Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 42 No.1 March 2011 ISSN 0046-5828

Quantifying the Influence of Geosynthetics on Performance of Reinforced Granular Bases in Laboratory

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ABSTRACT: Interaction between geosynthetics (geogrid and geotextile) and aggregates under traffic wheel loading has been considered as one of high-priority problems by the U.S. Transportation Research Board. The practical use of geosynthetics above a subgrade or within a base course has demonstrated the benefit of reducing rut depths and prolonging pavement life. However, no standard test method is available to appropriately evaluate the geosynthetic-soil confinement effect and distinguish the benefits of the different types of geosynthetics and soils. This paper provides an overview of existing test methods and outlines the advantages and disadvantages of each method. The newly developed test method by the authors is performance-based and modified from the Asphalt Pavement Analyzer to evaluate geosynthetic-soil confinement. In this test, a geosynthetic sheet is placed within a base course to form a reinforced base, which is subjected to wheel loading. The measured rut depth with the number of cycles of wheel loading can be used to evaluate the geosynthetic-soil confinement. In this study, two different base course materials and four different geosynthetics were used. The experimental results clearly show that this newly developed performance-based test method can distinguish the benefits of rut reduction among different types of geosynthetics and base course materials. The experimental tests of geotextile-reinforced bases were analyzed by a two-dimensional discrete element method. The limitations of this experimental method are also discussed.

1. INTRODUCTION

Geosynthetics (geogrid and geotextile) have been widely used for subgrade improvement and base reinforcement (Berg et al., 2000; Giroud and Han, 2004). The main function of geosynthetics used for base reinforcement is to provide confinement to soil particles to minimize their movement under traffic loading. Kinney (1999) clearly demonstrated in his laboratory tests that the particles in the unreinforced section moved away from the centerline of the wheel path after each pass of loading while those in the geogrid-reinforced section first slightly moved away and then mostly returned to the original locations. Kinney (1999) attributed this elastic behavior of the reinforced section to the torsional resistance of geogrid. Field studies have showed that different types of geosynthetics (geogrid or geotextile; flexible geogrid or stiff geogrid) perform differently (Berg et al., 2000; Webster, 1992). Webster (1992) identified the following properties of geogrid affecting the benefits of base reinforcement: thickness, stiffness, and shape of rib, size, shape, and rigidity of aperture, junction strength, and secant modulus and stability of grid as shown in Table 1. The numerical study by Dong et al. (2011) showed that the geogrid with triangular apertures, recently introduced into the market, has more uniform strength and stiffness distributions at different loading directions than the geogrid with rectangular apertures. Discrete element modeling showed that the interlocking or confinement between geogrid and aggregate developed only when local relative displacements occurred between geogrid and aggregate (McDowell et al., 2005). Interaction between geosynthetics (geogrid or geotextile) and aggregates under traffic wheel loading has been considered as one of the high-priority problems by the U.S. Transportation Research Board Geosynthetic Committee AFS70. Proper evaluation of geosynthetic-soil confinement has been a challenging task. Attempts have been made by a few researchers to find an effective and efficient test method.

2. EXISTING TEST METHODS

Kinney and Yuan (1995) developed an aperture rigidity test method to evaluate the stiffness of different geogrid products and correlate their torsional rigidity moduli to the field performance. Kinney and Yuan's method has reasonably well differentiated different types of geogrid based on their torsional rigidity moduli. However, Kinney's method cannot be used for geotextiles. Geosynthetic-soil confinement depends not only on the macro structure and index properties of geosynthetics but also on the properties of soil and most importantly the interaction between geosynthetics and soil particles. Kinney and Yuan's torsional rigidity test cannot evaluate the interaction between geosynthetics and soil, which is the key mechanism for confinement. In addition, geosynthetics used for base reinforcement are subjected to dynamic loading, i.e., traffic loading, which cannot be simulated by this test method either. Therefore, torsional rigidity modulus is a good material index for geogrid but not a performance index for confinement of geosynthetic to soil.

Table 1. Geogrid properties affecting base reinforcement (Modified from Webster, 1992)

Geogrid Item	Property	Test Standard	Judgment
Rib	Thickness	ASTM D1777	Thicker is better.
Rib	Stiffness	ASTM D6637	Stiffer is better. Need test to measure stiffness.
Rib	Shape	NA	Square or rectangular are better than rounded or curved shapes.
Aperture	Size	NA	Related to base aggregate size. Optimum size not known. .75 to 1.5 in. probably good target range.
Aperture	Shape	NA	Round or square is better.
Aperture	Rigidity	ASTM D6637	Stiffer is better.
Junction	Strength	(GRI – GG2)	Need some minimum strength. All geogrids tested were adequate.
Grid	Secant Modulus	ASTM D4595	Need minimum secant modulus value. Optimum not known.
Grid	Stability	ASTM WK24635	The "Grid Aperture Stability by In-Plane Rotation" test developed by Dr. Thomas Kinney shows good potential for traffic performance relationships. A minimum secant aperture stability modulus as a specified torque may be a good index test requirement.

Sprague et al. (2004) proposed a bending stiffness index for geogrid reinforcement of pavement bases. In this test, a geogrid is sandwiched into aggregate and confined by flexible membranes. A uniform vacuum pressure is applied onto the geosynthetic-soil "sandwich" and the deflection under such a pressure is measured. This method does include the geosynthetic into the soil. However, Yuan (2005) demonstrated using a theoretical analysis that the shear resistance between soil and chamber has a great influence on the test results. This test method also cannot simulate a repeated wheel loading condition.

Matys and Baslik (2004) proposed a push test to evaluate the interlocking effect of geogrid. In this test, a cone is pushed through the base course towards the geogrid layer. During this pushing process, the pushing force is recorded. The main advantage of this test method is to generate local displacements close to the geogrid layer. The apparent disadvantage is that it cannot simulate a repeated wheel loading condition.

Direct shear and pullout tests have been used to determine interface shear stiffness and strength between geosynthetic and soil; therefore, these methods do evaluate the interaction between geosynthetic and soil. However, these test methods cannot simulate repeated wheel loading and the shear mode in the direct shear or pullout tests is different from that under wheel loading.

Falling Weight Deflectometer (FWD) can be used in the field to evaluate the current condition and integrity of a pavement structure. The measured deflection can be used to back-calculate the moduli of pavement layers. This test method is suitable for all geosynthetics interacting with bases. Due to limited deflection of the pavement structure generated by the FWD, the contribution of geosynthetic cannot be readily mobilized and detected right after the construction of the pavement. Since geosynthetics can better maintain the integrity of pavement structures during service, the influence of geosynthetics on the performance of reinforced pavements with time can be evaluated. This evaluation has to be done parallel with a control section without a geosynthetic.

Cyclic plate loading tests have been successfully used to evaluate geosynthetic confinement effects with soil under dynamic loading in a large test box (Haas et al., 1988; Perkins, 1999; Gabr, 2001; Qian et al., 2011). However, the facilities of cyclic plate loading tests are not readily available in public or private agencies and they are mainly used as a research tool in very limited universities and research institutes. In addition, the cyclic plate loading test has a major drawback that cannot simulate moving wheels.

Accelerated pavement tests are excellent for evaluating the benefits of geosynthetics in roadways and have been used by a few researchers (Collin et al., 1996; Perkins, 2002; Pokharel et al., 2011). However, they are time-consuming and very costly; therefore, they are not suitable as a routine test method.

Field trafficking tests are another excellent method for evaluating the performance of geosynthetic-reinforced bases and have been conducted by limited researchers (Webster, 1992; Brandon et al., 1996; Huntington and Ksaibati, 2000; Holder and Andreae, 2004; Aran, 2006). However, they are time-consuming and very costly; thus, they are also not suitable for routine testing.

The Model Mobile Load Simulator 3 (MMLS3) represents a viable option for performance evaluation of asphalt pavements. Typical MMLS3 tests are performed on actual pavements or on cylinders and slabs, of different dimensions, prepared in the laboratory, with most of the testing being conducted to assess the rutting and fatigue susceptibility of the asphalt mixes. The asphalt concrete specimens are tested using pneumatic tires (300 mm in diameter, about one-third the diameter of standard truck tires) inflated to around 700 kPa (approximately 100 psi) rolling in one direction over the specimens. Thus, these conditions more closely simulate field trafficking. The mobile load simulator is still considered a reduced scale device in terms of contact area between the tire and the tested sample (Epps et al. 2003; Ebels et al. 2004; Hugo et al. 2004; Lee et al. 2006; Verhaeghe et al. 2007), allowing for a better evaluation of the asphalt mixture performance. It applies more realistic rolling wheel contact stresses, compared to the wheel tracking devices (i.e., APA), at a fraction of the cost of full-scale Accelerated Pavement Testing (APT) (Walubita et al. 2002; Hugo and Epps 2004). Recent studies have successfully evaluated asphalt pavements incorporating geosynthetic material using the MMLS3 (Tang et al. 2008; Kim et al. 2009). However, the MMLS3 facilities are not readily available in public or private agencies and they are mainly used as a research tool in very limited universities and research institutes.

In the authors' opinion, a reasonable test method to evaluate geosynthetic-soil confinement should be performance-based and have the following features: (a) applicable to all types of geosynthetics, (b) geosynthetic interacting with base course material, (c) development of local deformation, (d) repeated loading, (e) loading applied by a wheel tracking motion, and (f) easy, quick, and inexpensive. Table 2 summarizes the features of the existing test methods discussed above. It is clear that a new performance-based test method is needed to effectively and efficiently evaluate the geosynthetic-soil confinement and have all the necessary features.

Table 2. Features of test methods for geosynthetic-soil confinement

Test Method	Features					
	Appl. to all geosyn.	Geosyn. with base	Local deform.	Repeated loading	Wheel tracking	Cost
Aperture rigidity	No	No	Yes	No	No	$
Bending stiffness	Yes	Yes	No	Possible	No	$
Push test	Yes	Yes	Yes	No	No	$
Resilient modulus test	Yes	Yes	No	Yes	No	$
Direct shear test	Yes	Yes	Yes	No	No	$
Pullout test	Yes	Yes	Yes	Possible	No	$
FWD	Yes	Yes	Limited	No	No	$$
Cyclic plate load test	Yes	Yes	Yes	Yes	N	$$
Model Mobile Load Simulator 3	Yes	Yes	Yes	Yes	Yes	$$
Accelerated pavement test	Yes	Yes	Yes	Yes	Yes	$$$
Field trafficking	Yes	Yes	Yes	Yes	Yes	$$$
Wheel tracking test	Yes	Yes	Yes	Yes	Yes	$

3. NEWLY DEVELOPED TEST METHOD

The newly-developed test method proposed by the authors is performance-based and to use a modified Asphalt Pavement Analyzer (APA) to evaluate the benefit of geosynthetic reinforcement in the base course through geosynthetoc-soil confinement. APA is a multifunctional Loaded Wheel Tester used for evaluating permanent deformation (rutting), fatigue cracking, and moisture susceptibility of both hot and cold asphalt mixes (Kandhal and Cooley, 2003). Testing time for a complete permanent deformation evaluation is 2 hours and 15 minutes (8,000 cycles). The APA is available at a number of state DOTs and universities in the U.S., and can be easily modified to test the confinement effect of geosynthetics with soil. The University of Kansas has such a testing machine. This machine was modified by the authors for this research purpose. The major modification included a test box to hold soil with or without geosynthetics. Details of this modification can be found in Zhang (2007). A loaded wheel can move back and forth on the surface of soil as shown in Figure 1. The wheels and air pressurized hoses and the placement of a geosynthetic sheet within base course are shown in Figure 2. Rut depth can be measured manually or automatically after a certain number of passes. A relationship between rut depth and number of passes can be established. Comparing this relationship for a geosynthetic-reinforced base to that of an unreinforced base can evaluate the confinement effect of geosynthetics. As shown in Table 2, this newly-developed test method (i.e., the wheel tracking test) has all the features required for evaluating geosynthetic-soil confinement. This test was also adopted by Wu et al. (2010) to evaluate geogrid reinforcement in pavement bases. In the present study, four different types of geosynthetics and two different types of base course materials were tested. The results of this study show the proposed test method is capable of distinguishing the relative performance of different geosynthetics products in specific bases.

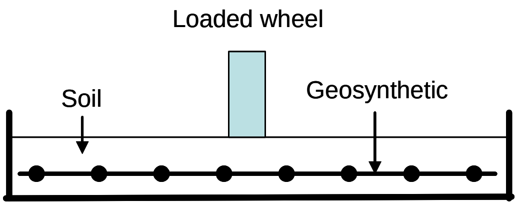
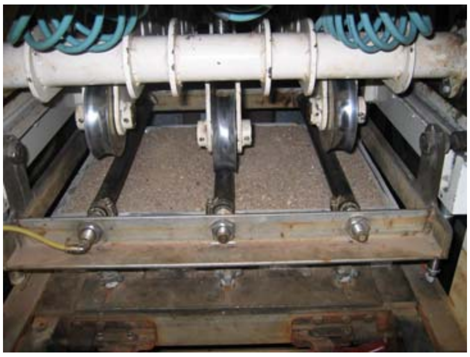


Figure 1. Test box and layout



(a) Wheels and pressured hoses

(b) Placement of geosynthetic

Figure 2. Wheel tracking/loading system and test box with a geosynthetic in a base course

4. EXPERIMENTAL STUDY

4.1 Material Properties

4.1.1 Base course materials

Two types of base materials were used in this study: the Kansas River sand and the AB-3 aggregate. The grain size distributions of these two materials are shown in Figure 3. The large particles (greater than 12.5mm) in the AB-3 aggregate were removed in this study. Figure 3 shows that these two base materials had almost an identical mean grain size of 2.6 mm. However, the Kansas River sand was poorly graded with subrounded particles while the AB-3 aggregate was well-graded with angular particles. Therefore, the Kansas River sand represents a poor-quality base material while the AB-3 aggregate represents a high-quality base material. The minimum and maximum void ratios of Kansas River sand were 0.384 and 0.560, respectively while those of AB-3 aggregate were 0.197 and 0.523, respectively.

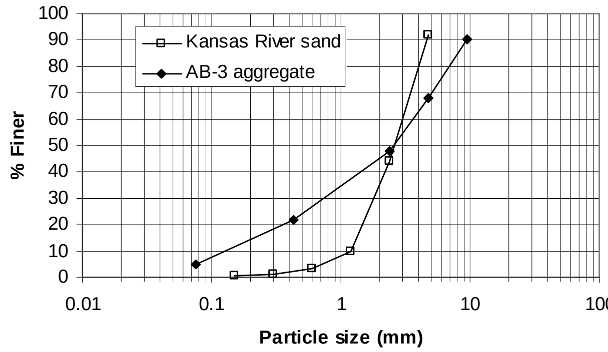


Figure 3. Grain-size distributions of base course materials

4.1.2 Geosynthetics

Three types of extruded and punched-drawn biaxial geogrid (named as GG1, GG2, and GG3) and one type of woven geotextile (named GT1) were used in this study. The properties of these geosynthetics are provided in Table 3. In terms of ultimate tensile strength and tensile strength at 5% strain, GT1 had the highest strength values followed by GG3, GG2, and GG1. However, GG3 had slightly higher tensile strength values at 2% strain. In this study, geosynthetic sheet was placed at a depth of either 25mm or 13mm. The wheel moving direction was parallel to the machine direction of the geosynthetics.

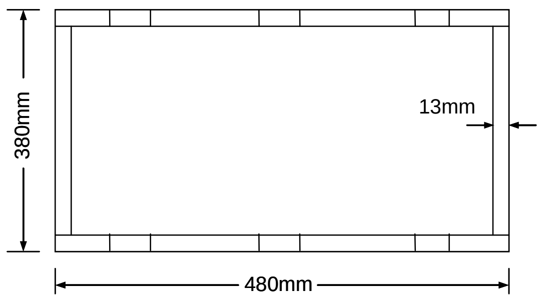
Table 3. Properties of geosynthetics used in this study

Geosynthetic	Property	MD	XMD
GG1	Aperture dimensions (mm)	25	33
	Minimum rib thickness (mm)	0.76	0.76
	Tensile strength @2% strain (kN/m)	4.1	6.6
	Tensile strength @5% strain (kN/m)	8.3	13.4
	Ultimate tensile strength (kN/m)	12.5	19.0
	Aperture stability modulus (m-N/deg)	0.32	
GG2	Aperture dimensions (mm)	25	33
	Minimum rib thickness (mm)	1.27	1.27
	Tensile strength @2% strain (kN/m)	6.0	9.0
	Tensile strength @5% strain (kN/m)	11.8	19.6
	Ultimate tensile strength (kN/m)	19.2	28.8
	Aperture stability modulus (m-N/deg)	0.65	
GG3	Aperture dimensions (mm)	25	30.5
	Minimum rib thickness (mm)	1.78	1.78
	Tensile strength @2% strain (kN/m)	8.5	10.0
	Tensile strength @5% strain (kN/m)	17.5	20.0
	Ultimate tensile strength (kN/m)	27.0	30.0
	Aperture stability modulus (m-N/deg)	0.75	
GT1	Tensile strength @2% strain (kN/m)	7.9	7.9
	Tensile strength @5% strain (kN/m)	19.8	22.3
	Ultimate tensile strength (kN/m)	47.3	39.4
	Mass/unit area (g/m^2)	284	

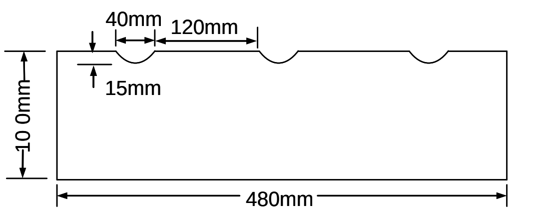
MD = machine direction and XMD = cross-machine direction.

4.2 Modification of Test Box

The standard molds for APA have three separated boxes to hold the asphalt mix samples, which are not suitable for the confinement tests because the space for the samples is too small and confined. Therefore, a modified test box, three times as large as the standard one, was designed and manufactured to hold the base course materials as shown in Figure 2. Given the large space the modified test box can provide, the geosynthetic sheet can be placed within the base course material as shown in Figure 2. Figure 4 provides the dimensions of this modified text box, which is made of aluminum. The three grooves on the front and rear sides of the box allow enough deformation of the pressurized hoses during the test. These grooves were covered by plastic tape to hold the base material before the test. Since the tape is flexible, they can deform with the pressurized hoses during the test.



(a) Plan view



(b) Cross-section view

Figure 4. Dimensions of the modified test box

4.3 Test Setup and Procedures

Before the confinement test, the base material was compacted to a target density (70% relative density in this study). All the samples were prepared in a dry condition. Considering the relatively large quantity of the soil mass, the soil was placed and compacted in four layers. To control the density of the sample, the mass of each layer was predetermined and that amount was compacted in the box by tamping until the base thickness reached to the desired thickness (the box was marked at different depths). After all the base layers were filled and compacted, the sample was ready for testing using the APA machine.

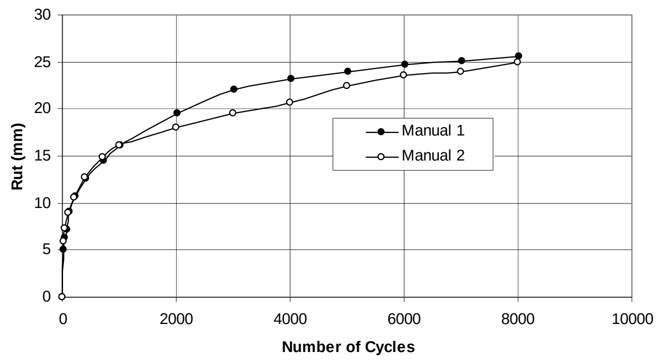
Since the two base materials differed in quality and strength, different wheel loads and hose pressures were applied. The wheel load used for the Kansas River sand was 89 N and the corresponding hose pressure was 138 kPa. The wheel load used for the AB-3 aggregate was 355 N and the corresponding hose pressure was 552 kPa. A constant contact area of 645 mm^2 for each pressurized hose was maintained based on the recommendation by Kandhal and Cooley (2003). The diameter of the pressurized hoses was 19 mm; however, they could generate 25 mm wide ruts under the wheel loads.

The Kansas River sand was also tested with and without surcharge. The surcharge was applied by placing the steel blocks on the surface of the base sample to simulate the overburden stress in the base course under pavement structures. The magnitude of surcharge was 2.9 kPa.

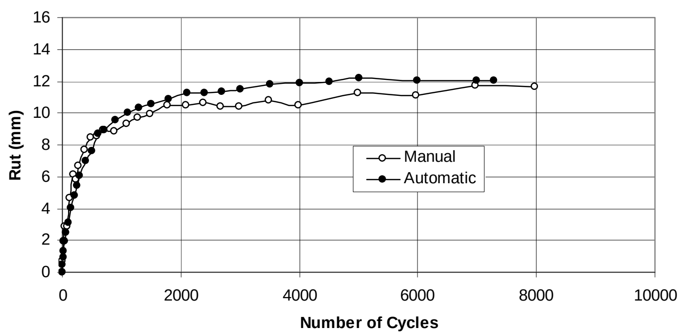
Both manual and automatic measurements were used for tests with the Kansas River sand but only manual measurement was used for tests with the AB-3 aggregate. As discussed later, the manual and automatic measurements yielded similar results. For tests with the Kansas River sand, only the middle wheel was used for loading and only the rut depth under the middle wheel was measured. The final rut depth was the average value of three rut depth measurements in the middle portion of rutting. For tests with the AB-3 aggregate, all the three wheels were used for loading and the rut depths were measured under all three wheels in order to get more accurate results. For the AB-3 tests, the final rut depth was the average value of nine rut depths measured close to the middle portions of rutting under the three pressurized hoses.

4.4 Repeatability Tests

Multiple tests were conducted in this study to evaluate how repeatable the test results are. As shown in Figure 5, the manual and automatic measurements yielded similar results. In addition, two manual measurements for the same base yielded similar results. Therefore, the repeatability of the test results was verified.



(a) Kansas River sand



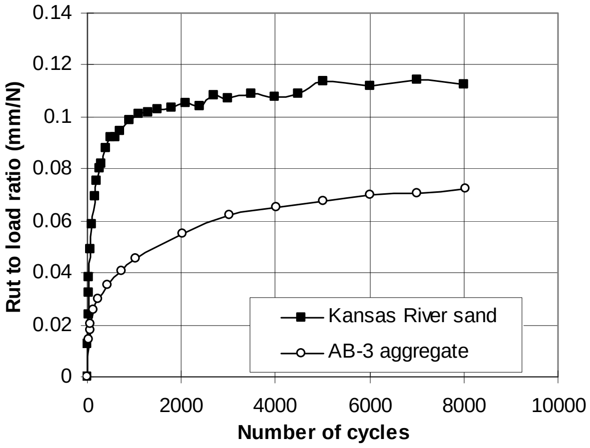
(b) AB-3 aggregate

Figure 5. Repeatability test results for unreinforced bases

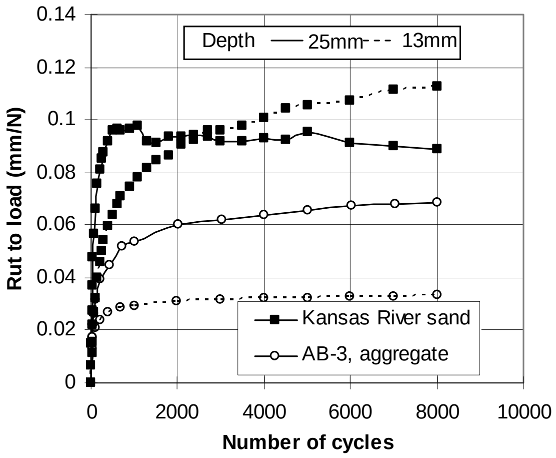
5. ANALYSIS OF TEST RESULTS

5.1 Effect of Base Course

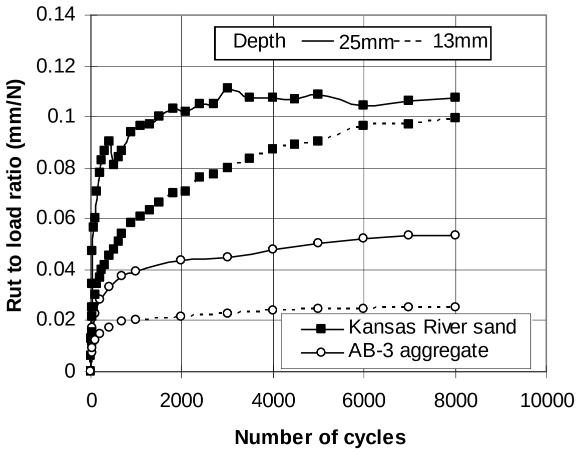
Since the Kansas River sand and the AB-3 aggregate had different mechanical properties, different load levels and hose pressures were used for testing these two base materials. For comparison purposes, the test results are expressed as the ratio of rut to load with respect to the number of cycles. Figure 6 presents the rut to load ratio with the number of cycles for these two base materials without and with geosynthetic at a depth of 25 mm or 13 mm below the surface. It is clearly shown that the Kansas River sand had much higher rut to load ratios than the AB-3 aggregate. In addition, the geosynthetic sheet placed at a depth of 13 mm typically yielded lower rut to load ratios. In other words, the geosynthetic sheet was more effective at the depth of 13 mm than that at the depth of 25 mm. The depth of 13 mm is equivalent to 0.5 times the width of the loading (also the rut) path.



(a) Unreinforced

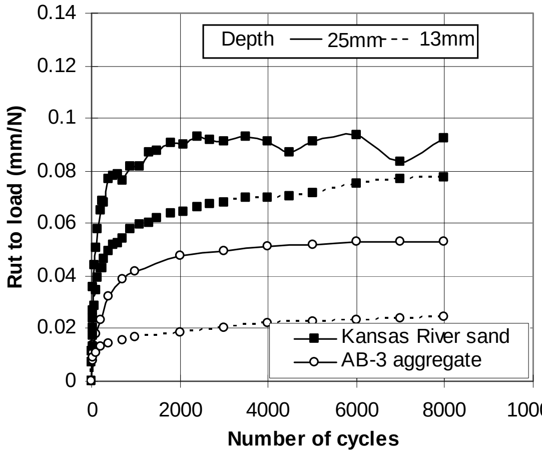


(b) GG1

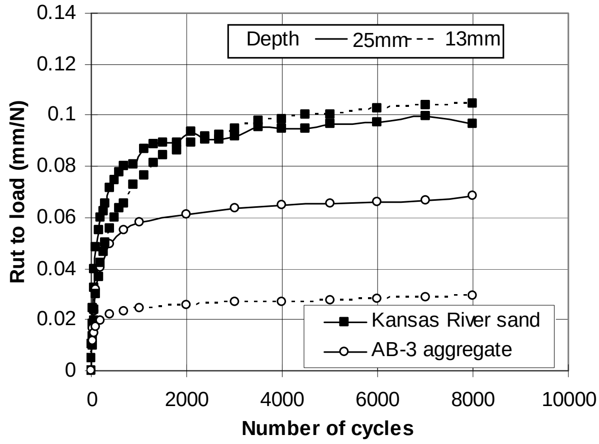


(c) GG2

Figure 6. Effect of base course material



(d) GG3



(e) GT1

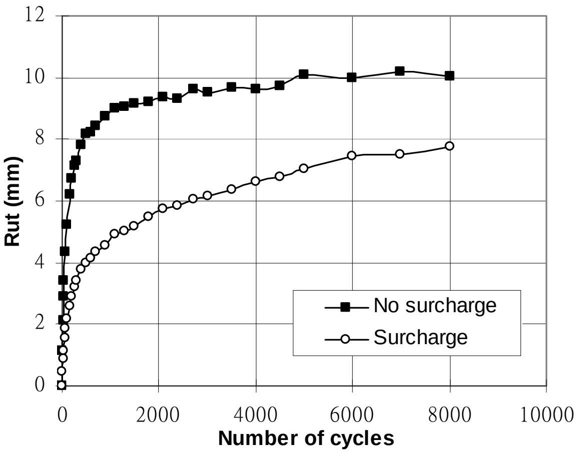
Figure 6. Effect of base course material (continued)

5.2 Effect of Surcharge

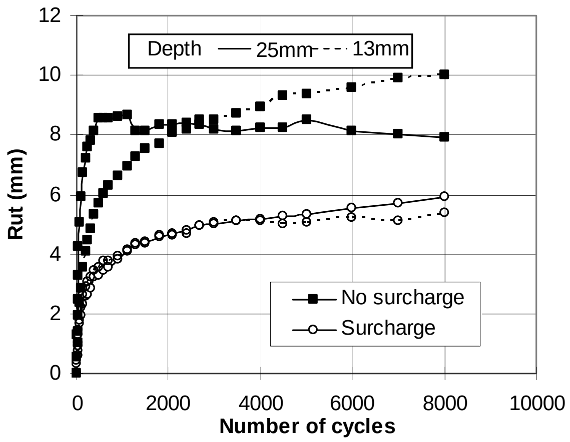
Surcharge is one kind of confinement on the geosynthetic-soil interaction. In this study, the surcharge was only used in the tests for the Kansas River sand. Figure 7 shows the comparisons of test results for unreinforced and reinforced cases without and with surcharge. It is shown that the rut depths for most cases with surcharge were less than those without surcharge. This effect proves that surcharge can provide confinement to the base course and effectively reduce the rut depth. In addition, Figure 7 shows that the geosynthetic sheet placed at a depth of 13mm typically had less rut depth than that placed at a depth of 25mm. It further demonstrates that 13 mm was an effective depth for geosynthetic-soil confinement in this study.

5.3 Effect of Geosynthetic Type

The capability of the newly developed test method to determine the relative benefits of the different types of geosynthetics was one of the key parameters evaluated in this study. The test results for the Kansas River sand and the AB-3 aggregate with different geosynthetics are presented in Figure 8. It is clearly shown that the AB-3 aggregate benefited more from using geosynthetics than the Kansas River sand, presumably because the AB-3 aggregate consists of angular particles that can interlock well with geosynthetics. Again, the geosynthetic at the depth of 13 mm provided a more significant benefit than that at the depth of 25 mm. Test results in Figure 8, especially for the geosynthetics at the depth of 13 mm, show that GG3 performed the best and was followed by GG2, GT1, and GG1. These comparisons demonstrate that the newly developed test method can distinguish the effect of geosynthetic-soil confinement among all the geosynthetic products, including geogrid and geotextile. It is worthwhile to point out that even though GT1 had the highest tensile strength at 5% strain or second highest tensile strength at 2% strain in the machine direction, it did not perform the best. This finding is consistent with the conclusion by Giroud and Han (2006) that the tensile strength at 5% strain was not relevant to the performance of geogrid-reinforced base. Figure 8 also shows that the woven geotextile GT1 performed better than the geogrid GG1 probably because the geotextile had additional separation function. It should be pointed out that geotextiles are rarely placed within granular bases due to installation damage concern. The purpose of this study including the geotextile within the base course is to demonstrate the flexibility of the test method.

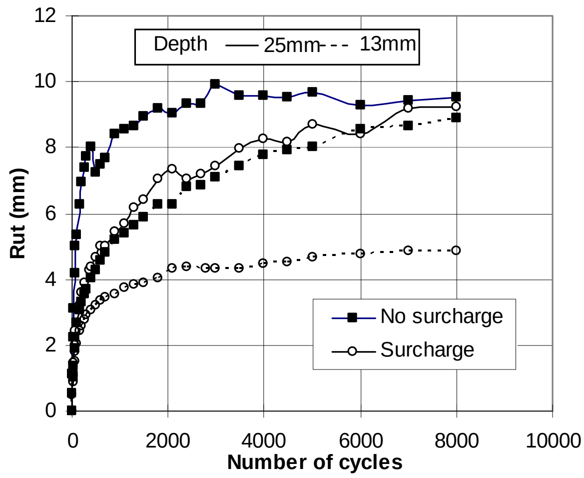


(a) Unreinforced

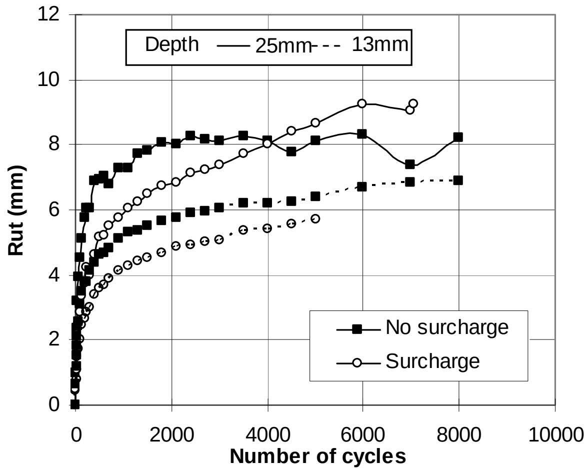


(b) GG1

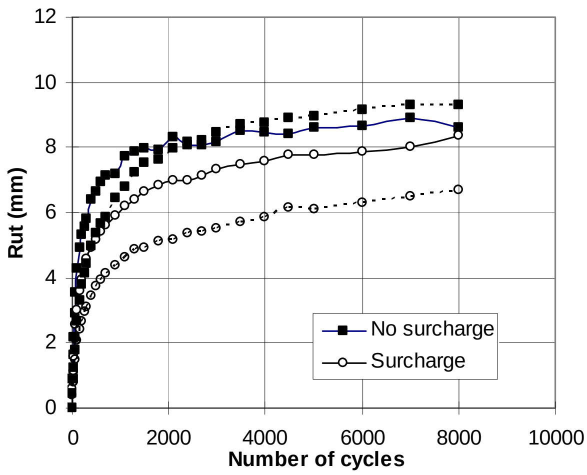
Figure 7. Effect of surcharge



(c) GG2

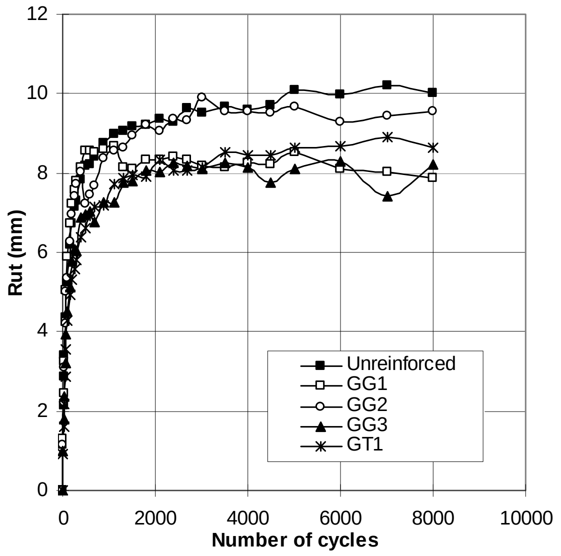


(d) GG3

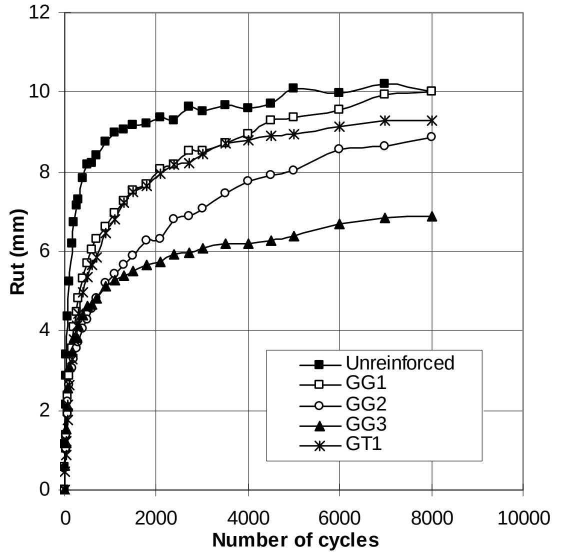


(e) GT1

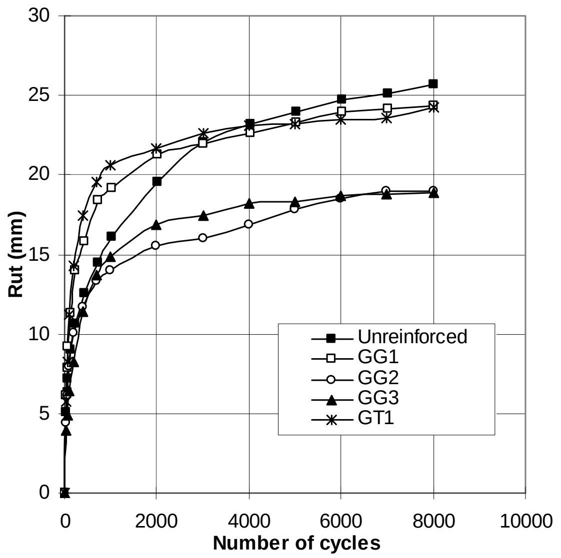
Figure 7. Effect of surcharge (continued)



(a) Kansas River sand and geosynthetic depth = 25mm

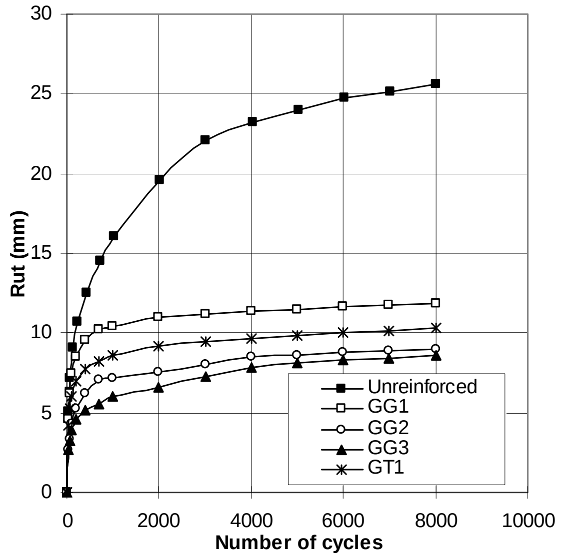


(b) Kansas River sand and geosynthetic depth = 13mm



(c) AB-3 aggregate and geosynthetic depth = 25mm

Figure 8. Effect of geosynthetic type



(d) AB-3 aggregate and geosynthetic depth = 13mm

Figure 8. Effect of geosynthetic type (continued)

5.4 Traffic Benefit Ratio

Traffic Benefit Ratio (TBR) is defined as the ratio of the number of cycles to reach a certain rut depth for the reinforced base to that to reach the same rut depth for the unreinforced base, which can be simply expressed as follows:

$$TBR = \frac{N_{reinforced}}{N_{unreinforced}} \tag{1}$$

where $N_{unreinforced}$ and $N_{reinforced}$ are the numbers of cycles for the unreinforced and reinforced bases.

This parameter has been commonly used to evaluate the effectiveness of geosynthetics in enhancing the road system in term of its service life. This parameter was proposed to compare the service life of a reinforced base over an unreinforced base when they have the same base thickness. TBR depends on the magnitude of the rut depth. In this study, the TBR values were determined based on the rut depth of 6.4 mm, which corresponds to ¼ the width of the wheel path. Figure 9 shows the example for the calculation of the TBR for GG3: $N_{unreinforced} = 55$, $N_{reinforced} = 1700$, TBR = 1700/55 = 31. The calculated TBR values for all the reinforced sections are provided in Table 4. Table 4 shows that the calculated TBR values range from 0.4 to 36, which are commonly seen from the field test data. The TBR data for the Kansas River sand under surcharge show large variations and do not correlate well with the properties of geosynthetics; therefore, further studies are required. For the tests without surcharge, the geogrid product with a higher torsional rigidity modulus had a higher TBR value, i.e., $TBR_{GG3} > TBR_{GG2} > TBR_{GG1}$. This result is consistent with the earlier field study by Webster (1992). Table 4 shows that the geosynthetic sheet placed at a depth of 25mm had little or no benefit in the TBR value. The comparisons also show that the Kansas River sand had relative higher TBR values than the AB-3 aggregate. However, Figure 8 shows that the reduction of the rut for the AB-3 aggregate by geosynthetics is much more significant than that for the Kansas River sand. This fact cannot be reflected through the TBR results.

Therefore, the authors propose another parameter, called the Rut Reduction Ratio (RRR), which is defined as the ratio of the rut of the reinforced base to that of the unreinforced base at the same service life (8,000 cycles in this study). This parameter can be used to evaluate the benefit or effect of geosynthetic-soil confinement on the rut reduction of the reinforced base using different geosynthetic products. It is obvious that the reinforced section with a lower RRR value is better in terms of performance improvement. The AB-3 aggregate clearly had much lower RRR values than the Kansas River sand for the geosynthetic sheet placed at a depth of 13 mm. In addition, the geogrid with a higher torsional rigidity modulus had a lower RRR value.

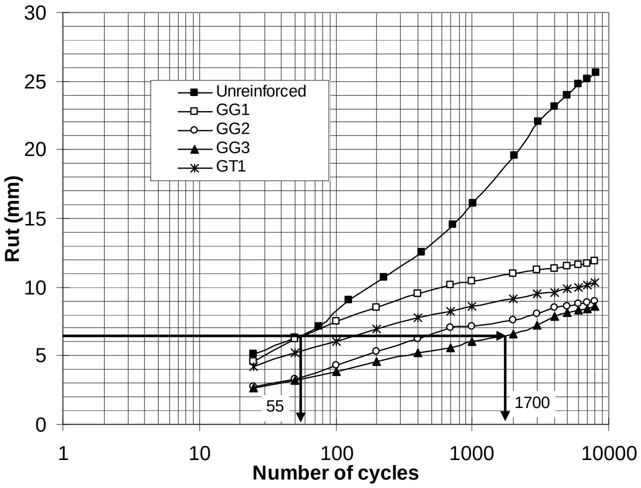


Figure 9. Calculation of TBR

Table 4. Calculated TRB and RRR values

Base	q	z (mm)	TBR				RRR			
			GG 1	GG 2	GG 3	GT 1	GG 1	GG 2	GG 3	GT 1
Kansas River sand	N	25	0.7	1.0	2.1	2.7	0.8	1.0	0.8	0.9
		13	5.7	7.9	36	6.4	1	0.9	0.7	0.9
	Y	25	4.6	0.4	0.4	0.4	0.8	1.2	1.2	1.1
		13	5.7	29	2.9	1.9	0.7	0.6	0.8	0.9
AB-3	N	25	0.5	1.1	2	0.6	1.0	0.7	0.7	1.0
		13	1	7.8	31	2.4	0.5	0.4	0.3	0.4

Note: q = surcharge, z = geosynthetic depth, Y = Yes, N = No.

5.5 Numerical Analysis

To further understand the mechanism of geosynthetic-soil interaction under repeated loading, a numerical analysis was conducted by Bhandari and Han (2010) using the discrete element method (DEM) incorporated in the software PFC^{2D} (Itasca, 2004). Details of this study can be found in Bhandari and Han (2010) including the model of contact and input parameters. Relevant information and numerical results are presented below. In this numerical study, only geotextiles were investigated. The analysis of geogrid-reinforced bases is under way and will be published in future publications.

For the numerical simulation, the test box with the same dimensions in the laboratory was created with four walls (Figure 10). The box was divided into two compartments based on the location of the geotextile in the laboratory tests. Uniform-sized cylindrical particles of 4.0 mm in diameter were generated simultaneously in both compartments and a radius expansion technique was chosen to obtain the required 2-D porosity (n = 0.16), which is equivalent to a medium dense condition in the laboratory. This particle size is about 1.5 times the actual size used in the laboratory to save the computation time. The geotextile layer modeled using bonded particles of 1.0 mm in diameter with the same tensile stiffness as the geotextile product in the laboratory was placed by generating the particles inside the guided walls. After the generation of the geotextile layer, the walls were deleted and a hose was created at the top of the assembly by particles with the same size and properties as the geotextile. The assembly was then subjected to the gravity loading and cycled to meet the equilibrium of forces. The time step for the analysis was 8.3E-7. On top of the hose, a wheel (diameter = 40 mm) was created at the mid-length to apply a vertical cyclic load of 353 N in the DEM model. The assembly was solved until the ratio of the maximum unbalanced force to the maximum contact force reached the value of 0.01 (default in the PFC^{2D}). The load was removed from the wheel and the assembly was again solved in the similar way. This loading and unloading process was repeated for 25 cycles (i.e. 25 loading and 25 unloading) and the vertical deformations were recorded.

Four cases were analyzed in the numerical analysis: (1) the model without any reinforcement, (2) the geotextile placed at a depth of 12.5 mm below the top surface, (3) the geotextile placed at a depth of 25.0 mm below the top surface, and (4) a sheet of tiny particles without any bonding strength at the depth of 25 mm to investigate a slippage effect. The first three cases qualitatively represent the laboratory tests for the geotextile-reinforced bases.

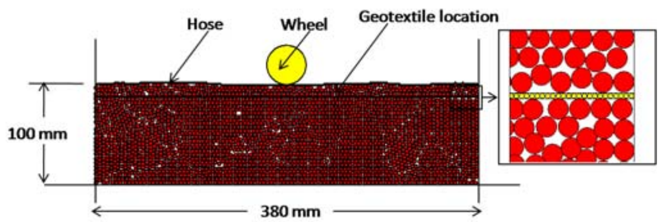


Figure 10. DEM model of APA test simulation (after Bhandari and Han, 2010)

Figure 11 presents the numerical results of the vertical permanent deformation vs. the number of cycles, which are qualititively similar to the experimental results. It is shown that a sheet of tiny particles significantly increased the permanent deformation. This result implies any possible slippage at the interface of the geotextile would increase permanent deformation. Figure 11 shows that the model with the geotextile at a depth of 25.0 mm had larger permanent deformation than that without a geotextile. This result is different from that in the experimental study. The reason for this difference may be attributed to different particle shapes and size distributions. Angular particles with different sizes in the experiment tend to interact with the geotextile better to minimize lateral movement of particles. This numerical result can be explained as that the slippage at the interface of the geotextile had more effect on the deformation than that limited by the confinement of the geotextile. It is clearly shown that the model with the geotextile at the depth of 12.5 mm had the smallest deformation because of the dominant confinement effect by the geotextile at this depth. The non-smooth curves with steps in the two cases could be due to a limited number of particles and a formation of a quasi-stable configuration of the particles during simulation, which collasped with additional loading and unloading steps. The smoothness of the curves can be improved using a larger number of particles, which requires significant computation time.

5.6 Limitations

The experimental study was based on the base course materials with particle sizes smaller than 12.5 mm. A base course with larger particles requires a larger test box, larger hoses, and deeper placement of the geosynthetic layer. A Model Mobile Load Simulator 3 can be used for this purpose, but requires more time and expenses. The TRB or RRR values obtained from this experimental method show the relative comparison of performance of different geosynthetics with specific base course materials and they should not be used for design before they are verified or correlated to large or full-scale test results. Geotextiles are rarely placed within base courses, but they were used in this study to demonstrate the flexibility of the experimental method.

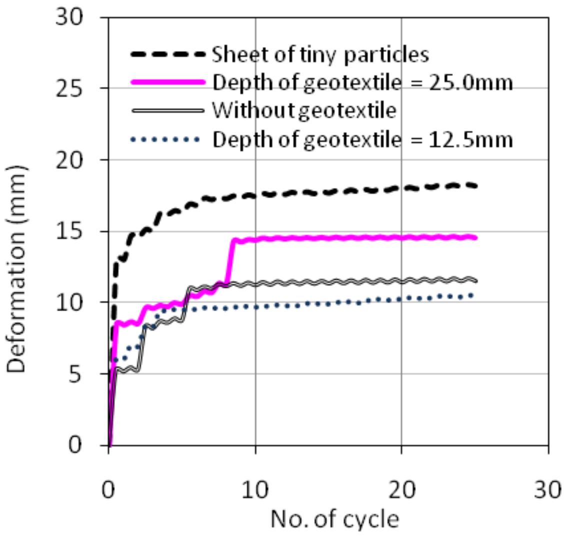


Figure 11**.** Simulated numerical results at particle porosity of n=0.16 (medium dense sand) (after Bhandari and Han, 2010)

6. CONCLUSIONS

To effectively and efficiently quantify the influence of geosynthetic confinement on reinforced bases is a challenging task. Considering the limitations of the existing test methods for evaluating the geosynthetic-soil confinement under traffic loading, a newly developed performance-based test method using the modified Asphalt Pavement Analyzer was investigated in this study. The experimental study shows that the newly developed test method had good repeatability of test results and could reasonably distinguish the effect of geosynthetic-soil confinement among all the geosynthetics investigated in this study. Effects of geosynthetic reinforcement depended on the quality of base material, the surcharge, and the type and depth of geosynthetic reinforcement. The effective embedment depth of geosynthetic sheet was at 0.5 times the width of the loading path in this study. The numerical analysis for geotextile-reinforced bases showed that any possible slippage at the interface of the geotextile would increase the permanent deformation and minimize the benefit of geotextile confinement.

7. ACKNOWLEDGEMENTS

This research was jointly funded by the University of Kansas, Transportation Research Institute from Grant # DT0S59-06-G-00047, provided by the US Department of Transportation – Research and Innovative Technology Administration and Tensar International Corporation. Their support is greatly appreciated. The authors also would like to thank Mr. Jim Weaver, the laboratory manager of the Civil, Environmental, and Architectural Engineering (CEAE) at the University of Kansas for his excellent technical support during this study.

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