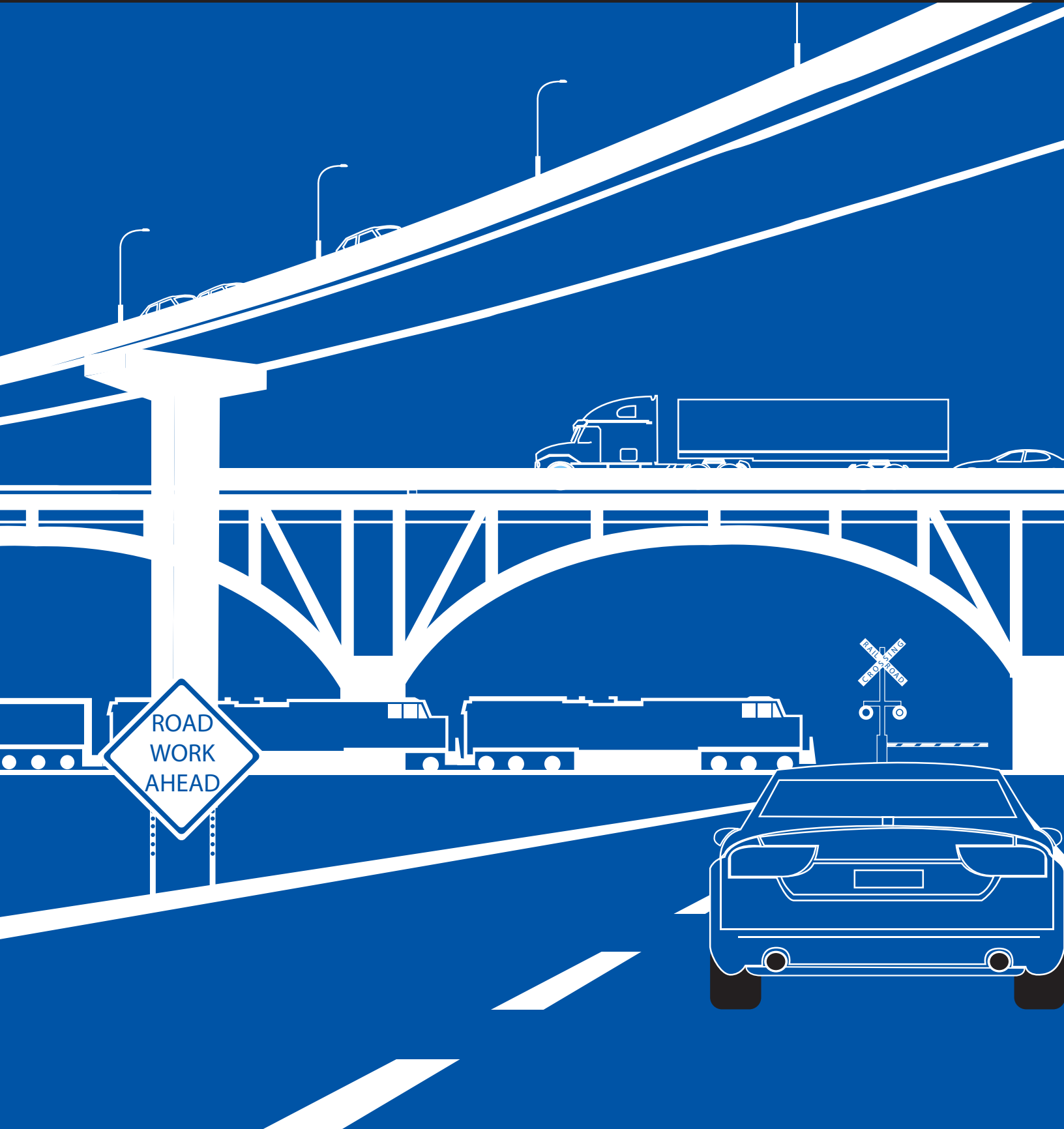




Development of a Laboratory Test for Evaluation of Geogrid Materials

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Kentucky Transportation Center
College of Engineering, University of Kentucky, Lexington, Kentucky

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Research Report
KTC-16-21/SPR15-493-1F

Development of a Laboratory Test for Evaluation of Geogrid Materials

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16. Abstract Two test methods have been developed in this project. The first test method is a compression test of a cylinder constructed out of geogrid material and filled with crushed stone. This test is simple and can be easily performed. Only a compression loading machine is needed for this test. The sample preparation is straightforward. However, multiple tests must be run to analyze geogrids with different ultimate tensile strength or different grid aperture size on machine direction and cross machine direction. The second test method is Geogrid Bearing Ratio (GBR) test. This test was developed to measure the effect of geogrids on bearing capacity improvement. The ratio of bearing capacity for the <i>with geogrid</i> treatment to the bearing capacity for the <i>without geogrid</i> treatment is an index that captures a geogrid's contribution to bearing capacity improvement. The GBR test result is one-parameter, which informs designers of how a geogrid functions in the pavement structure. This test enables comparisons of geogrids with differently aperture shapes. Any difference on grid single string strengths or aperture sizes or shapes are identified by GBR number. GBRs are related to the combined function of string strength, rigidity and integration properties of the geogrid. The optimal geogrid installation position under penetration loading is explored using GBR test. The optimum position is at 4 in. from bottom in 8 in. thick crushed stone configuration under 1.954 in. in diameter piston loading. It is critical to analyze or test particular cases in order to determine a practical, optimal design.			
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Executive Summary

Two test methods have been developed in this project. KYTC personnel can use these methods to quickly, easily and directly test geogrid performance.

The first test method is a compression test of a geogrid cylinder. This test method consists of applying a compressive axial load to the cylinder at a rate within a prescribed range until failure occurs. The geogrid's contribution to bearing capacity improvement is denoted by how high compressive axial load can be reached. Only a compression loading machine is needed for the test. Sample preparation is straightforward. The failure load can be reached either on grid rib broken, torn off, or on junction slippage. The failure loads are positively proportional to grid rib tensile strength and the number of grid ribs involved, if junction strength is strong enough. However, multiple tests must be run to evaluate geogrids with different ultimate tensile strength or grid aperture sizes on machine direction and cross machine direction.

The second test method is the Geogrid Bearing Ratio (GBR) test. This test was developed to measure the bearing capacity changes between treatments with and without a geogrid. The ratio of bearing capacity for the *with-geogrid* treatment to bearing capacity for the *without-geogrid* treatment is an index that captures a geogrid's contribution to improvements in bearing capacity. The GBR test result is one-parameter that informs designers about a geogrid's function in pavement structure. This GBR number indicates the bearing capacity improvement from geogrid contribution. Bearing capacity improvements can be compared based on the GBR number, regardless of differences of aperture shapes between geogrids. Any difference in grid single string strength, aperture size or shape is captured in the GBR number. All of the stress penetration curves have similar shapes before 0.20 in. penetration. The bearing capacity almost reaches ultimate value for the *crushed stone only* treatment when the piston achieves 0.60 in. penetration. As penetration increases, so does the GBR value. Combining crushed stone with a geogrid produces much stronger bearing capacity under larger penetration than does crushed stone alone. GBRs are positively proportional to the single string strengths of geogrids, irrespective of their apertures' shape. But they are not directly related to ultimate strength of geogrid only. GBRs are related to the combined effects of string strength, rigidity and integration properties of the geogrid. A GBR test cannot be used to identify improvement in bearing capacity for geosynthetic fabrics (or any combination of geosynthetic fabric materials with geogrids) because the interlocking function between crushed stone and these kinds of materials cannot be developed.

To deepen our analysis of pavement structure, we used the GBR test to explore the optimal geogrid installation position under penetration loading. The optimal geogrid installation position is at 4 in. from the bottom in an 8 in. thick crushed stone configuration under a 1.954 in. in diameter piston loading. Enhancing the interlocking structure of the geogrid and crushed stone is critical for maximizing a geogrid's contribution to pavement functioning. Different loadings may have different optimal geogrid installation positions. Therefore, we recommend testing and analyzing situations on a case-by-case basis to determine a practical, optimal design.

1. Introduction

1.1 Background

Subgrade stabilization for roadway construction generally requires that the subgrade geogrid-base layer system reach a stable condition. This condition is typically assessed by observing and evaluating the deformation of the system under the single pass of a loaded vehicle. Under stable conditions, bearing capacity failure of the subgrade does not occur. For this operational condition, it is anticipated that other geogrid properties which might be more significant for conditions of smaller loads and deformations will be important for assessing material performance. The goal of this research is to simulate operational conditions in a laboratory setting to identify the material properties of geogrids that impact their in-situ performance when used for subgrade stabilization. It will highlight the most appropriate geogrid properties that should be considered for the subgrade stabilization application. Information in this report will help designers at the Kentucky Transportation Cabinet (KYTC) objectively select an appropriate geogrid for a particular job. It will also help prevent or quell conflicts that may arise between KYTC and manufacturers/distributors when a particular geogrid is chosen over another. Avoiding these conflicts may stave off potential litigation, and save Cabinet personnel time and money.

1.2 Problem Statement

Highway construction routinely uses geogrid to stabilize the subgrade. This construction practice involves placing an appropriately specified geogrid on a weak subgrade prior to placement of roadway subbase. The geogrid stabilizes the subgrade by increasing the system's load-carrying capacity. A stable subgrade allows for a firm construction platform to be built with less aggregate and construction time. There is a general consensus concerning the effectiveness of geogrids; but there is a lack of understanding and agreement over the material's properties needed to achieve satisfactory performance. There are many new geogrid manufacturers entering the market. Many of these have developed their own methods to evaluate and compare different types and strengths of materials. In order to provide for the most economical geogrid selection while minimizing conflicts and promoting competitiveness, a study is needed that examines the performance of various geogrids for subgrade stabilization. This study relates geogrid performance to material properties, which can be incorporated into their standard specification to allow for a broad and economical use of geogrid products.

2. Objectives

The main objectives of this research study are:

1. Evaluate alternative laboratory tests to determine which material properties of geogrids impact their in-situ performance when they are used to stabilize the subgrade. This knowledge will let the Cabinet objectively evaluate various geogrid materials submitted for approval.
2. Illustrate cost savings that can be realized by optimizing geogrid position within the pavement structure.

3. Existing Test Methods

ASTM International and Geosynthetic Institute have fashioned dozens of methods for testing geogrid performance. These methods tested geogrid material properties under various conditions, such as:

- Standard Test Method for Determining Tensile Properties of Geogrids by the Single or Multi-Rib Tensile Method (ASTM D6637 – 11)
- Standard Test Method for Flexural Rigidity of Geogrids, Geotextiles and Related Products (ASTM D7748/D7748M – 14)
- Standard Test Method for Individual Geogrid Junction Strength (ASTM D7737 – 11)
- Standard Test Methods for Determining Small-Strain Tensile Properties of Geogrids and Geotextiles by In-Air Cyclic Tension Tests (ASTM D7556 – 10)
- Standard Test Method for Static Puncture Strength of Geotextiles and Geotextile-Related Products Using a 50-mm Probe (ASTM D6241 – 14)
- Determination of the Long-Term Design Strength of Stiff Geogrids (GRI GG4a)
- Determination of the Long-Term Design Strength of Flexible Geogrids (GRI GG4b)

3.1 ASTM D6637 - 11: Standard Test Method for Determining Tensile Properties of Geogrids by the Single or Multi-Rib Tensile Method

This test method covers the determination of the tensile strength properties of geogrids by subjecting strips of varying widths to tensile loading. Three alternative procedures are provided to determine the tensile strength, as follows:

Method A – A single, representative rib specimen of a geogrid is clamped and placed under a tensile force using a constant rate of extension testing machine. The tensile force required to fail (rupture) the specimen is recorded. The ultimate single rib tensile strength (N or lbf) is then determined based on the average of six single rib tensile tests.

Method B – A relatively wide specimen is gripped across its entire width in the clamps of a constant rate of extension type tensile testing machine operated at a prescribed rate of extension, applying a uniaxial load to the specimen until the specimen ruptures. Tensile strength (kN/m or lbf/ft), elongation, and secant modulus are calculated.

Method C - A relatively wide, multiple layered specimen is gripped across its entire width in the clamps of a constant rate of extension type tensile testing machine operated at a prescribed rate of extension, applying a uniaxial load to the specimen until the specimen ruptures. Tensile strength (kN/m or lbf/ft), elongation and secant modulus of the test specimen are calculated.

The determination of the tensile force-elongation values of geogrids provides index property values. This test method shall be used for quality control and acceptance testing of commercial shipments of geogrids.

In cases of dispute arising from differences in reported test results when using this test method for acceptance testing of commercial shipments, the purchaser and supplier should conduct comparative tests to determine if there is a statistical bias between their laboratories. Competent

statistical assistance is recommended for the investigation of bias. As a minimum, the two parties should take a group of test specimens which are as homogeneous as possible and which are from a lots of material of the type in question. The test specimens should then be randomly assigned in equal numbers to each laboratory for testing. The average results from the two laboratories should be compared using Student's t-test for unpaired data and an acceptable probability level chosen by the two parties before the testing began. If a bias is found, either its cause must be found and corrected or the purchaser and supplier must agree to interpret future test results in light of the known bias.

All geogrids can be tested by any of these methods. Some modification of techniques may be necessary for a given geogrid depending upon its physical make-up. Special adaptations may be necessary with strong geogrids, multiple layered geogrids, or geogrids that tend to slip in the clamps or those which tend to be damaged by the clamps.

3.2 ASTM D7748/D7748M - 14: Standard Test Method for Flexural Rigidity of Geogrids, Geotextiles and Related Products

This test method covers the measurement of stiffness properties of geogrids, geotextiles and geogrid-geotextile composites all of which are referred to as geosynthetics within this test method. Bending length is measured and flexural rigidity is calculated through use of the cantilever test procedure. This test method employs the principle of cantilever bending of the geosynthetic under its own mass.

This test method applies to geogrids, geotextiles and geogrid-geotextile composites. This test method is for manufacturing quality control purposes only, to ensure uniformity and consistency of flexural rigidity for a specific product from roll to roll and lot to lot. The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

A specimen is slid at a specified rate in a direction parallel to its long dimension, until its leading edge projects from the edge of a horizontal surface. The length of the overhang is measured when the tip of the specimen is depressed under its own mass to the point where the line joining the top to the edge of the platform makes a 41.5° angle with the horizontal. From this measured length, the bending length and flexural rigidity are calculated.

This test method is considered satisfactory for manufacturing quality control testing of a specific geosynthetic; however, caution is advised since precision between laboratories is uncertain. In case of a dispute arising from differences in reported test results when using this test method for acceptance testing of commercial shipments, the purchaser and the supplier should conduct comparative tests to determine if there is a statistical bias between their laboratories. Competent statistical assistance is recommended for the investigation of bias. As a minimum, the two parties should take a group of test specimens that are as homogeneous as possible and that are from a lot of material of the type in question. Test specimens should then be randomly assigned in equal numbers to each laboratory for testing. The average results from the two laboratories should be compared using the appropriate statistical analysis and an acceptable probability level chosen by the two parties before testing is begun. If a bias is found, either its cause must be found and

corrected or the purchaser and the supplier must agree to interpret future test results with consideration to the known bias.

This test method is not suitable for very limp geosynthetics or those that show a marked tendency to curl or twist at a cut edge. The stiffness of a geosynthetic may change with storage. No evidence has been found showing that bending length is dependent on specimen width. The tendency for specimens to curl or twist will affect the result, because of the rigidity provided at the edge. Consequently, the edge effect is less of an issue for a wider strip.

3.3 ASTM D7737 - 11: Standard Test Method for Individual Geogrid Junction Strength

This test method is an index test which provides a procedure for determining the strength of an individual geogrid junction, also called a node. The test is configured such that a single rib is pulled from its junction with a cross-rib to obtain the maximum force, or strength of the junction. The procedure allows for the use of two different clamps with the appropriate clamp selected to minimize the influence of the clamping mechanism on the specific type of geogrid to be tested.

This standard proposes a test method for performing tension tests on geogrid junctions. The procedure provides two clamping techniques for the junction to be tested including: Method A in which the clamps firmly grip the ribs transverse to the test direction on each side of the junction; and, Method B in which the ribs transverse to the test direction are constrained in a slot, constraining rotation of the junction, while the rib in the test direction passes through the slot without the junction clamp applying confinement to the junction. The junction clamping technique is selected for the specific type of geogrid in order to minimize rotation and corresponding peel of the junction during the test. The rib in the test direction going through the junction is then clamped at a distance from the junction and the system tensioned until junction (or rib) failure occurs. This forces a tension or shear force to occur within the junction in the direction of the applied load. The junction has no normal pressure on it, i.e., it is horizontally unconfined.

This index test method is to be used to determine the strength of an individual junction in a geogrid product. The test is performed in isolation, while in service the junction is typically confined. Thus the results from this test method are not anticipated to be related to design performance. The value of junction strength can be used for manufacturing quality control, development of new products, or a general understanding of the in-isolation behavior of a particular geogrid's junction (for example., in relation to handling during shipment and placement of the geogrid). This test method is applicable to geogrid products with essentially orthogonal ribs, yarns or straps, that is, geogrids which are composed of ribs, yarns or straps that are entangled through weaving or knitting, welded, bonded or formed through drawing.

3.4 ASTM D7556 - 10: Standard Test Methods for Determining Small-Strain Tensile Properties of Geogrids and Geotextiles by In-Air Cyclic Tension Tests

These test methods cover the determination of small strain tensile properties of geogrids and geotextiles by subjecting wide-width specimens to cyclic tensile loading. These test methods (A, B, and C) allow for the determination of small-strain cyclic tensile modulus by the measurement of cyclic tensile load and elongation. This test method is intended to provide properties for design. The test method was developed for mechanistic empirical pavement design methods requiring input of the reinforcement tensile modulus. The use of cyclic modulus from this test method for

other applications involving cyclic loading should be evaluated on a case-by-case basis. Three test methods (A, B, and C) are provided to determine small-strain cyclic tensile modulus on geogrids and geotextiles.

Test Method A - In this test method, a relatively wide geogrid specimen is gripped across its entire width in the clamps of a constant rate of extension type tensile testing machine operated at a prescribed rate of extension, applying a uniaxial cyclic load to the specimen over specified limits of cyclic axial strain and centered around six successively greater levels of prescribed or permanent axial strain. Tensile modulus in kN/m (lbf/ft) of the test specimen can be calculated at each level of prescribed axial strain from the last cycles of load.

Test Method B - A relatively wide, multiple layered geogrid specimen is gripped across its entire width in the clamps of a constant rate of extension type tensile testing machine operated at a prescribed rate of extension, applying a uniaxial cyclic load to the specimen over specified limits of cyclic axial strain and centered around six successively greater levels of prescribed or permanent axial strain. Tensile modulus in kN/m (lbf/ft) of the test specimen can be calculated at each level of prescribed axial strain from the last cycles of load.

Test Method C – A relatively wide geotextile specimen is gripped across its entire width in the clamps of a constant rate of extension type tensile testing machine operated at a prescribed rate of extension, applying a uniaxial cyclic load to the specimen over specified limits of cyclic axial strain and centered around six successively greater levels of prescribed or permanent axial strain. Tensile modulus in kN/m (lbf/ft) of the test specimen can be calculated at each level of prescribed axial strain from the last cycles of load.

Test Methods A, B, and C provide a means of evaluating the tensile modulus of geogrids and geotextiles for applications involving small-strain cyclic loading. The test methods allow for the determination of cyclic tensile modulus at different levels of prescribed or permanent strain, thereby accounting for possible changes in cyclic tensile modulus with increasing permanent strain in the material. These test methods shall be used for research testing and to define properties for use in specific design methods.

In cases of dispute arising from differences in reported test results when using these test methods for acceptance testing of commercial shipments, the purchaser and supplier should conduct comparative tests to determine if there is a statistical bias between their laboratories. Competent statistical assistance is recommended for the investigation of bias. As a minimum, the two parties should take a group of test specimens which are as homogeneous as possible and which are from a lot of material of the type in question. The test specimens should then be randomly assigned in equal numbers to each laboratory for testing. The average results from the two laboratories should be compared using Student's t-test for unpaired data and an acceptable probability level chosen by the two parties before the testing began. If a bias is found, either its cause shall be found and corrected or the purchaser and supplier shall agree to interpret future test results in light of the known bias.

All geogrids can be tested by Test Methods A or B. Some modification of techniques may be necessary for a given geogrid depending upon its physical make-up. Special adaptations may be

necessary with strong geogrids, multiple layered geogrids, or geogrids that tend to slip in the clamps or those which tend to be damaged by the clamps.

Most geotextiles can be tested by Test Method C. Some modification of clamping techniques may be necessary for a given geotextile depending upon its structure. Special clamping adaptations may be necessary with strong geotextiles or geotextiles made from glass fibers to prevent them from slipping in the clamps or being damaged as a result of being gripped in the clamps.

These test methods are applicable for testing geotextiles either dry or wet. It is used with a constant rate of extension type tension apparatus.

These test methods may not be suited for geogrids and geotextiles that exhibit strengths approximately 100 kN/m (600 lbf/in.) due to clamping and equipment limitations. In those cases, 100 mm (4 in.) width specimens may be substituted for 200 mm (8 in.) width specimens.

3.5 ASTM D6241 - 14: Standard Test Method for Static Puncture Strength of Geotextiles and Geotextile-Related Products Using a 50-mm Probe

This test method is an index test used to measure the force required to puncture a geotextile and geotextile-related products. The relatively large size of the plunger provides a multidirectional force on the geotextile.

A test specimen is clamped without tension between circular plates and secured in a tensile or compression testing machine, or both. A force is exerted against the center of the unsupported portion of the test specimen by a steel plunger attached to the load indicator until rupture occurs. The maximum force is the value of puncture strength.

This test method for determining the puncture strength of geotextiles is to be used by the industry as an index of puncture strength. The use of this test method is to establish an index value by providing standard criteria and a basis for uniform reporting. This test method is considered satisfactory for acceptance testing of commercial shipments of geotextiles. In case of a dispute arising from differences in reported test results when using this test method for acceptance testing of commercial shipments, the purchaser and the supplier should conduct comparative tests to determine if there is a statistical bias between their laboratories. Competent statistical assistance is recommended for the investigation of bias. As a minimum, the two parties should take a group of test specimens that are as homogeneous as possible and that are from a lot of the type in question. The test specimens then should be randomly assigned in equal numbers to each laboratory for testing. The average results from the two laboratories should be compared using Student's t-test for unpaired data and an acceptable probability level chosen by the two parties before the testing is begun. If a bias is found, either its cause must be found and corrected, or the purchaser and the supplier must agree to interpret future test results in the light of the known bias.

This test method is not applicable to materials that are manufactured in sizes that are too small to be placed into the test apparatus in accordance with the procedures in this test method. Furthermore, it is not appropriate to separate plies of a geosynthetic or geocomposite for use in this test method.

3.6 GRI GG4a: Determination of the Long-Term Design Strength of Stiff Geogrids

This standard practice is to be used to determine the long-term design load of stiff geogrids for use in the reinforcement of such structures as embankments, slopes, retaining walls, improved bearing capacity, and other permanent geotechnical and transportation engineering systems. “Stiff” includes geogrids exhibiting more than 1000 g-cm flexural rigidity in the ASTM D1388 stiffness test. The method is based on the concept of identifying and quantifying reduction factors for those phenomena which can impact the long-term performance of stiff geogrid reinforced systems and are not taken into account in traditional laboratory testing procedures.

The reduction factors to be considered are for installation damage, creep deformation, chemical degradation, biological degradation, junction strength (depending on the type of short-term laboratory strength test procedure) and joints (seams and connections). These reduction factor values can be obtained by direct experimentation and measurement, or by using default values which are given for the various applications which use geogrids.

This standard practice is meant to adjust a laboratory generated short term ultimate geogrid tensile strength value to a site-specific allowable tensile strength value by using reduction factors on selected phenomena. It is then to be used with a factor-of-safety for the site-specific situation under consideration. The focus of the standard is toward stiff geogrids with a flexural rigidity of 1000 g-cm, or higher. Specific procedures for quantifying each of the reduction factors are provided. If these procedures are not followed default values are provided.

Rather than use an unusually high overall factor-of-safety for geogrid reinforced structures (in comparison to those factors-of-safety used in a conventional design involving soil, concrete or steel), this standard of practice uses reduction factors for those particular phenomena which may diminish the long-term performance of the as received geogrid material.

The reduction factors to be discussed are those of installation damage, creep deformation, chemical degradation, biological degradation, junction strength (unless accounted for in prior testing) and joints (seams and connections). The result of compensating for these phenomena is an allowable geogrid strength which can be used directly in design.

Procedures are given as to how one obtains each of the above reduction factors for the various phenomenon. As an option to conducting the above procedures, default values are given for each of the different phenomena depending on the particular geogrid reinforcement application. The standard practice is site specific, application specific, and geogrid product specific, the latter being for stiff geogrids of flexural rigidity of 1000 g-cm or higher.

3.7 GRI GG4b: Determination of the Long-Term Design Strength of Flexible Geogrids

This standard practice is to be used to determine the long-term design load of flexible geogrids for use in the reinforcement of such structures as embankments, slopes, retaining walls, improved bearing capacity, and other permanent geotechnical and transportation engineering systems. “Flexible” includes geogrids exhibiting less than 1000 g-cm flexural rigidity in the ASTM D1388 stiffness test. The method is based on the concept of identifying and quantifying reduction factors for those phenomena which can impact the long-term performance of flexible geogrid reinforced systems and are not taken into account in traditional laboratory testing procedures. The reduction

factors to be considered are for installation damage, creep deformation, chemical degradation, biological degradation and joints (seams and connections). These reduction factors values can be obtained by direct experimentation and measurement, or by using default values which are given for the various applications which use geogrids.

This standard practice is meant to adjust a laboratory generated short term ultimate geogrid tensile strength value to a site-specific allowable tensile strength value by using reduction factors on selected phenomena. It is then to be used with a factor-of-safety for the site-specific situation under consideration. The focus of the standard is toward flexible geogrids with a flexural rigidity of less than 1000 g-cm. Specific procedures for quantifying each of the reduction factors are provided. If these procedures are not followed default values are provided.

Rather than use an unusually high overall factor-of-safety for geogrid reinforced structures (in comparison to those factors-of-safety used in a conventional design involving soil, concrete or steel), this standard of practice uses reduction factors for those particular phenomena which may diminish the long-term performance of the as received geogrid material. The reduction factors to be discussed are those of installation damage, creep deformation, chemical degradation, biological degradation and joints (seams and connections). The result of compensating for these phenomena is an allowable geogrid strength which can be used directly in design. Procedures are given as to how one obtains each of the above reduction factors for the various phenomenon. As an option to conducting the above procedures, default values are given for each of the different phenomena depending on the particular geogrid reinforcement application. The standard practice is site specific, application specific, and geogrid product specific, the latter being for flexible geogrids of flexural rigidity of less than 1000 g-cm.

3.8 Existing Test Method Summary

The above methods seek to compare varied geogrid configurations in reference to material properties. In practice, it is impossible to identify stabilization performance from geogrids with different aperture shapes and difficult to use the suite of testing to objectively identify the best geogrid.

4. New Test Method One: Compression Test of a Cylindrical Geogrid Filled with Crushed Stone

Inspired by the compression test of a concrete cylinder, we developed the *Compression Test of a Cylindrical Geogrid Filled with Crushed Stone*. This test method entails applying a compressive axial load to a $\phi 5\text{-}7/8$ in. by 15 in. geogrid cylinder that has been filled with crushed stone to a depth of 12 in. at a rate within a prescribed range until failure occurs. A higher achieved axial load during testing indicates a greater contribution by the geogrid to confining the sample.

4.1 Sample Preparation

A geogrid cylinder is made by rolling the geogrid around two $5\text{-}7/8$ in. metal cylinders with two rows of overlap, which are tied by wires (Figure 1). The geogrid cylinder has a $5\text{ }7/8$ in. inner diameter and is 15 in. long.



Figure 1. Geogrid wrapped on $5\text{-}7/8$ in. cylinder with two rows of geogrid connections by using wires to make $5\text{-}7/8$ in. inner diameter and 15 in. long cylinder.

Next, the geogrid cylinder was filled with crushed stone to a depth of 12in. (Figure 2). Crushed stones should be sized between $\frac{3}{4}$ in. and 1 in. Tamp down the crushed stone with a metal rod to reduce the amount of void space.



Figure 2. Fill the crushed stone in the geogrid cage to form a ϕ 5-7/8 in. by 12 in. geogrid caged crushed stone cylinder.

Place a metal cylinder atop the crushed stone cylinder and center both on a compression test machine (Figure 3). The sample is now ready for the compressive axial load test.



Figure 3. Place geogrid caged crushed-stone cylinder with a $\phi 5\text{-}7/8$ in. metal cylinder above crushed stone top on compression test machine.

4.2 Compression Testing Machine

A compression test machine with maximum load of 400 kips is used for this test (Figure 4). The range of 20 kips at 200 lbs/s loading rate is applied to the geogrid-caged crushed stone cylinder. Increase compression load on geogrid-caged crushed stone cylinder until it fails (Figure 5).



Figure 4. A compression test machine with maximum load 400 kips.



Figure 5. Cylindrical geogrid filled with crushed stone sample failure.

4.3 Tested Geogrid Samples

Three types of geogrids are tested. The first type of geogrid, called Type 1, is composed of polypropylene resin, which is extruded into a rectangular grid structure (Figure 6). Its ultimate tensile strengths are 1310 lbs/ft. on machine direction (MD) and 1970 lbs/ft. on cross machine direction (CD). The grid aperture sizes are 1.0 in. on MD and 1.3 in. on CD. The second type of geogrid, called Type 2, is composed of high molecular weight, high tenacity polyester multifilament yarns that are woven in tension and finished with a PVC coating with a rectangular formation (Figure 7). Its ultimate tensile strengths are 2500 lbs/ft. on MD and 4500 lbs/ft. on CD. The grid aperture sizes are 1.0 in. on both MD and CD. The third type of geogrid, Type 3, is manufactured from a punched polypropylene sheet, which is then oriented in three substantially equilateral directions so that the resulting ribs have a high degree of molecular orientation that continues, at least in part, through the mass of the integral node (Figure 8). Its nominal rib pitch is 1.6 in. on all three directions.

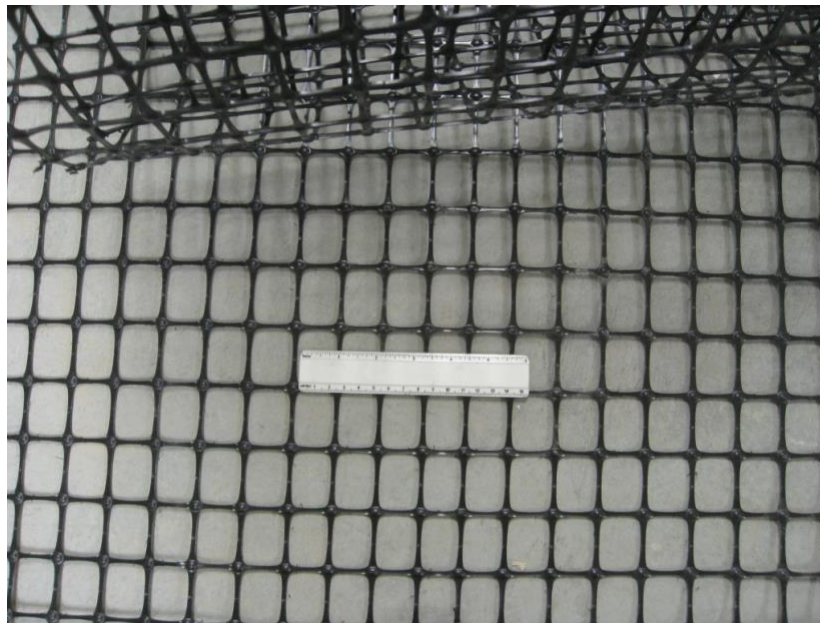


Figure 6. Type 1 - extruded polypropylene resin geogrid.

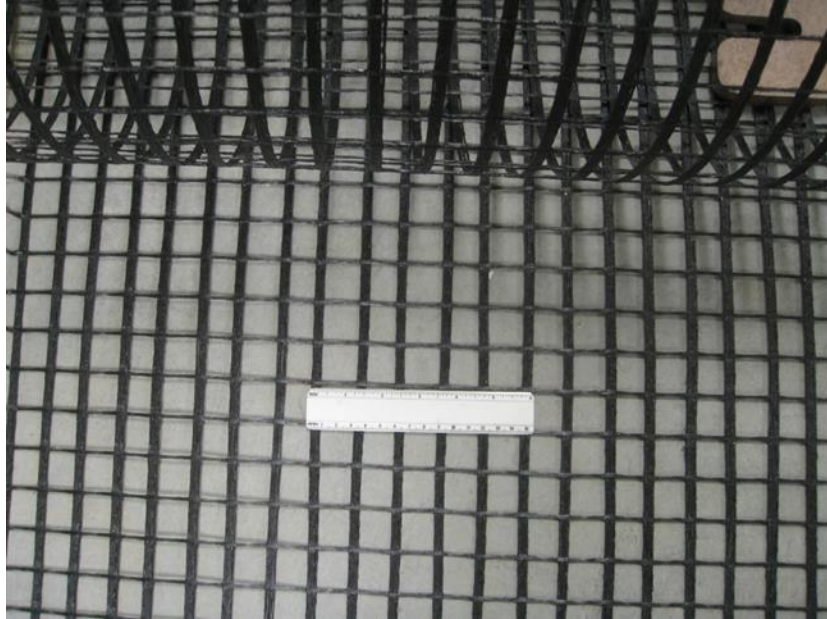


Figure 7. Type 2 – woven high molecular weight, high tenacity polyester miltifilament yarns geogrid.

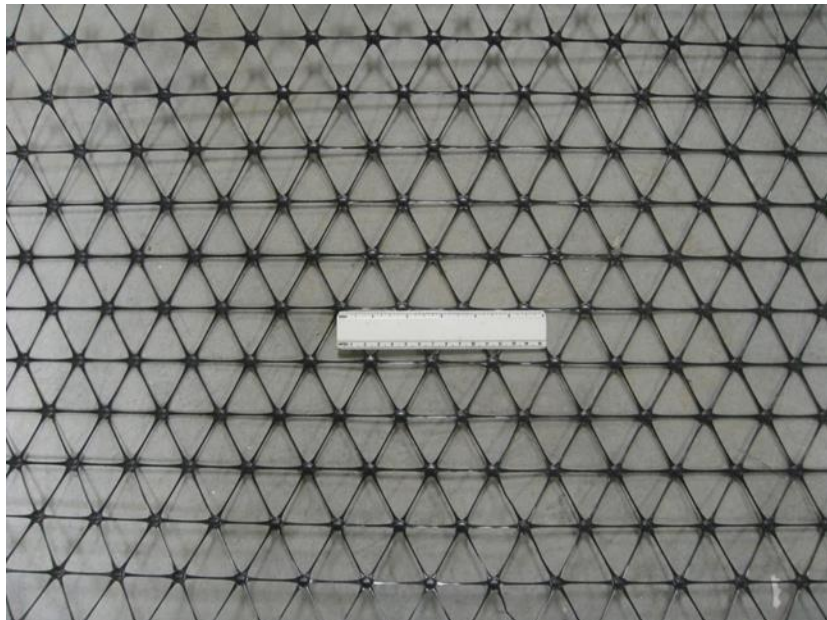


Figure 8. Type 3 – punched polypropylene triangular geogrid.

4.4 Test Results and Discussion

Two geogrid cylinders were made from each geogrid type due to the different strengths on MD and CD. The compressive axial loads at 200 lbs/s loading rate were applied to the geogrid cylinders until failure. Failure occurred when no further increase in load could be applied. Type 1 failed with ribs breaking both horizontally and vertically in both MD and CD directions (Figure 9). The failure load in the CD was larger than the failure load in the MD. Failure occurred at an ultimate tensile strength of 1970 lbs/ft. in the CD and 1310 lbs/ft. in the MD.

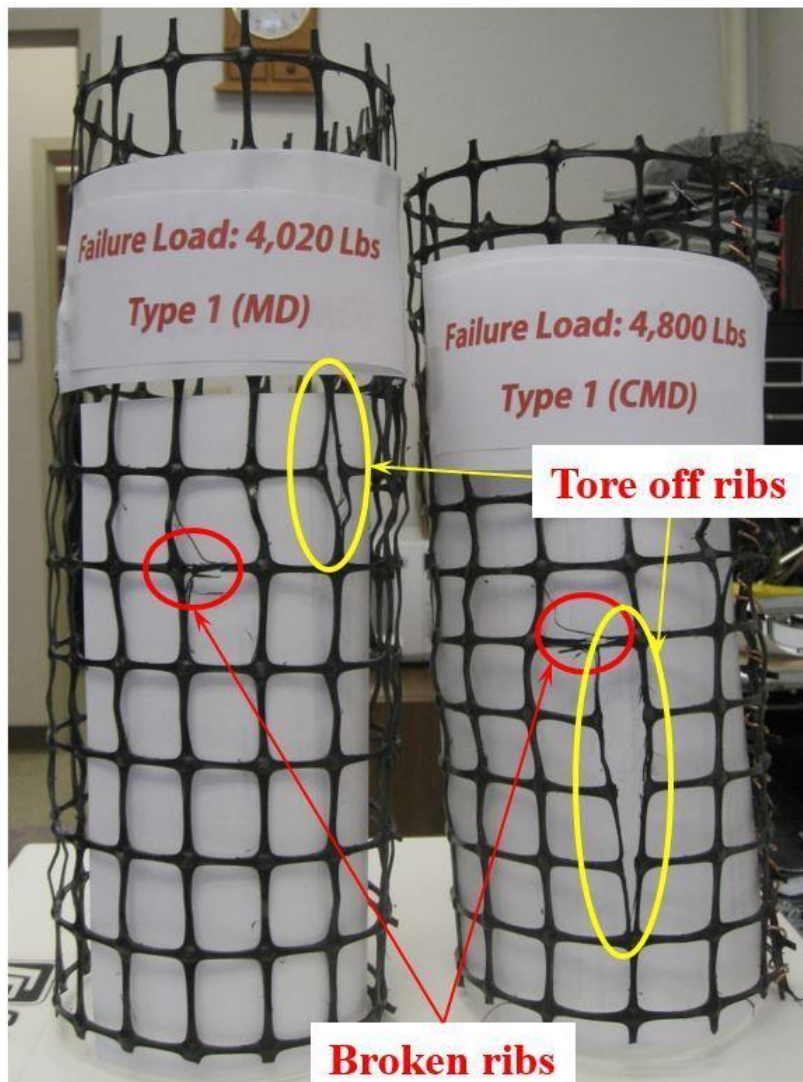
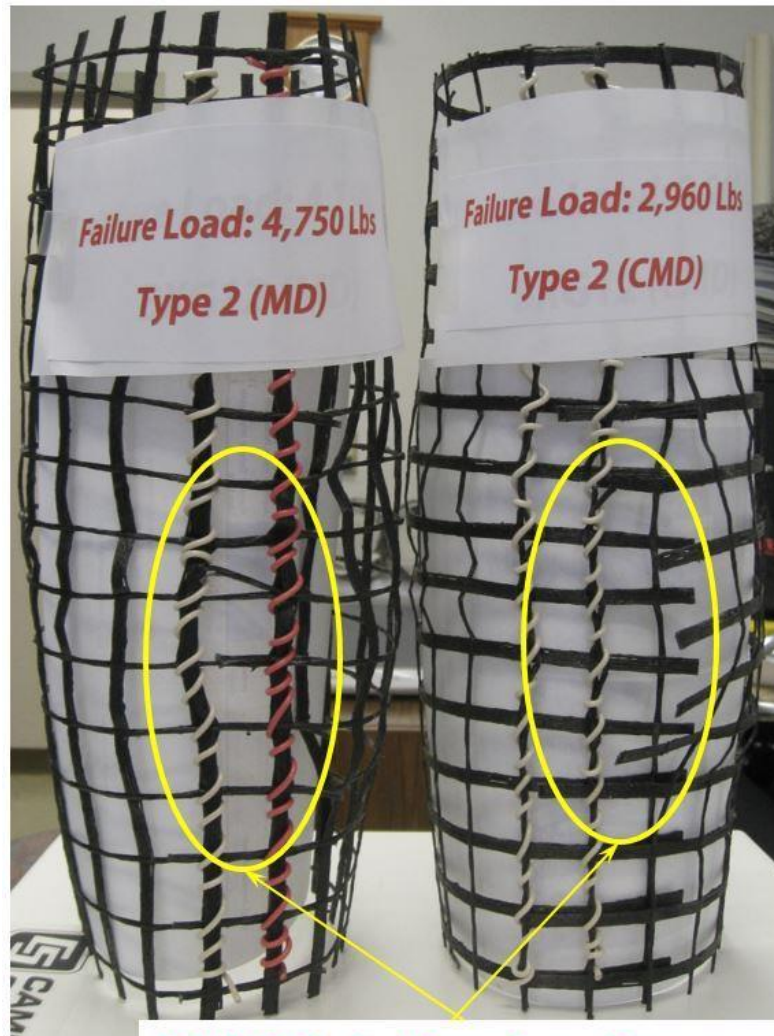


Figure 9. Type 1 failure with rib broken horizontally and rib tore off vertically on both machine direction and cross machine direction.

Type 2 failed due to junction slippage in both the MD and CD directions (Figure 10). For this geogrid, junction strength controlled failure. The failure load in the MD direction was larger than the failure load in the CD direction.



Both failed at junction slippage

Figure 10. Type 2 failure with junction slippage on both machine direction and cross machine direction.

Type 3 failed due to broken ribs in the MD and failed in the CD due to both ribs tearing and breaking (Figure 11). The failure load in the MD was larger than the failure load in the CD. In the MD, there were two groups of grid ribs that failed due to tension; while in the CD, only one group of grid ribs failed.

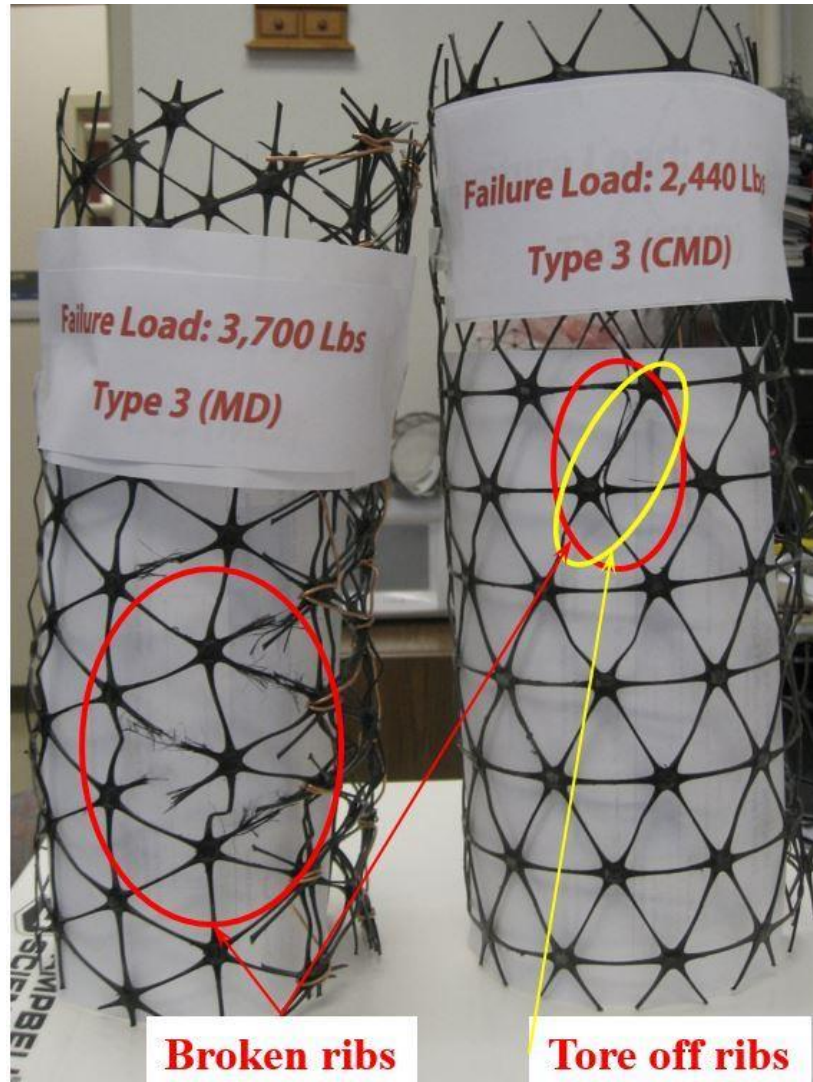


Figure 11. Type 3 failure with rib broken only on machine direction and both rib broken and rib tore off on cross machine direction.

4.5 Summary of Test Results

Table 1 summarizes the test results and geogrid properties.

Table 1. Geogrid properties and results from compression test on geogrid caged crushed-stone cylinder

Geogrid Type		Type 1 - Extruded, Rect. Formation	Type 2 - Woven, Coated, Rect. Formation	Type 3 - Punched, Triang. Formation
Ultimate Tension Strength (lbs/ft)	MD ¹	1,310	2,500	
	CD ¹	1,970	4,500	
Grid Aperture Size (in)	MD	1.0	1.0	
	CD	1.3	1.0	
Failure Load (lbs)	MD	4,020	4,750	3,700
	CD	4,800	2,960	2,440
Note		Failed at ribs broken and torn off	Failed at junctions slippage	Failed at ribs broken and torn off

Notes: 1. MD - Machine direction. CD - Cross-machine direction.

Based on implementation of this methods and the test results, we reached the following conclusions:

- a. This test is simple and can be easily performed. Only a compression loading machine is needed for this test. Sample preparation is straightforward.
- b. In this test setting, the failure load can be reached either on grid rib broken, torn off (Type 1 and Type 3 geogrids), or, on junction slippage (Type 2 geogrid). Two failure mechanism can be evaluated. Grid rib breakage (type 1 and Type 3 geogrids) and junction slippage (Type 2 geogrids).
- c. Multiple tests were run for the geogrid with different ultimate tensile strengths or different grid aperture sizes on MD and CD.
- d. Failure loads are directly proportional to grid rib tensile strength (Type 1 geogrid) and number of grid ribs involved (Type 3 geogrid) if junction strength is strong enough.
- e. The junction strength controls failure load for woven type geogrid (Type 2 geogrid) since ultimate tensile strength of grid rib is much stronger than junction strength.

5. New Test Method Two: Geogrid Bearing Ratio (GBR) Test

One of the most important functions performed by geogrid is increasing the subgrade's bearing capacity. The California Bearing Ratio (CBR) test is used to evaluate bearing capacity for subgrade, subbase and base materials, and can facilitate the design of pavements. Similar to the CBR test, the Geogrid Bearing Ratio (GBR) test measures the bearing capacity ratio between two conditions – with a geogrid installed and without a geogrid installed. The ratio of the bearing capacity *with* the geogrid installed to the bearing capacity when a geogrid *is not* installed is an index that measures the geogrid's contribution to bearing capacity improvement.

5.1 Test Apparatus Development

There is no existing whole set of test apparatus that satisfies the requirements of the GBR test. Some need to be designed from scratch. Some need to be modified to suit our purpose.

5.1.1 Loading Frame

A maximum concentrated load is designed for this loading frame. It stands independently and hosts 2' x 2' x 2' test box. Four (4) ϕ 1-1/8 in. by 7 foot threaded rods make the height of the top beam adjustable. Two (2) MC10X28.5 with 3'-0" long steel channels are used as top beam and frame base. Two extra MC10X28.5 with 2'-0" long steel channels are connected to the frame base to stabilize the loading frame (Figure 12(a)).

5.1.2 Power for Loading Piston

A CBR Jack is connected to loading ring and CBR test rod, a 1/4 horse power Right-Angle Shaft DC Gearmotor, and a ϕ 5/8 in. Flexible Shaft Coupling are assembled on wood support as a unit. This unit is installed on top beam to provide power for penetration loading piston (Figure 12(b)).

5.1.3 Control Box for Powered Loading Piston

This control box can be purchased from an online tool and parts dealer. It can shift Gearmotor rolling direction and adjust Gearmotor speed (Figure 12(c)).

5.1.4 Test Box with Dimension 2' x 2' x 2'

The 2' x 2' x 2' test box is made of 1/2 in. thick Plexiglass. The Plexiglass is used on four (4) sides and the bottom of box (Figure 12(d)).

5.1.5 Penetration Piston

A metal piston 1.954 in. in diameter and 7.5 in. long in length is used for this test.

5.1.6 Penetration Measuring Device

A mechanical dial micrometer is used as the penetration measuring device. It can make readings to the nearest 0.001 in. It is affixed to the penetration piston and connected to the surface of the surcharge weights to take accurate penetration measurements.

5.1.7 Surcharge Weights

One annular metal weights has a weight of 5 lbf and two half annular metal weights have a total weight of 5 lbf. The annular weight has 5 7/8 in. outer diameter and a center hole approximately 2 1/8 in. in diameter.

5.1.8 Weed Block

Weed Block is used to separate Pudgee (5.2.1) and crushed stones.

5.1.9 Rammer

A drop weight is used as the rammer for this test. It distributes the hammer blows uniformly over the surface of the crushed stones when compacting them in the 2' x 2' x 2' test box.

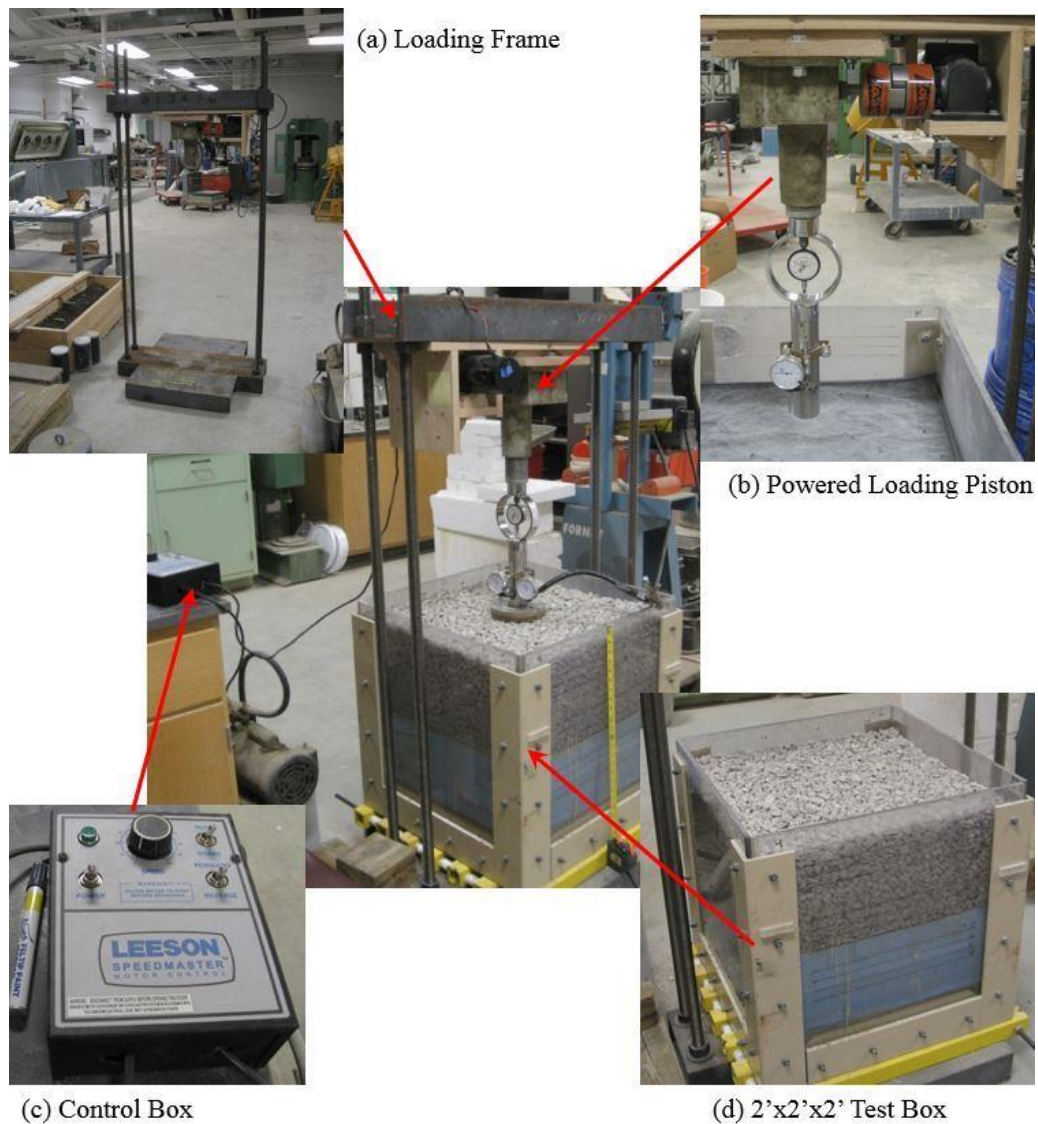


Figure 12. Loading apparatus used on Geogrid Bearing Ratio test.

5.2 Materials Involved in Geogrid Bearing Ratio (GBR) Test

5.2.1 Pudgee – Used to Simulate Weak Soil

Previous studies [Sun, 2015, 2016] revealed that geogrids will more significantly contribute to pavement structure when subgrade is very weak (e.g., $CBR \leq 1$) and undergoes large deformations. A very weak subgrade condition is difficult and time-consuming to replicate. Finding a synthetic material to simulate weak subgrade condition is a crucial for simulating field conditions in a reproducible fashion. Pudgee (Figure 13), a commercial product made by Dynamic System, Inc., is an ideal material to simulate weak soil in a GBR test. Its Yong's Modulus, $E = 5$ psi, which is close to the stiffness of weak soil with $CBR = 0.5$. Two (2) pieces of 2' x 2' x 2" Pudgee blocks are used for the GBR test. It makes test preparation much easier for the GBR test.



Figure 13. Pudgee – used to simulate weak soil.

5.2.2 Aggregate – Crushed Stone

#57 stone between the $\frac{3}{4}$ in. and $\frac{1}{4}$ in. sieves were used for the test (Figure 14). The stones were placed above the geogrid to create an interaction between the geogrid and the stones. This interaction will form an interlocking structure between the crushed stones and geogrid, resulting in improved bearing capacity on crushed stones.



Figure 14. Crushed stone – used to interact with geogrid.

5.3 Tested Geogrids and Geosynthetic Materials

5.3.1 Tested Geogrids in Stage 1

The purpose of this test stage is to investigate the feasibility of identifying the geogrid contribution by using the test apparatus and materials described in Sections 5.1 and 5.2. Four types of geogrids — designated Types 3-6 — are used for this stage. The Type 3 geogrid has a triangular formation, (Figure 15; see Section 4.3 for a full description). Its nominal rib pitch is 1.6 in. on all three directions, one transverse direction and two diagonal directions. Types 4-6 are composed of polypropylene resin, which is extruded into a rectangular grid structure (Figure 15).

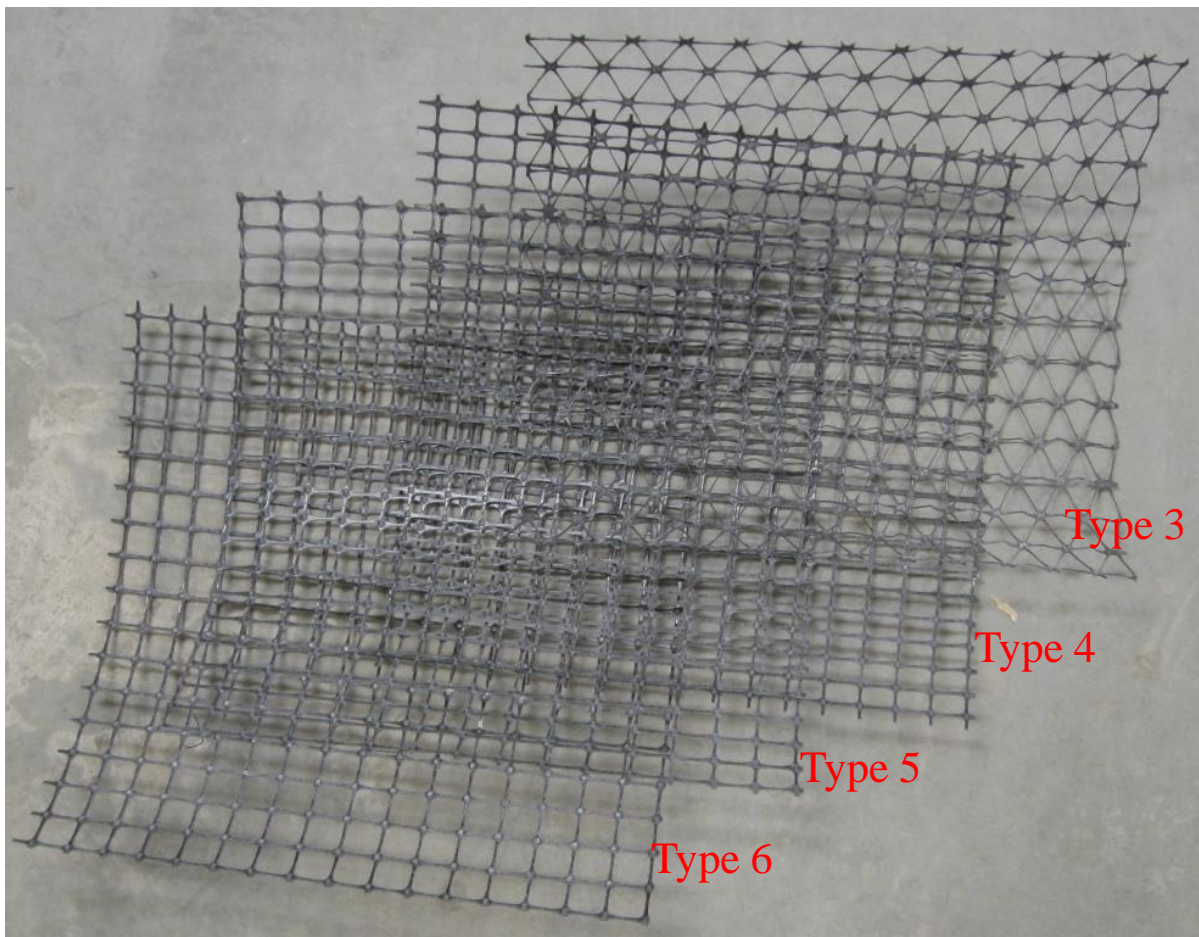


Figure 15. Four types of geogrids used in test stage 1.

The single string strengths of four geogrids are tested because the unit length strength of triangular geogrid is not available. Testing the single string strength of a geogrid was the only way to compare its strength prior to the current study. Table 2 summarizes the strengths and aperture sizes for geogrids used in Stage 1.

Table 2. Summary of strengths and aperture sizes for geogrids used in test stage 1

Geogrid Type		Type 3 (Triangular)		Type 4 (Rectangular)		Type 5 (Rectangular)		Type 6 (Square)
Direction		Transverse	Diagonal	CD ¹	MD ¹	CD	MD	
Single String Strength (Lb)	2% Strain	48.5	31.4	37.6	32.8	51.5	44.8	63.0
	5% Strain	103.0	77.9	86.7	70.6	112.1	131.9	149.3
	Ultimate	148.6	117.7	118.7	101.8	139.3	183.6	199.6
Unit Length Strength (Lb/ft)	2% Strain	Not Available		450.0	280.0	620.0	410.0	685.0
	5% Strain			920.0	580.0	1340.0	810.0	1370.0
	Ultimate			1300.0	85.0	1970.0	1310.0	2055.0
Aperture Dimension (in.)		1.60	1.60	1.38	1.02	1.38	1.02	1.42
Rib Thickness (in.)		0.047	0.051	0.039	0.047	0.051	0.077	0.083

Notes: 1. MD - Machine direction. CD - Cross-machine direction.

5.3.2 Tested Geogrids and Geosynthetic Materials in Stage 2

Stage 2 is an extension of Stage 1. Wider materials are tested during this stage. The geosynthetic materials include a ropey-type geogrid similar to Type 2 (see Section 4.3) with different strength of single string and aperture sizes (Ropey 1 and Ropey 2 in Figure 16), a triangular geogrid similar to Type 3 (see Section 5.3.1) with different strength of single string and aperture size (Triangular 1 in Figure 16), Woven Geosynthetics (WG 1 in Figure 17), and Composite Paving Grids (CPG 1 and CPG 2 in Figure 17).

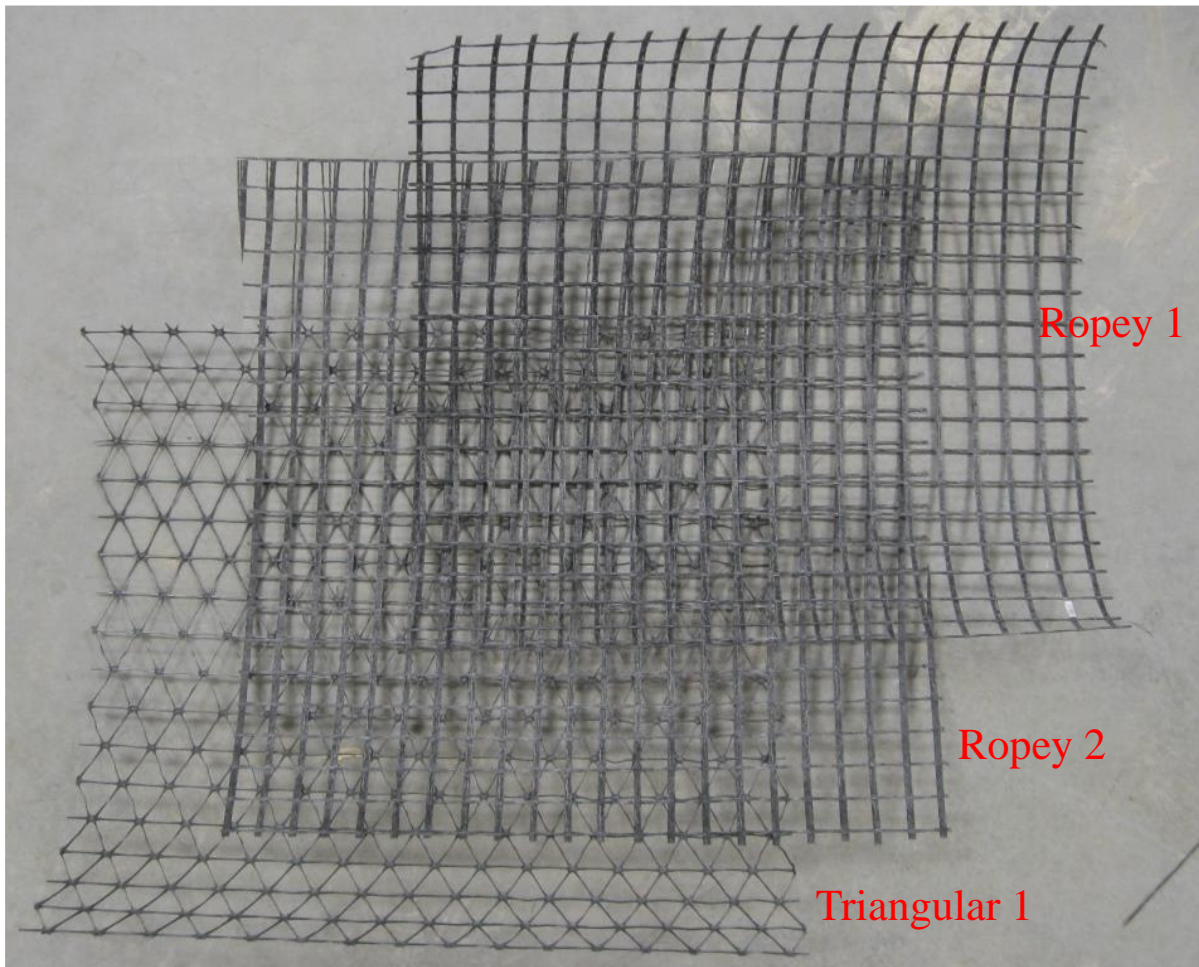


Figure 16. Ropey type geogrid and triangular geogrid used in test stage 2. Ropey – ropey type geogrid; Triangular – triangular shape aperture.

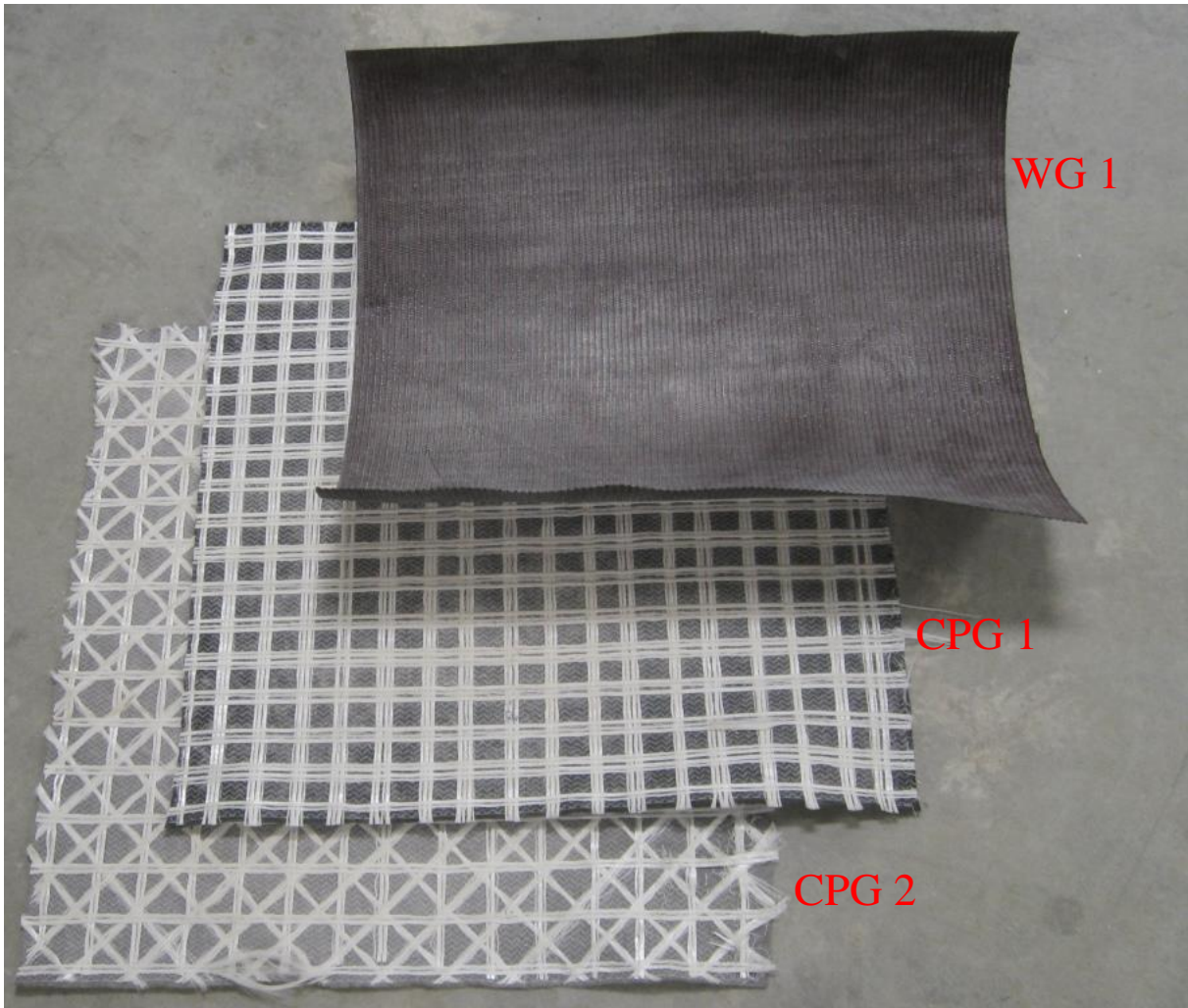


Figure 17. Woven geosynthetics and composite paving grids used in test stage 2. WG – woven geosynthetics; CPG – composite paving grid.

5.4 GBR Test Procedure

Initially, one penetration test without the geogrid is run. After this test, another penetration test with the geogrid placed between Pudgee and crushed stones is run under the same conditions. A four-inch layer of crushed stone is used above Pudgee for Geogrid Bearing Ratio (GBR) test. This thickness is the optimal dimension based on two-inch, four-inch, six-inch, eight-inch, and ten-inch thick crushed stone tests.

5.4.1 Pudgee Stack

Two (2) pieces of 2' x 2' x 2" Pudgee blocks are stacked in 2' x 2' x 2' test box to form a 4 in. thick simulated soft soil layer.

5.4.2 Weed Block Laid over Pudgee

One (1) pieces of 2' x 2' Weed Block is laid over Pudgee layer separate the Pudgee layer and crushed stone layer.

5.4.3 Geogrid Installation (omitted when running test without geogrid)

The geogrid is laid on the Weed Block. Seven (7) small weight blocks (approximately 10 ounces each) are placed on four (4) corners, two (2) warped edges, and the center to keep the geogrid flat. These seven (7) weight blocks will be moved out after first layer of crushed stones is installed.

5.4.4 Crushed Stone Installation

Four (4) in. of crushed stone are installed in three equal 4/3 in. thick layers. Fifty (50) hammer blows are uniformly distributed over the surface of the each layer when compacting the 2' x 2' x 2' test box.

5.4.5 Surcharge Weights Installation

To prevent surface upheaval of the crushed stones, one (1) 5-lbf annular surcharge weight and two (2) 2.5-lbf half annular surcharge weights were placed on the crushed stone surface before seating the penetration piston. Align the center of annular surcharge weights with the center of the piston.

5.4.6 Seat Penetration Piston

Seat the penetration piston with the smallest possible load on the surface of crushed stones. Either set both the load and penetration gauges to zero or make provisions to subtract any initial values from all subsequently collected data. This initial load is required to ensure satisfactory seating of the piston and is considered the zero load when determining the load penetration relation. Mount the mechanical dial micrometer to the piston and connect it to the surface of the surcharge weights to ensure accurate penetration measurements. Mount another mechanical dial micrometer to the edge of the 2' x 2' x 2' test box. Connect it to the surface of the surcharge weights to measure settlement of the surcharge weights.

5.4.7 Loading on Penetration Piston

Apply the load to the penetration piston so that the rate of penetration is approximately 0.05 in./min. Record the penetration readings and surcharge weight settlement readings at loading gauges of 0.050 in., 0.100 in., 0.150 in., 0.200 in., 0.250 in., 300 in., 0.350., 0.400 in., 0.450 in., 0.500 in., 0.550 in. and 0.600 in.

5.4.8 Geogrid Bearing Capacity Ratio Calculation

Calculate the penetration stress in pounds per square inch (psi) and then plot the stress versus penetration curve. To calculate the Geogrid Bearing Capacity Ratios at 0.50 in. and 0.60 in. penetrations (*Note 1*), respectively, divide the stress value obtained from the test *with* geogrid partitions by the stress value obtained at the corresponding penetration level from the test *without* geogrids in place —values for 0.50 in. and 0.60 in. are derived through interpolation on the stress penetration curves (see Equations 1 and 2):

$$GBR_{0.5} = \frac{\sigma_{0.5,with\ geogrid}}{\sigma_{0.5,without\ geogrid}} \quad (1)$$

and,

$$GBR_{0.6} = \frac{\sigma_{0.6,with\ geogrid}}{\sigma_{0.6,without\ geogrid}} \quad (2)$$

Where:

- $GBR_{0.5}$ or $GBR_{0.6}$ = Geogrid Bearing Capacity Ratio at 0.50 in. or 0.60 in. penetration.
- $\sigma_{0.5,with\ geogrid}$ or $\sigma_{0.6,with\ geogrid}$ = Penetration stress with geogrid at 0.50 in. or 0.60 in. penetration.
- $\sigma_{0.5,without\ geogrid}$ or $\sigma_{0.6,without\ geogrid}$ = Penetration stress without geogrid at 0.50 in. or 0.60 in. penetration.

These formulae are used to calculate improvements in bearing capacity realized by inserting geogrid between layers of simulated soft soil and crushed stone at 0.50 in. and 0.60 in. piston penetrations, respectively. The increased portion ($GBR_{0.5} - 1$) and ($GBR_{0.6} - 1$) shows the contribution from geogrid at 0.50 in. and 0.60 in. piston penetrations, respectively.

Note 1 -- The bearing capacity almost reaches ultimate value for the crushed stone only treatment when the piston achieves 0.60 in. penetration.

5.5 GBR Test Results and Discussion

Test results are presented in two parts, one for each test stage.

5.5.1 Results from Stage 1

Following test procedures described in Section 5.4, the geogrids in Stage 1 were tested. Test data was then processed and plotted (Figure 18). The GBRs derived from Equations 1 and 2 are shown in Table 3.

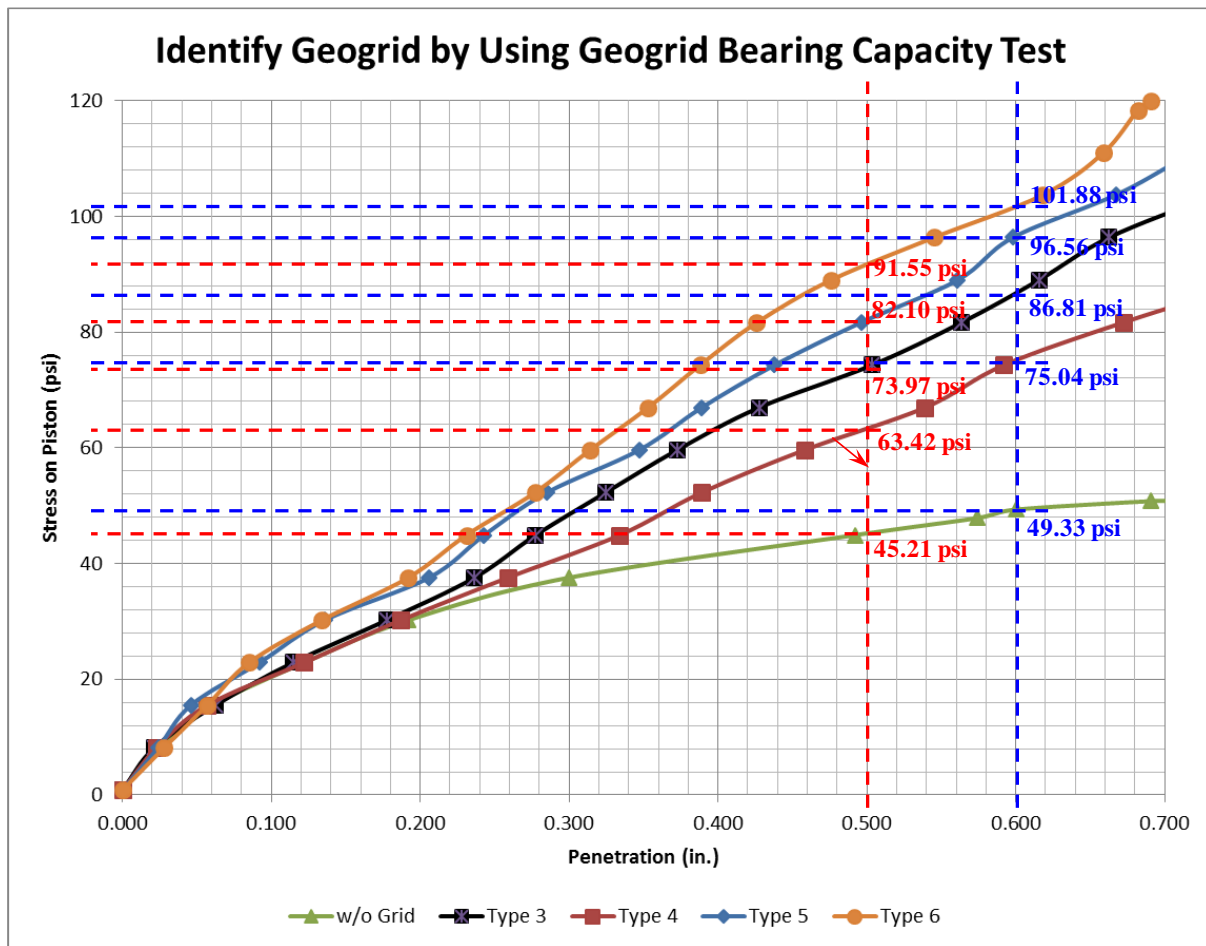


Figure 18. Stress penetration curves for geogrids in test stage 1.

Table 3. Geogrid Bearing Capacity Ratios for geogrids in Stage 1

@ Penetration Depth (in.)	0.50	0.60
Type 3	1.64	1.76
Type 4	1.40	1.52
Type 5	1.82	1.96
Type 6	2.03	2.07

From stress penetration curves in Figure 18 and GBRs in Table 3, we have concluded:

- a. The GBR test result is one-parameter that informs designers of a geogrid's performance in pavement structure. In the pavement, the geogrid never functions alone. It always works together with soil and crushed stone. The interlocking structure formed between a geogrid and crushed stone creates a higher bearing capacity than would be created by crushed stone or geogrid alone. The GBR number indicates a geogrid's contribution to the improvement in bearing capacity.
- b. This test enables us to compare geogrids with differently shaped apertures. Before this test was developed, no methods were available to compare geogrids with similar properties but different aperture shapes (e.g., rectangular and triangular).
- c. The GBR test identifies the geogrid's contribution to bearing capacity by judging bearing capacity improvement after a geogrid has been emplaced. Any difference on grid single string strengths or aperture sizes or shapes are discernible in the GBR number. The test improves the simplicity and efficiency of geogrid selection.
- d. All of the stress penetration curves display similar trends before 0.20 in. penetration (Figure 18). The stress penetration curve for the crushed stone without geogrid test evinces the smallest slope after 0.20 in. penetration. Its slope is nearly flat after 0.60 in. penetration. This indicates that the bearing capacity is approaching ultimate strength at 0.60 in. penetration for the *crushed stone only* situation.
- e. Cross-referencing Tables 2 and 3, we can see GBRs are positively proportional to single string strengths of a geogrid, irrespective of aperture shape. For example, the single string strength of Type 3 geogrid (triangular apertures) is between single string strengths of Types 4 and 5 (rectangular apertures). Accordingly, the GBR of Type 3 is between the GBRs of Types of 4 and 5.
- f. Table 3 shows that with deeper piston penetration the GBR ratio increases. This is because the stress penetration curve tends to flatten after penetration reaches 0.50 in. for the crushed stone *without* geogrid test; conversely, the slopes of stress penetration curves for the other tests maintain almost the same slope even after 0.50 in. penetration.
- g. As Figure 18 shows, the stress penetration curves increase above the 0.60 in. penetration threshold, meaning the combination of crushed stone and any geogrid type can potentially increase bearing capacity under a larger deformation. The bearing capacity from these combinations did not reach the ultimate point even at 0.70 penetration level. The combination of crushed stone and geogrid has a much stronger bearing capacity under larger penetration (compared to the crushed stone in isolation).

5.5.2 Results from Test Stage 2

Extending the work of Stage 1, more geosynthetic materials such as Ropey-type geogrids, Woven Geosynthetics and Composite Paving Grids were tested in this stage. We followed the procedures laid out in Section 5.5.1 to process and plot data (Figure 19). In this figure, the x- and y-axes have the same scale as Figure 18 to facilitate comparisons. GBRs are listed in Table 4.

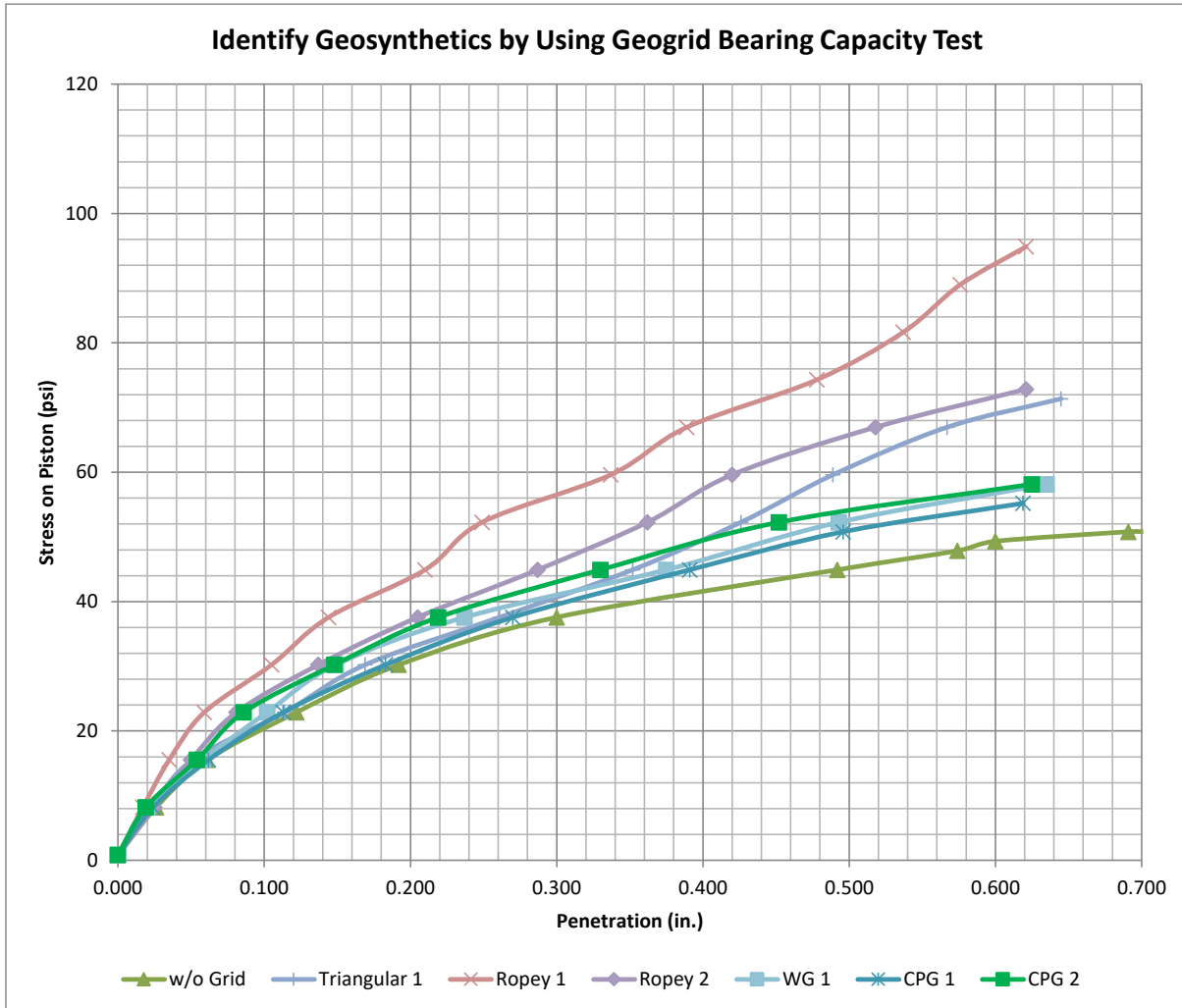


Figure 19. Stress penetration curves for geosynthetic materials in test Stage 2.

Table 4. Geogrid Bearing Capacity Ratios for geosynthetic materials in test Stage 2

@ Penetration Depth (in.)	0.50	0.60
Triangular 1	1.34	1.40
Ropey 1	1.70	1.87
Ropey 2	1.45	1.45
WG 1	1.16	1.15
CPG 1	1.13	1.11
CPG 2	1.19	1.16

Based on these test results, we have reached the following conclusions:

- a. This GBR test method can be used to test geosynthetic materials such as WG 1, CPG 1 and CPG 2. However, the gains in bearing capacity realized by using these materials are small since it is difficult to snugly interlock the crushed stone and tested materials. For instance, the GBRs for CPG 1 and CPG 2 (see Figure 17), which combine reinforced fibers with geosynthetic fabric, are nearly identical to the GBRs for WG 1. WG 1 is a geosynthetic fabric-only material. Therefore, the GBR test cannot be used to identify geosynthetic materials like WG 1, CPG 1 and CPG 2.
- b. Ropey-type geogrids are similar to Type 2 (see Table 1). They are woven and coated to achieve a much higher ultimate tensile strength than extruded or punched geogrids. Examining Tables 3 and 4, GBRs for the Ropey-type geogrids occupy the middle tier among the tested geogrids. As such, GBR is not directly related to the geogrid's ultimate strength, it is related to a combination of string strength, rigidity and integration properties of a geogrid.

5.5.3 Optimize Geogrid Install Position by Using Geogrid Bearing Capacity Test

To further optimize the benefit of a geogrid in the pavement structure, we used the GBR test to explore the optimal geogrid installation position under penetration loading. A Type 6 geogrid and eight (8) inches of crushed stone were used for this analysis. The test *without* geogrid was conducted first. Following this test, we ran four additional tests by placing Type 6 geogrid at the following positions: a) at the bottom of crushed stone layer, b) 2 in. from bottom, c) 4 in. from bottom, and d) 6 in. from bottom. Figure 20 displays the processed and plotted data. It also lists GBRs by using equations (1) and (2).

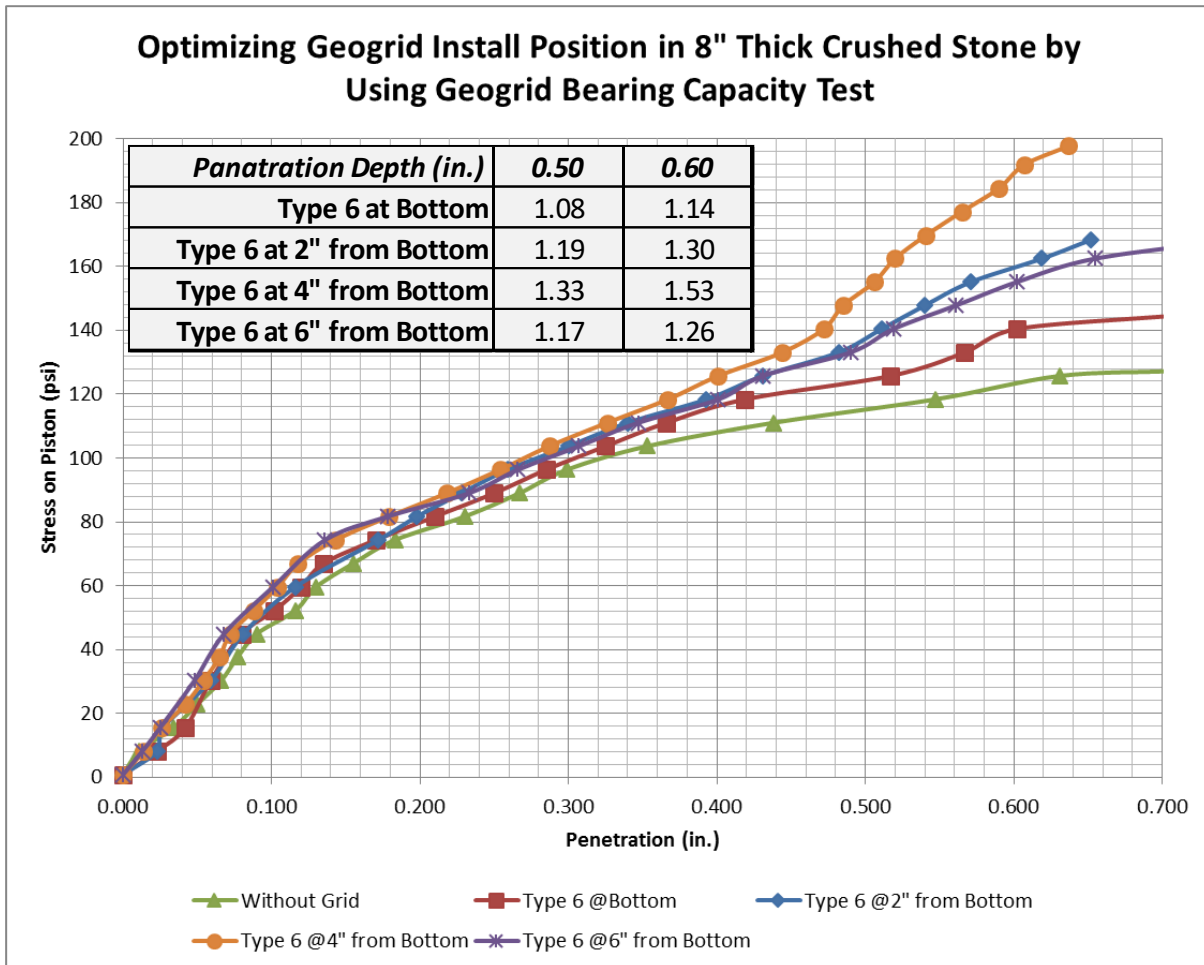


Figure 20. Optimize Type 6 geogrid install position in 8 in. thick of crushed stone by using geogrid bearing capacity test.

Of the test settings described above, the optimal location for geogrid installation is 4 in. from the bottom. At the size used in testing (1.954 in. in diameter piston loading) it is more challenging for the crushed stone and geogrid to firmly interlock when the geogrid is positioned at the bottom than when it is placed in 4 in. above the bottom.

At less than 0.30 in. of penetration, all five stress penetration curves nearly mirror one another. In this less deformation, the development of an interlocking structure between crushed stone and geogrid has not yet developed. Above the 0.30 in. penetration threshold, the interlocking action between crushed stone and the geogrid develops gradually. This action peaks when the geogrid is placed 4 in. from the bottom.

Placing a Type 6 geogrid 6 in. from the bottom leads to the quick development of an interlocking structure between the crushed stone and geogrid (as soon as 0.20 in. penetration). Above this threshold, the penetration stress rises more gradually than is observed for the treatment where geogrids are placed 4 in. from the bottom. At a penetration level of 0.40 in., the curves for the 6 in. and 2 in. treatments diverge. The curve for the 6 in. treatment rises less quickly than for the treatment where the geogrid is placed 2 in. from the bottom. The reason for this is that placing two inches of crushed stones above the geogrid is not sufficient to ensure the stones interlock with the geogrid.

6. Conclusions and Future Works

Two test methods have been developed in this project. KYTC personnel can use these methods to quickly, easily and directly test geogrid performance.

The first test method is a compression test of a geogrid cylinder. This test method consists of applying a compressive axial load to the cylinder at a rate within a prescribed range until failure occurs. A high compressive axial load is an indication of how much the geogrid can improve the bearing capacity of the crushed stone alone. Only a compression loading machine is needed for the test. Sample preparation is straightforward. The failure load can be reached when either the grid rib breaks, tares off, or from junction slippage. The failure loads are positively proportional to grid rib tensile strength and the number of grid ribs involved, if junction strength is strong enough. However, multiple tests must be run to evaluate geogrids with different ultimate tensile strength or grid aperture sizes on machine direction and cross machine direction.

The second test method is the Geogrid Bearing Ratio (GBR) test. This test was developed to measure the bearing capacity changes between treatments with and without a geogrid. The ratio of bearing capacity for the *with-geogrid* treatment to bearing capacity for the *without-geogrid* treatment is an index that captures a geogrid's contribution improvements in bearing capacity. The GBR test result is a parameter that informs designers about a geogrid's function in pavement structure. This GBR number indicates the bearing capacity improvement from geogrid contribution. This test makes it possible to compare geogrids with different aperture shapes. Any difference on grid single string strengths or aperture sizes or shapes is captured in the GBR number. All of the stress penetration curves have similar shapes before 0.20 in. penetration. The bearing capacity almost reaches ultimate value for the crushed stone only treatment when the piston achieves 0.60 in. penetration. As penetration increases, so does the GBR. Combining crushed stone with a geogrid produces much stronger bearing capacity under larger penetration than does crushed stone alone. GBRs are positively proportional to the single string strengths of geogrids, irrespective of their apertures' shape. But they are not directly related to ultimate strength of geogrid only. GBRs are related to the combined effects of string strength, rigidity and integration properties of the geogrid. A GBR test cannot be used to identify geosynthetic fabric or any combination with geosynthetic fabric materials because the interlocking function between crushed stone and these kinds of materials cannot be developed.

We also used the GBR test to explore the optimal geogrid installation position under penetration loading. The optimal geogrid installation position is at 4 in. from the bottom in an 8 in. thick crushed stone configuration under 1.954 in. in diameter piston loading. Enhancing the interlocking structure of the geogrid and crushed stone is critical for maximizing a geogrid's contribution to pavement functioning. Different loadings may have different optimal geogrid installation positions. Therefore, we recommend testing and analyzing situations on a case-by-case basis to determine a practical, optimal design.

Data acquired during testing was done by manually reading dial numbers for loading, piston penetration and surface settlement. Automatic data acquisition systems should be used in future GBR testing.

With respect to implementation, the test device can be transferred to KYTC for future use. Or, KTC can evaluate vendors' submitted geogrids in-house. The second strategy would give KTC the opportunity to promote these new test methods in practice.

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