the sampled geotextile and subbase in the test that simulated rigid interstate highway and the amounts of migrated fines into the sampled subbase in the identical test without geotextile.

Table 4. Comparison of subgrade migration in flexible pavement tests with and without geotextile

Number of Cycles	Total Mass of Migration into the Sampled Area (gr)			
	Without geotextile	With geotextile		
	Subbase	Subbase	Geotextile	Total
100,000	72.0	23.94	17.81	41.75
200,000	124.30	42.85	29.4	72.25
300,000	187.12	64.14	37.82	101.96
432,000	293.49	79.78	43.2	122.98

Table 5. Comparison of subgrade migration in rigid pavement tests with and without geotextile

Number of Cycles	Total Mass of Migration into the Sampled Area (gr)			
	Without geotextile	With geotextile		
	Subbase	Subbase	Geotextile	Total
200,000	164.06	44.52	22.30	66.82
1,000,000	388.55	106.25	70.05	176.30

Tables 4 and 5 suggest that the total amount of subgrade migration in tests with geotextile were considerably less than the corresponding values in the tests without geotextile (in subbase). The results show that geotextile could significantly reduce the traffic-induced pore water pressure generated at the subgrade-subbase interface, which is another indicator of the capability of geotextile in reducing pumping.

As a result of the intrusion of additional fines into the granular layers of a pavement, its behavior and performance may change. For example, a typical subbase used in Pennsylvania, No. 2A aggregate, can contain up to 10% fines (i.e., minus #200 sieve). The subbase aggregate used in this study had already 6% fines and may be representative of a typical field condition. Permeability, resilient modulus, shear strength, and drainage capacity of the materials have been found to decrease rapidly when fines content increases to approximately 8 to 9 percent (Brown et al. 1977). Also, increasing excess pore pressure in poorly drained areas adversely affects the strength, stiffness, and stability of subgrade and ultimately leads to failure of the pavement (Kermani et al. 2019b, 2019c). Moreover, migration of more than 6% fines to the subbase layer, as occurred in the tests without geotextile, would change the classification of the soil and affect the soil behavior. This may indicate that a properly selected geotextile (in terms of opening size and thickness) can provide effective filtration and separation of pavement layers, leading to long lasting pavement systems.

To investigate the effect of fines content on permeability of the subbase layer, the permeability of 2A subbase aggregate with different fines contents was measured using a constant-head permeability test. The results are presented in Figure 7. A decreasing trend in the permeability of the subbase was clearly observed as more subgrade fines migrated into the subbase.

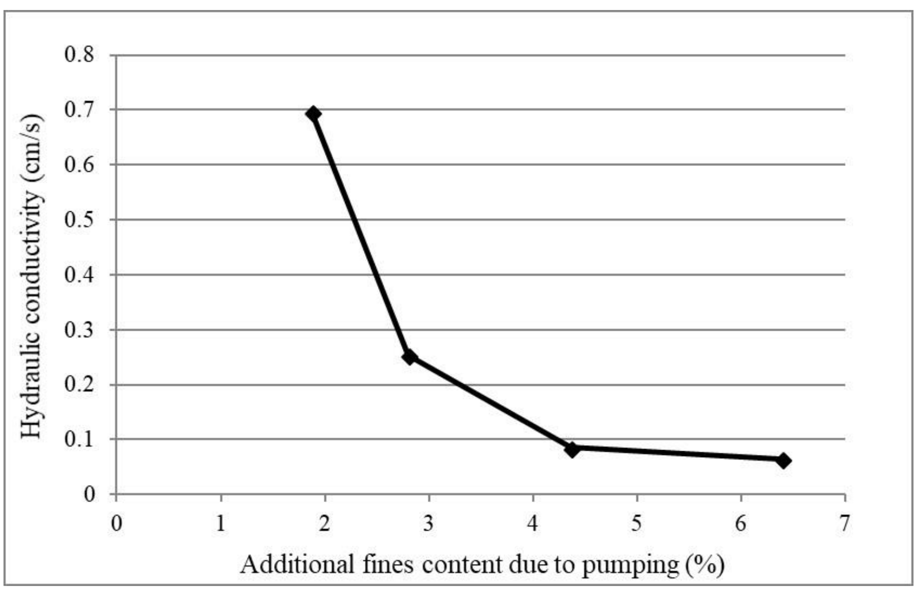


Figure 7. Effect of fines content on permeability of 2A aggregate subbase (from Kermani et al. 2019d)

4. CONCLUSIONS

From this study, the following concluding remarks are provided:

(1) Significant migrations of subgrade soil into subbase were observed in all the tests without geotextile layer performed in this project. Pumping was affected by traffic-induced downward pressure at the interface of subbase and subgrade. This downward pressure is governed by the type of pavement (flexible or rigid) and the class of roadways.

(2) Migration of fines in pavement system may be due to the development of pore water pressure at subgrade-subbase interface caused by traffic loads. Higher stress induced on top of the subgrade can cause higher excess pore water pressure, which in turn would lead to migration of fines.

(3) The migrated subgrade soil in mass percentage increased with the increase of simulated traffic loading cycles.

(4) The migration of subgrade soil into subbase also varied with the depth in the subbase: more migration occurred in the lower section (closer to the subgrade) than in the upper section of the subbase.

(5) In the simulated rigid pavement, the soil migrations were different under the approach slab and leave slab of a joint; the mass percentage of migrated soil into the samples taken from the approach slab was more than that from the leave slab. This indicates that the migration of fines occurred not only in the vertical direction (from subgrade to subbase), but in the horizontal direction (in subbase layer).

(6) Migrations of subgrade soil into subbase were significantly reduced by using geotextile as a separator at the subgrade-subbase interface. Moreover, the amount of fines migration without geotextile was much more than the total amount of migrated fines into the subbase and geotextile together when using geotextile. This shows geotextile as a filter and separation layer can effectively reduce the migration of fine particles from subgrade to subbase.

(7) An approximately 30% reduction was observed in the amount of pavement rutting when using geotextile at the top of subgrade layer. This indicates that the geotextile, due to its effectiveness in reducing fines migration, was capable of decreasing the subgrade deformation, hence increasing the serviceability of the pavement.

(8) An approximately 52 percent reduction was observed in the amount of pavement faulting when using geotextile at the top of subgrade layer. This indicates that the geotextile was capable of decreasing the slabs faulting, hence increasing the serviceability of the pavement.

ACKNOWLEDGEMENTS

The financial and technical support provided by the Pennsylvania Department of Transportation (PennDOT) for this project is acknowledged. The Geosynthetic Institute (GSI) provided GSI fellowships to the first author. The authors thank SKAPS Industries for providing geotextile product for this research. Mr. Dan Fura, laboratory supervisor in the Department of Civil and Environmental Engineering at Penn State, provided technical assistance; his help throughout the project is highly appreciated.

REFERENCES

AASHTO (American Association of State Highway Transportation Officials). (2012). Standard Specifications for Transportation Materials and Methods of Sampling and Testing, 32th Edition. *The American Association of State Highway and Transportation Officials.*, Washington, D.C.

Alobaidi, I., and Hoare, D. J. (1994). Factors affecting the pumping of fines at the subgrade subbase interface of highway pavements: a laboratory study. *Geosynthetics International,* 1(2), 221-259.

Alobaidi, I., and Hoare, D. J. (1996). The development of pore water pressure at the subgrade-subbase interface of a highway pavement and its effect on pumping of fines. *Geotextiles and geomembranes,* 14(2), 111-135.

Alobaidi, I., and Hoare, D. J. (1999). Mechanisms of pumping at the subgrade-subbase interface of highway pavements. *Geosynthetics International*, 6(4), 241-259.

Al-Qadi, I. L., Brandon, T. L., Valentine, R. J., Lacina, B. A., & Smith, T. E. (1994). Laboratory evaluation of geosynthetic-reinforced pavement sections. *Transportation Research Record*, (1439), 25-31.

Al-Qadi, I., & Appea, A. (2003). Eight-year field performance of secondary road incorporating geosynthetics at subgrade-base interface. *Transportation Research Record: Journal of the Transportation Research Board*, (1849), 212-220.

Brorsson, I., & Eriksson, L. (1986). Long-term properties of geotextiles and their function as a separator in road construction. Proceedings of Third International Conference on Geotextiles, Vienna, Austria, Vol. 1 (93-98).

Brown, S. F., Andersen, K. H., and McElvaney, J. (1977), The Effect of Drainage on Cyclic Loading of Clay. Proceedings of the Ninth International Conference on Soil Mechanics and Foundation Engineering, Vol. 2, pp. 195-200, Tokyo, Japan.

Christopher, B. R., Schwartz, C., and Boudreau, R. (2006). *Geotechnical Aspects of Pavements*. Report No. FHWA NHI-05-037, Washington, D.C., US Department of Transportation, Federal Highway Administration.

Guram, D., Marienfeld, M., & Hayes, C. (1994). Evaluation of nonwoven geotextile versus lime-treated subgrade in Atoka County, Oklahoma. *Transportation research record*, (1439), 7-11. National Research Council, Washington, D.C.

Henry, K. S., Cole, D. M., & Durell, G. D. (2013). Mixing in an Aggregate/Fine-Grained Soil System Subjected to Cyclic Loading with a Geotextile Separator. In Sound Geotechnical Research to Practice: Honoring Robert D. Holtz II, pp. 306-317.

Holtz, R. D., Christopher, B. R. and Berg, R. R. (2008). "Geosynthetic Design & Construction Guidelines: Reference Manual." FHWA NHI-07-092. NHI Course No. 132013. Washington, D.C., US Department of Transportation, Federal Highway Administration, National Highway Institute.

Hufenus, R., Rueegger, R., Banjac, R., Mayor, P., Springman, S. M., & Brönnimann, R. (2006). Full-scale field tests on geosynthetic reinforced unpaved roads on soft subgrade. *Geotextiles and Geomembranes*, 24(1), 21-37.

Kermani, B., Stoffels, S. M., and Xiao, M. (2019b). "Assessment of Geotextile Effectiveness in Decreasing Subgrade Pumping and Increasing Service Life in Rigid Pavements Using Scaled Model Mobile Load Simulator." In *Geo-Congress 2019, American Society of Civil Engineers*.

Kermani, B., Stoffels, S. M., Xiao, M. (2019c), "Evaluation of Effectiveness of Geotextile in Reducing Subgrade Migration in Rigid Pavement." *Geosynthetics International*, DOI: 10.1680/jgein.19.00052

Kermani, B., Stoffels, S. M., Xiao, M., and Qiu, T. (2018a). "Experimental simulation and quantification of migration of subgrade soil into subbase under rigid pavement using model mobile load simulator." *Journal of Transportation Engineering, Part B: Pavements*, *144*(4), 04018049.

Kermani, B., Xiao, M., and Stoffels, S. M. (2019d). "Analytical study on quantifying the magnitude and rate of subgrade fines migration into subbase under flexible pavement." *Transportation Geotechnics*, 18, 46-56.

Kermani, B., Xiao, M., Stoffels, S. M., and Qiu, T. (2018b). "Reduction of subgrade fines migration into subbase of flexible pavement using geotextile." *Geotextiles and Geomembranes*, 46(4), 377-383.

Kermani, B., Xiao, M., Stoffels, S. M., and Qiu, T. (2018c). "Magnitude and Rate of Migration of Fine Subgrade Soil into Granular Subbase under Scaled Flexible Interstate Pavement." *Proceeding of IFCEE; Geotechnical Special Publication*, *2018* (GSP 296), 425-434.

Kermani, B., Xiao, M., Stoffels, S. M., and Qiu, T. (2019a). "Measuring the migration of subgrade fine particles into subbase using scaled accelerated flexible pavement testing–a laboratory study." *Road Materials and Pavement Design*, 20(1), 36-57.

Koerner, R. M. (2012). *Designing with geosynthetics.* 6th edition, Vol. 2. Xlibris Corporation.

Koerner, R. M. and Koerner, G. R., 2015. Lessons learned from geotextile filter failures under challenging field conditions. *Geotextiles and Geomembranes*, 43(3), 272–281.

Narejo, D. B. (2003). Opening size recommendations for separation geotextiles used in pavements. *Geotextiles and Geomembranes*, 21(4), 257-264.

PennDOT (Pennsylvania Department of Transportation) Publication 408. (2016). *Construction Specifications for PennDOT Projects*. Department of Transportation, Commonwealth of Pennsylvania, USA.

Su Jung, Y., Zollinger, D. G., Won, M., & Wimsatt, A. J. (2009). *Subbase and Subgrade Performance Investigation for Concrete Pavement*. (No. FHWA/TX-09/0-6037-1)

Trani, L. D. O., and Indraratna, B. (2010). Assessment of subballast filtration under cyclic loading. *Journal of Geotechnical and Geoenvironmental Engineering*, 136(11), 1519-1528.

Zornberg, J. G., and Thompson, N. (2012). *Application guide and specifications for geotextiles in roadway application*s (No. FHWA/TX-10/0-5812-1). University of Texas at Austin. Center for Transportation Research.