Correlation of ASTM D4833 and D6241 Geotextile Puncture Test Methods and Results for Use on WisDOT Projects

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Final Report

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16. **Abstract**

Geotextiles are commonly used in pavements, earth retaining structures, and landfills, as well as other geotechnical applications. Various tests are conducted to evaluate and classify geotextiles to determine their suitability for different applications. One of these tests is the puncture strength test. This test evaluates the ability of geotextiles to withstand stresses and loads during construction, which is among the severe conditions that geotextiles can experience. ASTM has recently replaced the standard pin puncture strength test, D4833, with the CBR puncture strength test, D6241. However, many departments of transportation (DOTs) throughout the country and the Federal Highway Administration still refer to D4833. Other state DOTs refer to both D4833 and D6241, or provide a list of alternative test methods to be considered in place of either of these tests. This inconsistency is the result of a missing connection between the old and new ASTMs. The objective of this research is to attempt to correlate the CBR and pin puncture strengths for various categories of geotextiles, regardless of weave type and mass per unit area. Subsequent to this, deterioration of geotextiles due to freeze-thaw conditioning as well as Ultraviolet light exposure was investigated. Puncture resistances of materials with like mass per unit area and base material but with different weave type were also examined. Various types of geotextiles (nonwoven and woven) were subjected to testing in accordance with ASTM D4833 and ASTM D6241 standard procedures. In phase I, ten and fifteen samples of each geotextile type were tested using CBR and pin punctures strength tests, respectively, while a total of ten samples per geotextile type were tested in phase II. All types of geotextiles exhibited puncture strength values, whether pin or CBR, that were consistent within each group with coefficients of variation ranging from 2.8 and 41% for samples tested in phase I and II. It should be noted that distinct load-displacement curves were exhibited within each material group. Statistical analyses were conducted to establish a correlation between CBR and pin puncture strength values. Correlations were successfully used to estimate the CBR puncture strength values from the pin test with a reasonable accuracy. In Phase III, an attempt was made to investigate the freeze-thaw cycle effects on the geotextile fabric as well as UV light exposure effects. The freeze-thaw conditioning showed minor levels of degradation on the puncture test. However, UV and weathering tests showed significant degradation in the puncture strength after exposure. Finally, we include a section in this report with recommended specifications for puncture load values based on the testing performed in this project in the spirit of providing a transition to the new ASTM D6241 puncture test standard.

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Chapter 1

Introduction

Geotextiles are a broad grouping, yet specific type, of fabric used in civil engineering and geotechnical applications. According to American Society for Testing and Materials (ASTM) standard test method ASTM D4439 (2015), a geotextile is “A permeable geosynthetic comprised solely of textiles. Geotextiles are used with foundation, soil, rock, earth, or any other geotechnical engineering-related material as an integral part of human-made project, structure, or system.” (2015). Geotextiles are commonly used in civil engineering applications and can be found above and below water, behind retaining walls, under pavement surfaces, and practically anywhere there is soil. With material advances, the list of applications for geotextiles continues to grow. Geotextiles can serve one or more of the following functions: separation, filtration, reinforcement, protection, and drainage.

1.1 Problem Statement

There is variety of tests that can be conducted to evaluate and classify geotextiles. One of the tests is the puncture strength test that evaluates the quality of geotextiles to withstand stresses and loads during construction process, which is severe condition that a geotextile is subjected to in geotechnical applications. Therefore, the puncture resistance is commonly used to select a geotextile and predict its performance over time. Over the last several years ASTM D4833 (2013), the “Standard Test Method for Index Puncture Resistance of Geomembranes and Related Products,” was used to determine the puncture resistance value.

The American Association for State Highway and Transportation Officials (AASHTO), ASTM, and the geotextile industry have since proposed replacement of the ASTM D4833 standard with ASTM D6241 (2014), the “Standard Test Method for the Static Puncture Strength of Geotextiles and Geotextile Related Products Using a 50-mm Probe,” as ASTM D4833 has been deemed insufficient in classifying geotextile materials. Many departments of transportation (DOTs) throughout the country and the Federal Highway Administration (FHWA) Section 716, however, still refers to ASTM D4833. Other states refer to both ASTM D4833 and ASTM D6241, or provide a list of alternative test methods to be considered in place of either of these tests. This inconsistency is the result of a missing connection between the old and new standard test methods. Should DOTs wish to adopt the ASTM D6241 testing procedure, a correlation between the two ASTM tests, regardless of material, is required. Many research studies have passively compared ASTMs D4833 and D6241 or determined a trend among a specific manufacturing or material classification, but a direct connection of pin puncture resistance and CBR puncture resistance *testing* methods, independent of manufacturing or material type, has not been concluded. This study will attempt to define the required connection.

1.2 Objectives

The objective of this research is to test several geotextiles with a controlled material type and mass per unit area using ASTMs D4833 and D6241 in order to describe the relationship between the two testing methods rather than a relationship between material types. In addition, this study aims at determining whether weave type impacts the puncture resistance of a geotextile's performance and at investigating the effects of freeze-thaw conditioning on needle-punched nonwoven materials and exposure to UV radiation.

1.3 Scope

The scope of this research is represented in the following. In Phase I it runs on using the standard ASTM puncture strength tests on five types of woven and nonwoven geotextiles obtained by the research team independently from geotextile manufacturers. Phase II is an expanded test program performed on test specimens provided by WisDOT from actual projects.

1.4 Organization of the report

This research report is organized in seven chapters. Chapter 1 presents an introduction of the problem statement, objectives and scope of the research. The literature review is summarized in Chapter 2. Chapter 3 discusses the research methodology and experimental approaches used to test the D6241 and D4833 geotextile test specimens. Results of experimental tests are presented and discussed in Chapter four with a discussion of the statistical analysis tools used. Geotextile specifications of U.S. State DOTs are summarized in Chapter five with emphasis on the sections describing the puncture testing and UV limits imposed. Recommended specifications based on the testing performed is presented in Chapter 6 and the final summary of the project is included in Chapter 7 of this report

Chapter 2

Literature Review

This chapter presents the literature review results of geotextile in terms of their material type, manufacturing process, usage in civil engineering applications, and physical and mechanical properties with an emphasis on puncture strength resistance. Papers, reports, and standards were reviewed, compiled and synthesized herein. In addition, the differences between ASTM D4833 (pin) and ASTM D6241 (CBR) puncture strength tests are also highlighted.

2.1. Geotextiles

Geotextiles are a broad grouping, yet specific type, of fabric used in civil engineering and geotechnical applications. According to ASTM D4439, a geotextile is "A permeable geosynthetic comprised solely of textiles. Geotextiles are used with foundation, soil, rock, earth, or any other geotechnical engineering-related material as an integral part of human-made project, structure, or system." (ASTM Standard D4439, 2014). Because the term "geotextile" describes such a vast network of materials, geotextiles are commonly further classified by the function they serve, the manufacturing process used to make them, and their base material.

2.1.1 Function Classification

Geotextiles are commonly used in civil engineering applications and can be found above and below water, behind retaining walls, under pavement surfaces, and practically anywhere there is soil. With material advances, the list of applications for geotextiles continues to grow. Geotextiles can serve one or more of the following functions: separation, filtration, reinforcement, protection, and drainage.

2.1.1.1. Separation (Subgrade Aggregate Separation)

Geotextiles allow two or more soil layers to act independently, yet as part of the same system. Separating soils that have different grain size distributions allows each layer to function as an independent component of the soil structure. For example, during pavement construction, a granular base course is typically constructed over the subgrade or subbase course layer.

Repetitive loading can cause the larger aggregate in the base course to penetrate into the soft subgrade beneath. Contamination in the other direction is also possible when the moisture content of the soil is increased. When saturated, soft subgrade particles could transfer via the flow of water to the lower pressure region within the larger voids of the granular base. The newly combined soil will have a different grain size distribution, and therefore different properties. As installation of geotextile costs approximately the same amount as one 1 in. (25.4 mm) of base course, the benefit of using geotextiles is apparent.

2.1.1.2. Filtration (Drainage Filtration)

Geotextiles can also function as a filter, designed for the dual purposes of allowing water to flow but preventing the movement of soil particles. Good filtration is especially important for the control of water behind embankments, retaining walls, and other structures. Well-designed geotextiles will relieve hydrostatic pressure buildup yet prevent the loss of soil, and therefore, prevent a loss in stability of the overall system.

2.1.1.3. Reinforcement

Some geotextiles are used to mechanically stabilize soil by employing the shear strength developed at the soil-geotextile interface. They can be used to reinforce embankments, roadways, ponds, and many other geotechnical structures.

2.1.1.4. Protection

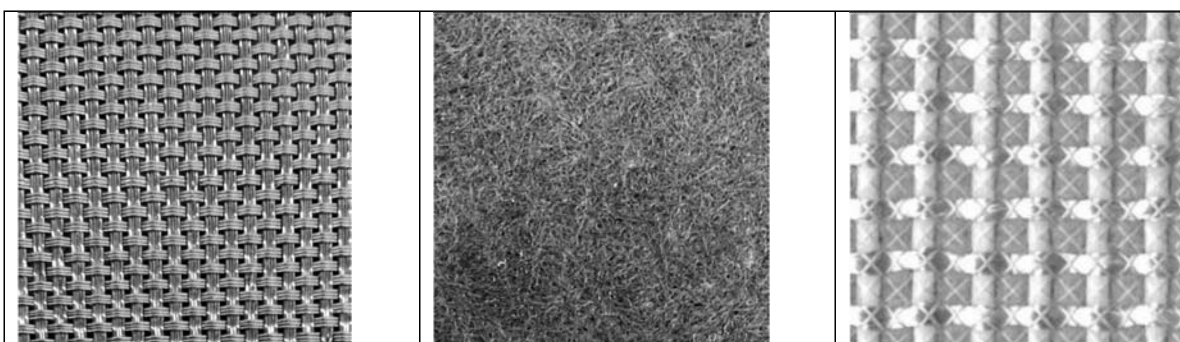
Geotextiles are commonly found in a geotextile-geomembrane system. In situations where fluids must be contained, such as surrounding a landfill, *geomembranes* are used. Many geomembranes, however, are not resilient enough to withstand the effects of aggregate forces and puncture. Geotextiles can be used as a protective cushion surrounding the geomembrane, allowing for the desired system properties: zero permittivity and protection from puncture caused by stones in adjacent soil or drainage aggregate.

2.1.1.5. Drainage

The transmission of water into or out of a soil system can also be accomplished using geotextiles. Drainage is especially important in large systems where large pore water pressure can develop. For example, retaining walls built several meters high can experience a large pressure differential across the stem of the wall as one side will retain water and the other will not. Using a drainage geotextile in combination with weep holes and drainpipes, water pressure can be greatly reduced. The water will transfer within the material to the base rather than developing into a large hydrostatic force behind the wall.

2.1.2 Manufacturing Classification

In addition to being divided into a functional group, geotextiles can be classified by the process used to manufacture them. Regardless of the manufacturing process, all geotextiles are composed of small fiber elements. They can be natural fibers, such as bamboo and cotton, or synthetic polymers. Because polymer-based fibers are more resistant to biological and chemical degradation, they are most commonly used for geotextiles. Only polymer-based geotextiles will be discussed further in this chapter. Three main groups are defined to describe the manufacturing process of a geotextile: woven, nonwoven, and knitted. Figure 2.1 depicts geotextiles constructed using the previously mentioned manufacturing processes. These groups of geotextiles are further split into their subgroups as shown in Figure 2.2. summarizes the types of forms produced from different manufacturing processes of geotextile types (Bhatia and Smith 1996). Important aspects from their paper are highlighted in the following sections.



(a) Woven geotextile	(b) Nonwoven geotextile	(c) Knitted geotextile

Figure 2.1. Geotextile Material Forms

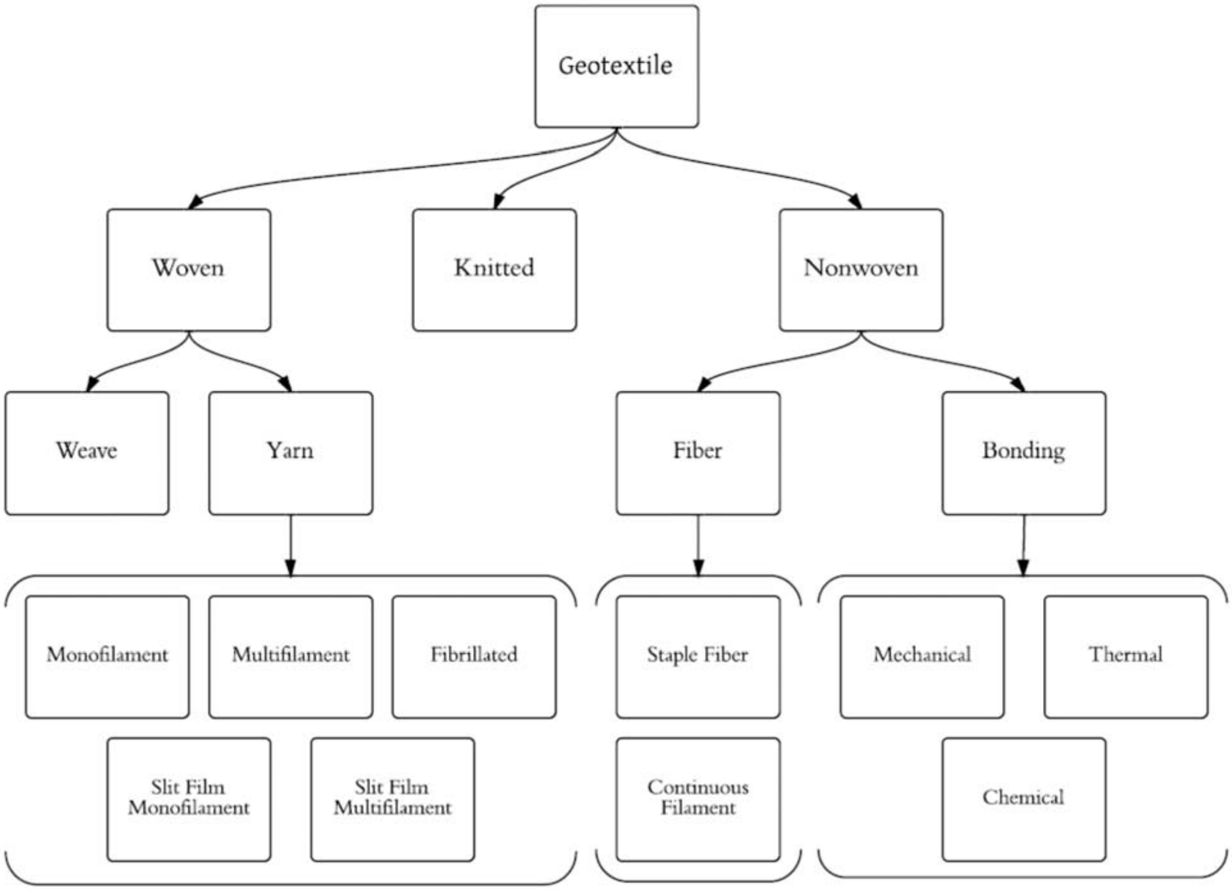
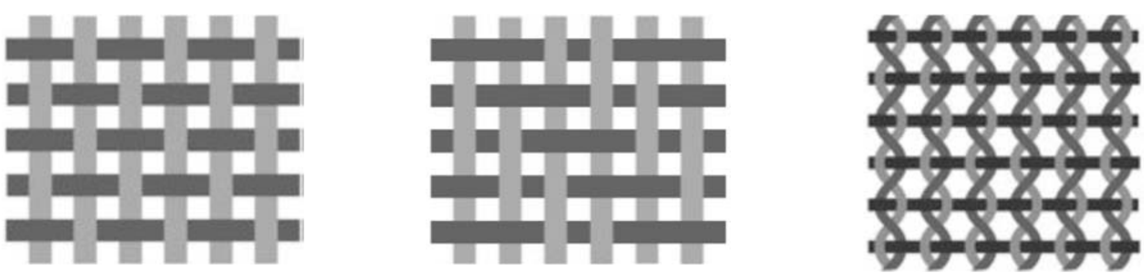


Figure 2.2. Classification of geotextiles based on manufacturing process (Bhatia and Smith 1996)

2.1.2.1. Woven Geotextiles

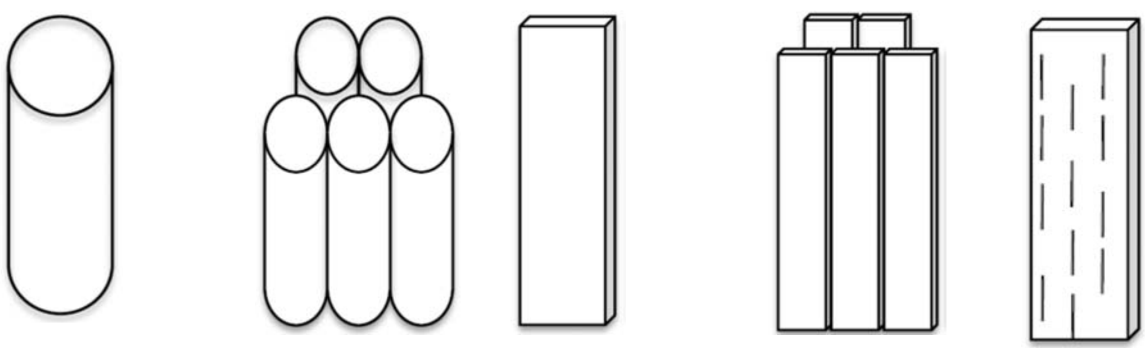
Woven geotextiles can be sub-grouped based on both the weaving type and yarn type used. The most common weaves are plain, twill, and leno (Kumar 2008), as shown in Figure 2.3.



(a) Plain weave (b) Twill weave (c) Leno weave

Figure 2.3. Common geotextile weaves (Kumar 2008)

Woven geotextiles are composed of monofilament, multifilament, and slit film fiber yarns as depicted in Figure 2.4. They are classified as follows: Monofilament Yarn: Individual polymer fibers with an ovular cross section are extruded from a polymer mass (Figure 2.4a). These fibers, or monofilaments, are then woven together. Multifilament Yarn: *Groups* of polymer monofilaments, or polymer multifilaments, are woven together (Figure 2.4b). Figure 2.5a shows a woven multifilament yarn. It should be noted that each woven section is composed of several monofilaments. Slit Film Monofilament Yarn: A polymer mass is extruded into a long, smooth film. Individual flat yarns are then slit from the film (Figure 2.4c) and woven together as shown in Figure 2.5b. Slit Film Multifilament Yarn: Slit polymer film monofilaments are grouped together (Figure 2.4d) and then woven. Fibrillated Slit Film Yarn: Slit polymer film is scored with small, non-continuous cuts (Figure 2.4e). This modified slit film is then woven.



(a) Monofilament	(b) Multifilament	(c) Slit Film Monofilament	(d) Slit Film Multifilament	(e) Fibrillated Slit Film

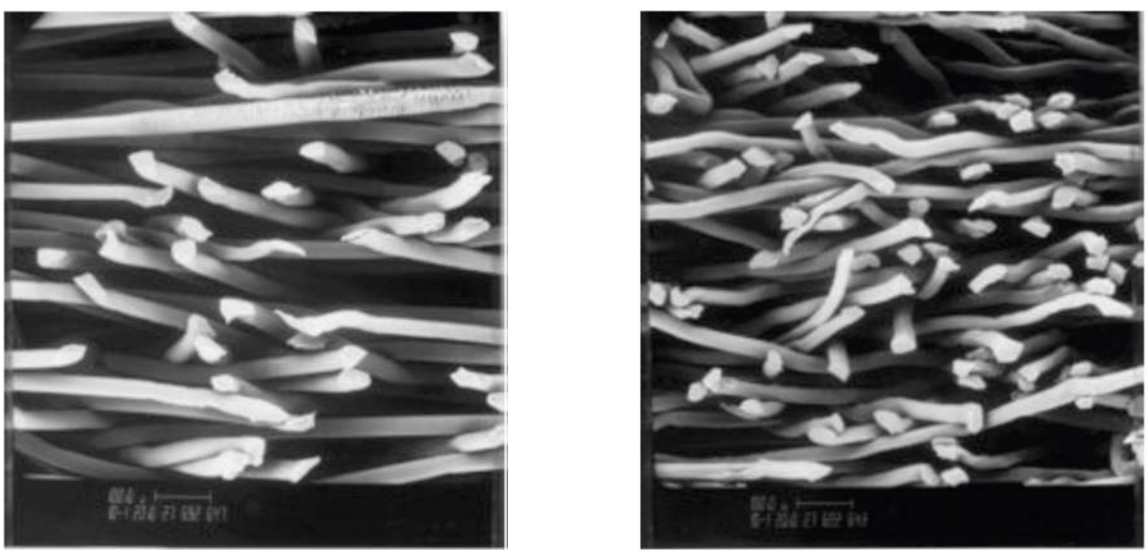
Figure 2.4. Common yarns used in woven geotextiles (Kumar 2008)

(a) Multifilament (b) Slit Film

Figure 2.5 Common yarn types at 8x magnification

2.1.2.2. Nonwoven Geotextiles

Nonwoven geotextiles are composed of either continuous filaments or staple fibers as shown in Figure 2.6. Continuous filaments are made much like the monofilament yarns used in woven materials: by extruding a polymer through tiny holes in order to form a long continuous filament. A staple fiber is made by cutting continuous filament into shorter lengths (<4 in. (101.6 mm)).



(a) Continuous filament (b) Staple fiber

Figure 2.6 Nonwoven fibers at 80x magnification.

The subgroups for nonwoven materials are based on the bonding methods used to keep these fibers intact. They are classified as follows: Mechanical Bonding: Polymer filaments or fibers are laid into a web and then passed through thousands of needles. The needles penetrate the web with additional outside fibers, interlocking them with one another. The geotextile relies on fiber-to-fiber interaction to maintain the geotextile properties. Heat Bonding: Polymer filaments or fibers are laid into a web and then heat-treated. The heat melts fiber-to-fiber contact points together. Addition of controlled pressure points is also used to form heat-bonded geotextiles. Chemical Bonding: Chemical binders, such as acrylic resin or hydrogen chloride gas, are applied to a fiber web. The binder is cured when the web is passed through an oven or hot rollers.

2.1.2.3. Knitted Geotextiles

Knitted geotextiles are composed of filaments in a directionally oriented structure (DOS). Yarns are aligned in four directions: warp, weft, and both diagonals. During the manufacturing process, a “sheet” of reinforcing yarns is laid out. These reinforcing yarns are then knitted together at their crossover points using loops of an additional yarn in order to maintain the DOS. This structure optimizes the multiaxial strength. Regardless, the use of knitted geotextiles is limited because they expand easily and have relatively low strength compared with woven geotextiles (Kumar 2008).

2.1.3 Polymer Classification

The base material of the fabric determines the last classification of geotextiles.
Geotextiles are made from both naturally occurring and synthetically made polymers. A polymer’s properties are defined by its monomers and the links bonding the monomers together. Four polymer groups are commonly used to manufacture geotextiles: polyamides, polyesters (Polyethylene terephthalate - PET), polyethylenes (PE), and polypropylenes (PP). Basic chemistry and properties for each are described in Table 2.1.

Table 2.1 Polymers Used in Geotextile Materials

Polymer	**Chemical Structure**	**Advantages**	**Disadvantages**
Polyamide	Contain amide functional group formed from the condensation of an amino group and a carboxylic acid or acid chloride group	High resistance to alkalis, high temperature resistance, good wear resistance	High moisture absorption, require UV stabilizers
Polyester	Contain the ester functional group formed from dicarboxylic acid and two hydroxl groups	High resistance to UV light and detergents, high creep resistance, wear resistant, low moisture absorption	Low resistance to alkalis
Polyethylene	Produced from the polymerization of ethylene	High chemical, abrasion and puncture resistance, high creep resistance, variety of densities available	Most sensitive to UV light
Polypropylene	Produced from the polymerization of propene	Very high chemical resistance, low moisture absorption, low cost, high mass per unit weight	High creep, requires UV stabilizers

2.1.4 Basic Geotextile Properties

With different base materials, filaments, weaving, thickness, mass and bond type, geotextiles have a range of characteristics. Because of this, determining physical, mechanical and hydraulic properties of geotextiles becomes a crucial step in the proper selection of geotextiles. Basic properties used to describe geotextiles as well as their ASTM standards and relevant functions are summarized in Table 2.2.

2.2. History of Geotextile Testing

The earliest of geotextile testing dates back to the 1970's with the ASTM Subcommittee D13.61 of ASTM Committee D13 on textiles. The ASTM subcommittee D13.61 provided standards for textiles used in civil engineering applications with additional testing involving soil-fabric interactions. In an effort to accelerate the development of this specific group of textiles, geotextiles, ASTM Committee D35 was developed in 1984 when subcommittee D13.61 elected to become a joint committee under D18 on Soil and Rock. The committee currently has over 155 approved standards (Committee D35 on Geosynthetics).

Table 2.2 Basic Properties of Geotextiles

Geotextile Property	**Description**	**ASTM Standard**	**Relevant Functions***
Tensile Strength (Grab)	Maximum stress a geotextile can experience while being pulled before failing	D4632	S, R, F
Tear Strength	Ability of a geotextile to withstand the effects of tearing	D4533	S, R, P
Elongation	Ratio of the length of a geotextile at its breaking point relative to its original length	D4632	S, F, R
Puncture Strength	Maximum force required to penetrate a geotextile	D6241	S, F, R, P
Apparent Opening Size	Approximate largest opening dimension of a geotextile available for soil to pass through	D4751	S, D, F, R
Permittivity	Quantity of liquid that can pass through a geotextile	D4491	S, D, F, R
UV Resistance	Measure of how a geotextile will deteriorate due to exposure to ultraviolet light	D4355	S, P
Chemical	Ability of a geotextile to resist	D6389	S, D, F, R, P

Resistance	changes in properties due to exposure to chemicals or liquid waste		
Mass/Unit Area	Average amount of mass per unit area of a geotextile	D5261	S, R, P
Thickness	Average thickness of the geotextile	D5199	S, D, F, P

*S=Separation, D=Drainage, F=Filtration, R=Reinforcement, P=Protection

2.2.1 Evolution of Puncture Strength Testing

Puncture strength testing of geotextiles dates to the 1970s with ASTM D751-79 Method of Testing Coated Fabrics. The U.S. Army Corps of Engineers proposed using the tension testing machine with ring clamp of ASTM D751 (2011), but replacing the steel ball with an 8 mm-diameter solid steel, flat-tip probe. The flat-tip probe was temporarily replaced with a hemispherical probe, but inaccurate data resulted because the tip slipped through textiles rather than rupturing them. By the 1980s the ASTM D35 committee recommended the puncture test be run using ASTM D3787-80 Test Method for Bursting Strength of Knitted Goods: Constant-Rate-of-Traverse (CRT) Ball Burst Test, but with a constant rate of extension, 8mm-diameter, flat-tip probe, a strain rate of 300 mm/min, and compression ring clamps(Suits, Carroll et al. 1987). By the turn of the century, four key standards were available for geotextile puncture strength testing. The first, ASTM D3786 (2013): Standard Test Method for Hydraulic Bursting Strength of Textile Fabrics-Diaphragm Bursting Strength Tester Method used an inflatable rubber membrane to deform the geotextile into the shape of a hemisphere through a 30 mm-diameter ring until it burst. The second, ASTM D4833: Standard Test Method for Index Puncture Resistance of Geomembranes and Related Products, is a variation of ASTM D3787, which utilizes a slip-free ring clamp and 8 mm-diameter, 45 degree beveled edge probe. The samples are subjected to either tension or compression until rupture occurs. Neither ASTM D3786 (Mullen Burst) nor ASTM D4833 (Pin) are currently recognized by the ASTM as acceptable geotextile test methods. These tests were no longer accepted because, as described by Koerner et al. (2011), “lightweight nonwoven fabrics had a rather large statistical variation” in puncture strength “between small areas of somewhat dense fibers and other small areas with sparse fabrics.” The larger probe used in the ASTM D6241 standard reduces this statistical impact. The final method, ASTM D5494:

Standard Test Method for Determination of Pyramid Puncture Resistance of Unprotected and Protected Geomembranes, is also relevant but should only be used on a geotextile when a geotextile-geomembrane *system* is being tested. Currently, the AASHTO M288 (McKnight and Carman 2002) has replaced ASTM D4833 with ASTM D6241 Standard Test Method for the Static Puncture Strength of Geotextiles and Geotextile-Related Products Using a 50 mm Probe. In 2010, ASTM D3786 and ASTM D4833 information was no longer reported by Geosynthetic Materials Association members (Bygness, 2010).

2.2.2 Current Significance and use of ASTM Standards

The significance and use for the most relevant ASTM standard test methods are described in the *active* standards as follows (ASTM Volume 04.13). Their common names are listed in parenthesis.

- ASTM D3786 (Mullen Burst): "This method for the determination of diaphragm bursting strength of knitted, nonwoven and woven fabrics is being used by the textile industry for the evaluation of a wide variety of end uses" (ASTM Standard D3786/D3786M, 2013).
- ASTM D4833 (Pin or Index): **"**This test method is an index test for determining the puncture resistance of geomembranes and related products. The use of this test method is to establish an index value by providing standard criteria and a basis for uniform reporting." (ASTM Standard D4833/D4833M, 2013)
- ASTM D5494 (Pyramid): **"**The test method is to be used as an index test to determine the pyramid puncture resistance of geomembranes and, or both, geomembranes protected by non-woven geotextiles and other puncture protective geosynthetics." (ASTM Standard D5494, 2011)
- ASTM D6241 (CBR): **"**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." (ASTM Standard D6241, 2009) According to the standards, the puncture strength resistance of a geotextile should, therefore, be tested using only ASTM D6241.

2.2.3 Comparison of Testing Parameters for ASTM D4833 and ASTM D6241

The ASTM D4833 and D6241 standards are similar with the exception of a few key alterations of the clamp and probe system. A summary of the standards is shown in Table 2.3. Figures 2.7 and 2.8 show the testing fixtures and plungers used in testing.

Table 2.3 Comparison of pin and CBR testing standards

Measure	D4833 (Pin)	D6241 (CBR)
Probe Diameter	8 mm ± 0.1mm	50 mm ± 1mm
Probe Chamfer/Edge	45°, 0.8 mm	2.5 mm ± 0.5 mm
Specimen Minimum Outer Diameter	100 mm	Clamp outer dia. + 10 mm
Specimen Unsupported Diameter (Clamp Inner Diameter)	45 mm ± 0.025 mm	150 mm
Compression Speed	300 mm ± 10 mm/min	50 mm/min
Maximum Allowable Slippage	None allowed	5 mm
Number of Tests	15	10
Lab Temperature	21 ± 2°C	21 ± 2°C
Lab Relative Humidity	65 ± 5%	50-70%
Test Conclusion	Break	Break
Resistance Reported	Maximum	Maximum

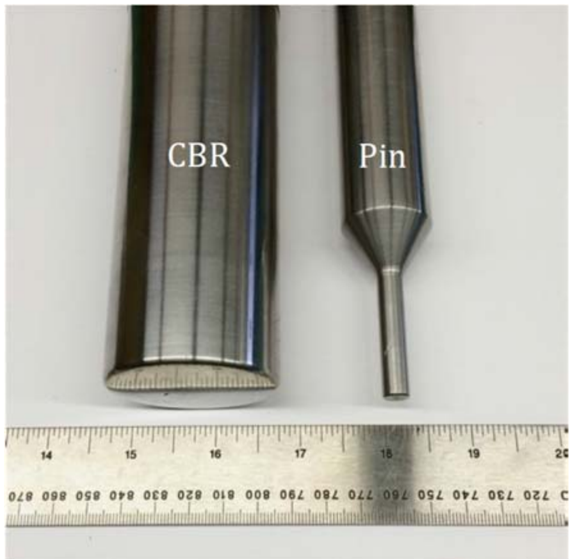
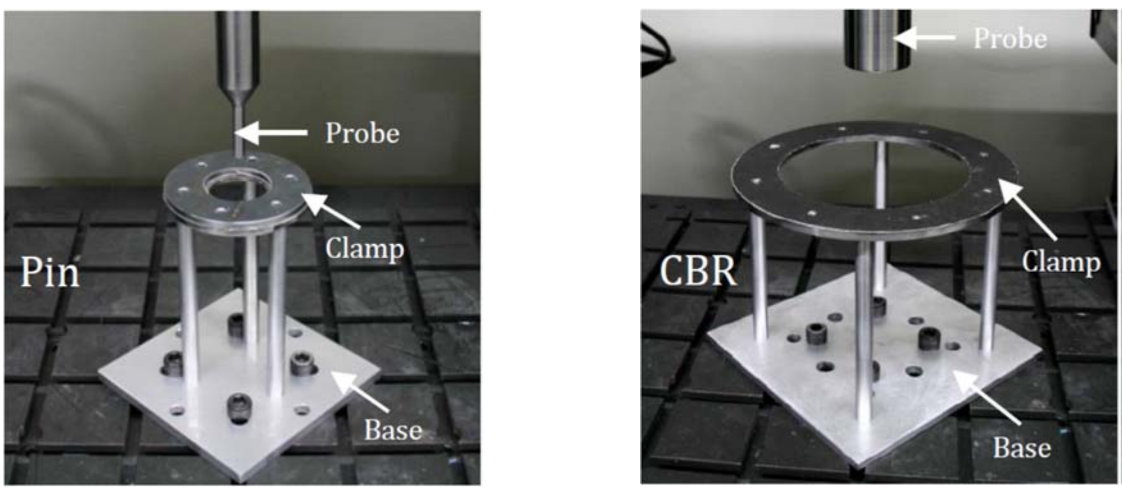


Figure 2.7. Plungers used for CBR and pin puncture strength testing of geotextiles in the UW-Milwaukee Engineering Mechanics and Composites Lab.



(a) Pin puncture fixture (b) CBR fixture

Figure 2.8. Clamping fixtures used for puncture strength testing of geotextiles in the UW-Milwaukee Engineering Mechanics and Composites Lab.

2.3. State of the Art Research on Puncture Strength Testing of Geotextiles

A select few research projects (Narejo, Koerner et al. 1996, Jones, Shercliff et al. 2000, Hsieh and Wang 2008, Koerner and Koerner 2011, Rawal and Saraswat 2011, Askari, Najar et al. 2012) have been reviewed in relation to this report. Of those, they consist of two groups: studies that address variations in puncture strength testing methods (Hsieh and Wang 2008), (Askari, Najar et al. 2012) and studies to address variations in the materials tested (Jones, Shercliff et al. 2000, Koerner and Koerner 2011, Rawal and Saraswat 2011). Also note that although geotextiles can be found in geomembrane/geotextile systems, discussion of geomembranes is beyond the scope of this literature review. Research studies involving puncture strength testing of geomembrane/geotextile *systems* (Narejo, Koerner et al. 1996), however, will be considered when relevant.

2.3.1 Testing Method Variations

2.3.1.1. Clamping Mechanism

Because both ASTM D4833 and ASTM D6241 have a dual plate-screw clamping mechanism, clamping slippage and technician variations inherently result. Hsieh and Wang (Hsieh and Wang 2008)suggested hydraulic clamping mechanisms for pin (Figure 2.9a) and CBR (Figure 2.9b) puncture strength testing in addition to studying the time savings and puncture strength resistance variation related to the proposed mechanism.

(a) ASTM D4833 (pin) hydraulic puncture apparatus (Hsieh and Wang (2008))

(b) ASTM D6241(CBR) hydraulic puncture apparatus (Hsieh and Wang (2008))

Figure 2.9 Hydraulic pin and CBR puncture strength testing apparatuses proposed by Hsieh and Wang (Hsieh and Wang).

Hsieh and Wang (2008) tested a polypropylene and woven polypropylene and polyester mix (PP/PET). All tests were performedat the constant rates of compression of 300±10 mm/min and 50 mm/min for ASTM D4833 and ASTM D6241, respectively. The puncture strength resistance varied more significantly for the ASTM apparatus than it did using the hydraulic testing mechanism. A skilled technician took an average of 119 seconds to perform the pin puncture strength test using the conventional clamp and took an average of only 8 seconds to perform the pin puncture strength test using the hydraulic apparatus A skilled technician also saved time using the hydraulic apparatus for the CBR puncture strength test, taking only 19.6 seconds, on average, using the hydraulic clamp rather than 105 seconds using the conventional CBR clamp. The proposed hydraulic apparatus saved approximately 20 minutes per test. The puncture resistance difference between skilled and unskilled technicians was also reduced. The polypropylene average puncture strength and standard deviation varied less than those for polyester. Skilled technician pin and CBR puncture strengths using the conventional clamps were an average of 1,092.37 N and 9,365.88 N for PP geotextiles, respectively. Using the hydraulic clamps, skilled technician pin and CBR puncture strengths of PP geotextiles were an average of 1,082.65 N and 8,669.09 N, respectively. The CBR puncture strength (ASTM D6241) for both the PP and PP/PET geotextiles, both woven materials, were eight times the pin puncture strength (ASTM D4833). Hsieh and Wang (Hsieh and Wang 2008) also indicated that ASTM D4833 results varied less than ASTM D6241.

2.3.1.2. Rate of Compression

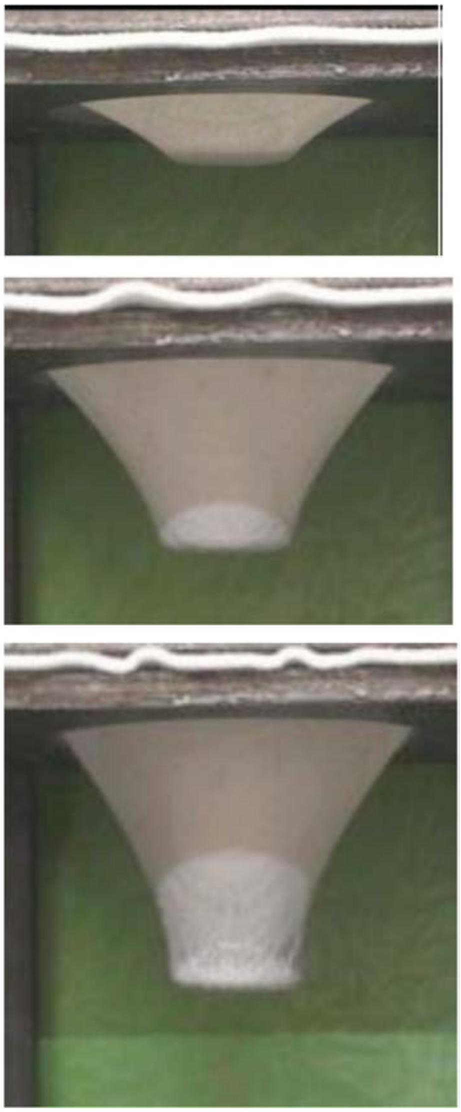
The rate of compression used for puncture strength testing is inherently expected to affect the maximum puncture strength recorded. Askari et al. (2012) studied the effects of both test speed and fabric weight on the puncture resistance of polyester needle punched nonwoven geotextiles using ASTM D6241 and D4833. The materials weights were 460, 715, 970, and 1070 g/m^2 and the tests were conducted at 5 speeds: 25, 50, 75, 100, and 125 mm/min. The CBR puncture strength testing results are shown in Table 2.4.

Table 2.4. The CBR puncture strength testing results

Sample	Test Speed (mm/min)	Force (kN)	Standard Deviation (kN)
A	25	1.73	0.37
	50	2.08	0.21
	75	1.64	0.15
	100	1.77	0.18

	125	1.80	0.29
B	25	3.87	0.16
	50	3.94	0.31
	75	3.72	0.23
	100	3.80	0.57
	125	3.98	0.24
C	25	5.34	0.33
	50	5.26	0.51
	75	5.41	0.20
	100	5.46	0.20
	125	5.24	0.43
D	25	5.27	0.18
	50	4.95	0.58
	75	5.03	0.54
	100	6.25	0.24
	125	6.16	0.26

They determined that the weight and speed both impacted the maximum puncture strength resistance for both tests. They also used an “R-value” concept or weight/thickness ratio, measured in g/m^2*mm, to indicate the number of fibers in the layer’s cross-section. The 50 mm plunger size used in D6241 is preferred because it is less influenced by the irregularities in the fiber densities (Koerner and Koerner 2011). Askari et al. (2012) also described the failure of a geotextile using three distinct stages of the material failure. During the first stage, the compression forces result in a rearrangement or movement of fibers. During the second stage, the fibers have become more tightly packed and will have an added frictional interaction among them, which increases their ability to resist higher loads. The third stage includes the puncture failure as a result of a sudden separation of fibers. The three stages are shown in Figure 2.10.



(a) Fibers are rearranging

(b) Fibers experience added frictional forces in their new arrangement

(c) Fibers separate just before failure

Figure 2.10. Failure stages of polyester needlepunched nonwoven geotextile (Askari, Najar et al. 2012).

2.3.2 Geotextiles Tested

2.3.2.1. Testing Approach

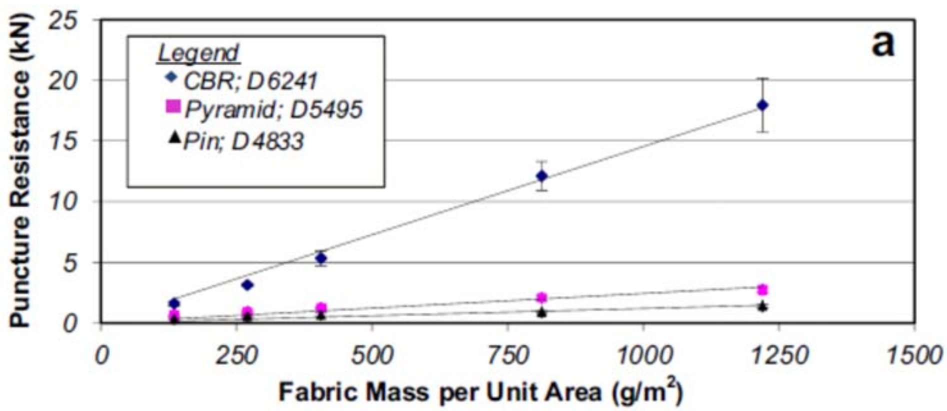
Narejo et al. (1996) measured the puncture strength resistance of polyethylene geomembranes with and without nonwoven needle-punched geotextiles used as protection. The combination of geomembranes and nonwoven geotextiles is common in the landfill applications where the geomembrane acts as a nonporous liquid barrier, and the geotextile acts as a cushion of protection to the geomembrane, which has a lower puncture resistance. They developed empirical design equations based on truncated cone and stone puncture test results to be used for the design of high density polyethylene (HDPE) geomembranes using failure pressures, rather than yield pressures, as the measure of comparison. The equations involve factors for chemical and biological degradation, creep, soil arching, packing, density, and stone shapes. They found that the puncture resistance of geomembranes increased as the mass per unit area of protection geotextile increased.

2.3.2.2. Mass per unit area

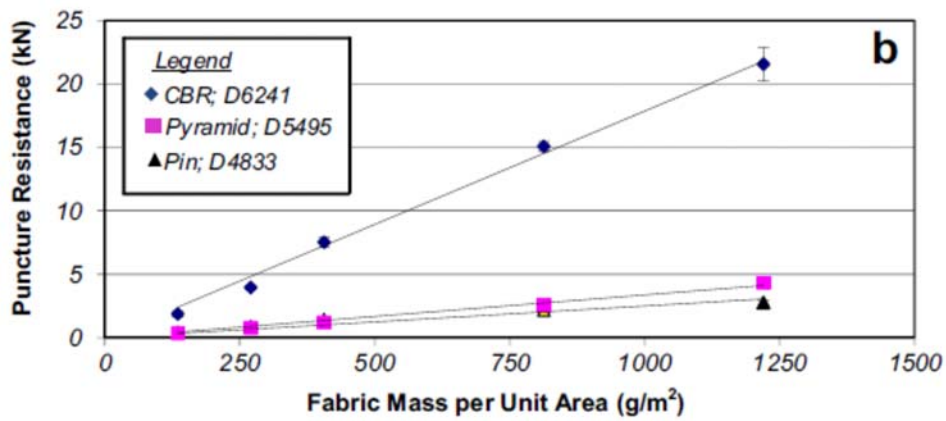
Jones et al.(2000) later found the relationship between mass per unit area and puncture strength resistance to be non-linear for needle punched geotextiles. It was proposed that the performance was derived from the frictional interaction between fibers. During the study high, medium, and low performance needle punched, non-woven geotextiles with matching mass per unit areas of 1,000 g/m^2 were tested. The base material used for testing was not indicated. Their CBR puncture strength resistances were determined using BS EN ISO 12236 (Geosynthetics – Static puncture test (CBR test)) to be 11,443, 7,974, and 7,353 N, respectively. Although the study described using mass per unit area to specify geotextile layers as "inappropriate," Jones et al. (2000) stated that CBR puncture resistance gives "a better indication of protection performance" than mass per unit.

Koerner and Koerner (2011) directly compared nonwoven PP and PET samples with similar mass per unit area. All PP samples were continuous filament, but two types of PP materials were used: continuous filaments and staple fibers. They were all tested without a geomembrane system and on three puncture resistance tests, ASTM D4833, D5494, and D6241, two of which are being explored in this report. Five different mass per unit areas of three classifications of material were used. Unlike Jones et al. (2000) (Jones, Shercliff et al. 2000), all of the materials tested by Koerner and Koerner(2011) showed an essentially linear connection between increased mass per unit area and puncture resistance. Because the material used by Jones et al. was not indicated, it is difficult to say why the linear relationship was not found. Koerner also found relationships between the three puncture mechanisms used. Note that the test relationships were developed among nonwoven materials exclusively. The PET continuous filament resulted in triangular and CBR puncture resistances two and nine times the index pin resistance as shown in Figure 2.11a. The PP continuous filament resulted in comparable triangular and pin resistances and CBR about seven times the pin resistance (Figure 2.11b). The puncture resistance curves of

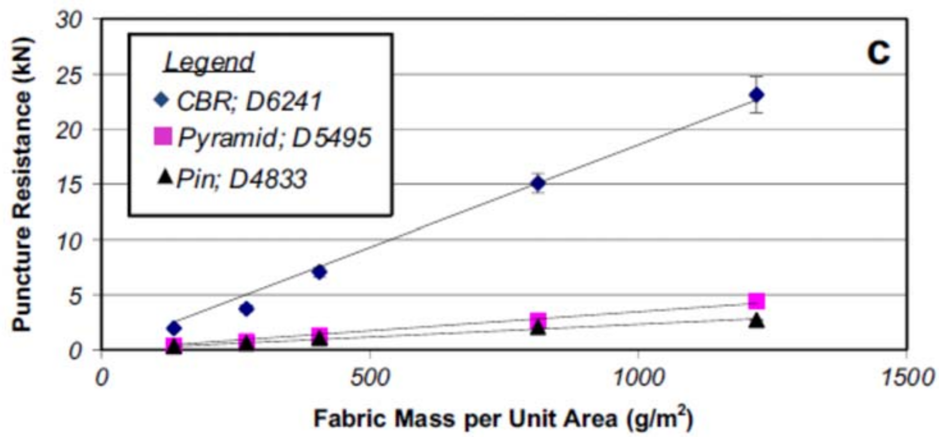
PP staple fiber had comparable triangular and pin puncture strengths and CBR about seven times the pin resistance (Figure 2.11c). For ASTM D4833 results, the PP continuous filament and staple fiber give similar results and are two times larger than PET values. The PP results were, again, about the same, and 35% higher than PET puncture strengths for ASTM D5494 testing. The ASTM D6241 PP puncture strengths were comparable and 25% higher than PET values. Koerner and Koerner (2011) also determined that the material structure, i.e. continuous filaments vs. staple fibers, has little to no effect on the puncture strength for nonwoven geotextiles. Figures 2.11band 2.11c show two PP materials with different nonwoven fiber structures (continuous vs. staple). It is apparent the values in these two charts are nearly the same for all test and all unit weights, supporting the assumption that the materials filament type does not impact puncture resistance results for nonwoven geotextiles.



(a) PET continuous



(b) PP continuous filament



(c) PP staple fiber

Figure 2.11*. Puncture resistances of polyester and polypropylene materials, a) Puncture resistance of PET continuous filament material, b) Puncture resistance of PP continuous filament material, c) Puncture resistance of PP staple fiber material (Koerner and Koerner 2011)

(*Correction to figure 2.11 from literature review: D5494 not D5495 as it shown in the figure)

2.3.2.3. Base Material

Rawal and Saraswat (2011) studied the puncture resistance of hybrid PP/viscose and PET/viscose geotextiles using ASTM D4833 for use in the stabilization of soil. Viscose is manufactured from naturally occurring cellulose found in wood pulp. The materials wereadjusted to weight proportions of 0, 20, 40, 60, 80, and 100. The mass per unit area was held at 200 g/m^2 and 400 g/m^2. The thickness of the materials was also measured at varying pressures to determine changes in porosity. They found that adding up to 40% weight of viscose in PP materials with a mass per unit area of 400 g/m^2 did not affect the puncture resistance. Adding up to 20% weight of viscose in PET materials with a mass per unit area of 200 g/m^2 had the same puncture resistance as 100% PET materials.

2.3.2.4. Weave

Of the studies found involving both pin and CBR puncture tests, *none* used a combination of woven and nonwoven materials. Studies either examined *exclusively* nonwoven or *exclusively* woven materials. It is in the authors' interest to discover if geotextiles made of like materials and with the same mass per unit area, yet with different manufacturing processes perform similarly in puncture resistance tests.

Chapter 3

Experimental Methods

The research methodology followed to accomplish the research objectives is presented in this chapter. The experiment design, developed to include a sufficient number of test specimens, as well as the types of researched geotextiles are highlighted. Details of obtaining geotextile samples, preparing test specimens, and performing pin and CBR puncture strength tests are presented. In addition, a description of test equipment and procedures is presented.

3.1 Materials Selection for Research

<u>Phase I</u>: The authors examined literature of geotextile suppliers in the Midwestern United States. Of the most common materials used within those states, nearly all of them were composed of 100% polypropylene. This is likely due to the fact that polypropylene costs less than polyester and has a lower specific gravity, resulting in about 25% more fibers per unit weight. The high fiber count increases the mass per unit area and, therefore, the puncture strength of the material as well. The average puncture strength and standard deviation of polypropylene materials also vary less than those of polyester Hsieh and Wang (2008). For these reasons, polypropylene materials were tested as they are more commonly used and statistically vary less, allowing for a better comparison of the tests rather than the material. Major geotextile manufacturers in the U.S. were contacted to obtain materials for testing to accomplish the objectives of this research. The geotextiles selected for testing were both woven and nonwoven and had one of three different mass per unit areas. The material uses varied. The geotextiles selected for testing in Phase I were both woven and nonwoven and had one of three different mass densities. A total of 125 specimens were tested in this phase of the project. A description of the materials tested are presented in Table 3.1 and the samples are shown in Figure 3.1.

Table 3.1 Materials selected for research in Phase I

Geotextile Designation	Material Type	Weave Type	Use/Application	Mass/Unit Area, oz/yd^2 (g/m^2)
A	PP	Nonwoven	Drainage, Separation	4 (136)
B	PP	Woven	Separation	4 (136)
C	PP	Nonwoven	Drainage, Separation	8 (271)
D	PP	Woven	Filtration, Separation	8 (271)
E	PP	Nonwoven	Drainage, Separation	12 (406)

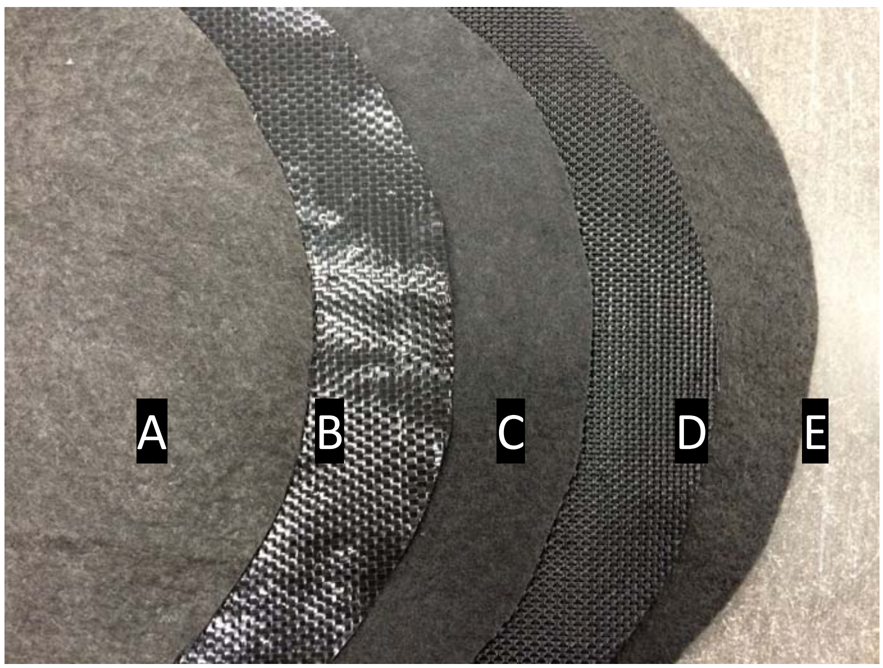


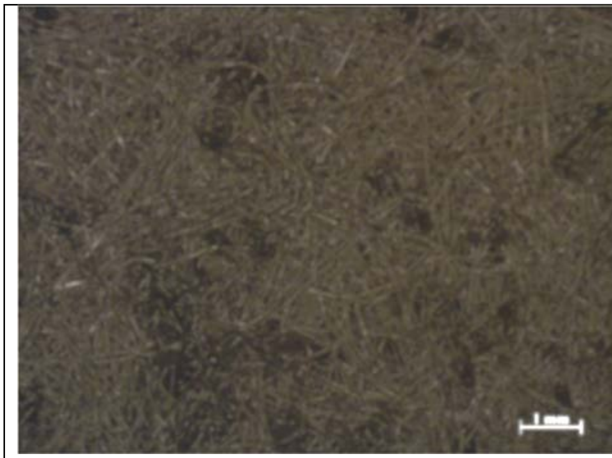
Figure 3.1 Geotextile materials (as shown) selected for research – Phase I

<u>Phase II</u>: The specimens in this category were provided by WisDOT from *29 different projects*. A total of 280 *specimens* were tested as part of this phase representing six different fabric types and different weights including woven and non-woven materials. Table 3.2 below also shows that the fabrics provided cover a wide range of weights which can be considered representative of what can be observed in practice. A subset of these specimens was used in Phase III to test the effects of exposure to Ultraviolet (UV) light, temperature and moisture. Five specimens from each project/type/manufacturer were used to test the material on ASTM D4833 and five specimens on ASTM D6241. For the Phase III tests, five specimens were also used from each project provided to test using ASTM D6241. Pictures taken by an optical microscope of geotextiles tested in Phase II are shown in Figure 3.2

Table 3.2: Test matrix of evaluated fabrics supplied by WisDOT – Phase II

Fabric Type	Project Number	Total Number of Specimens	Manufacturer	Avg. Weight (g/m^2)
DF	1195-13-71	10	PROPEK GEOTEX	137.9
DF	1030-11-70	10	TENCATE	229.4
DF	1195-13-71	10	PROPEX GEOTEX 401	156.5
DF	1170-01-70	10	WILLACOOCHEE INDUSTRIAL FABRICS	124.0
DF	1206-07-77	10	THRACE LINQ	227.8
DF	NA	10	TENCATE	254.2
DF	NA	10	NA	234.0
DF	1060-33-70	10	SKAPS Industries	147.2
DF	9200-04-71	10	HONES GEO Component	207.7
DF	1030-11-70	10	TENCATE	198.4
DF	1206-07-77	10	NA	199.9
DF	1030-11-70	10	TENCATE GEOSYNTHETICS AMERICAS	248.0
DF	2753-06-71	10	SKAPS	244.9
DF	1060-33-73	10	PROPEX	223.2
ES	1133-11-74	10	HUESKER INC	223.0
HR	NA	10	NA	153.1
HR	NA	10	Advanced Geosynthetics 120 NW	483.9

MS	6968-01-70	10	TENCATE MIRAT	206.1
MS	NA	10	TENCATE	303.8
SAS	1133-03-71	10	PROPEX701	227.8
SAS	8160-14-71	10	Geo Synthetics-LLC	228.5
SAS	5658-00-75	10	Tencate Mirafi 600x	206.2
SAS	1030-11-70	10	NA	189.1
SAS	NA	10	WESTERN EXCELSIOR CORP	310
SAS	9240-10-61	10	PROPEX	238.7
SAS	1060-33-75	10	TENCATE	227.8
SR	5994-00-72	10	WILLACOOCHEE	229.4
SR	5994-00-72	10	WILLACOOCHEE	207.7



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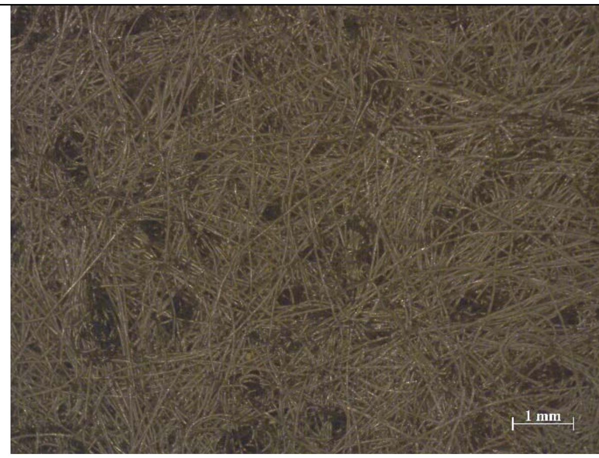

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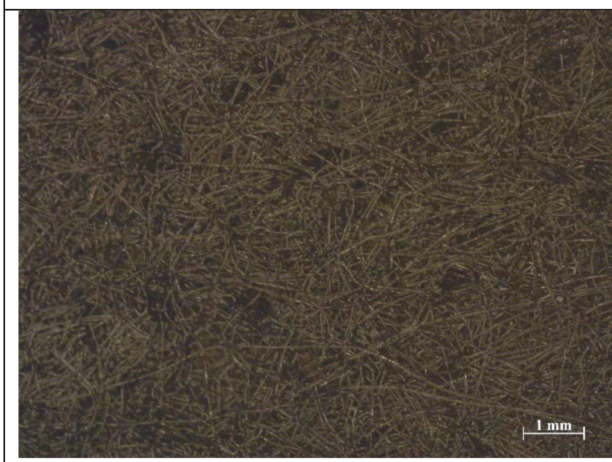

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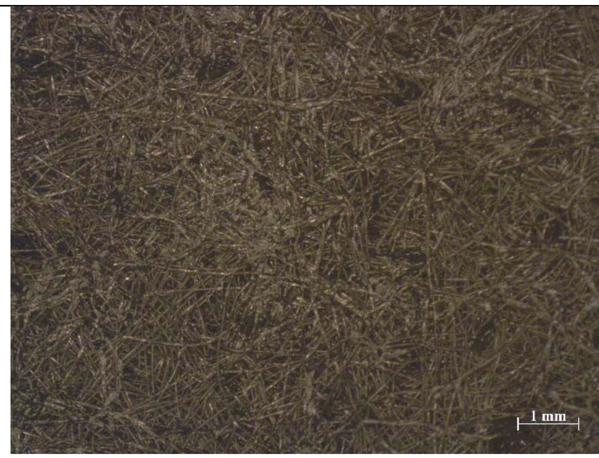

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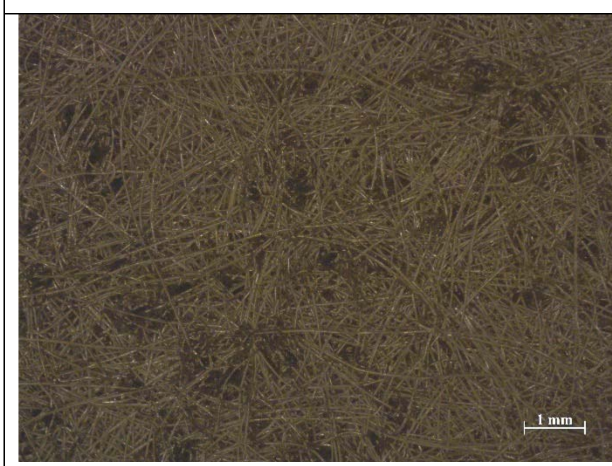

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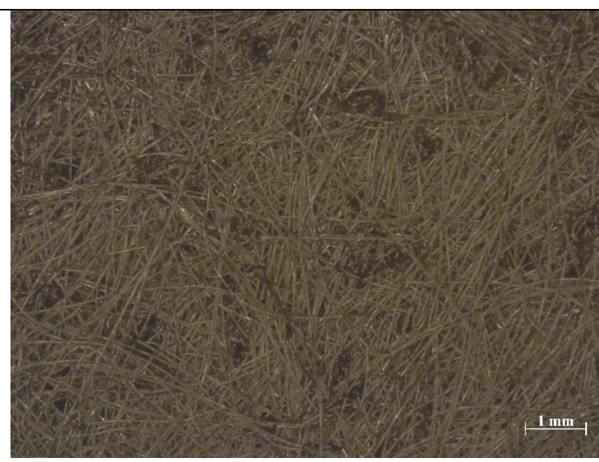

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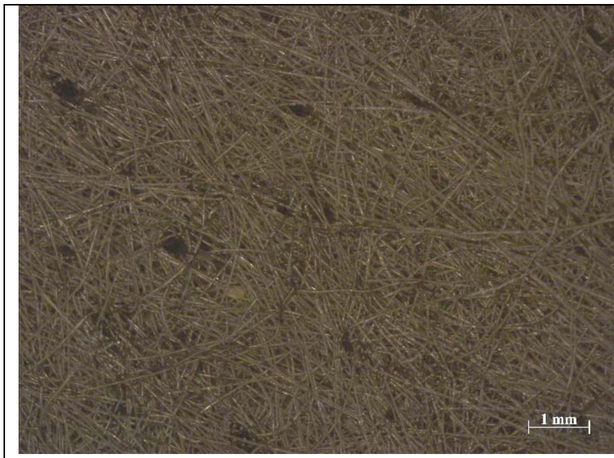
Figure 3.2: Pictures taken by optical microscope of geotextiles tested in Phase II.



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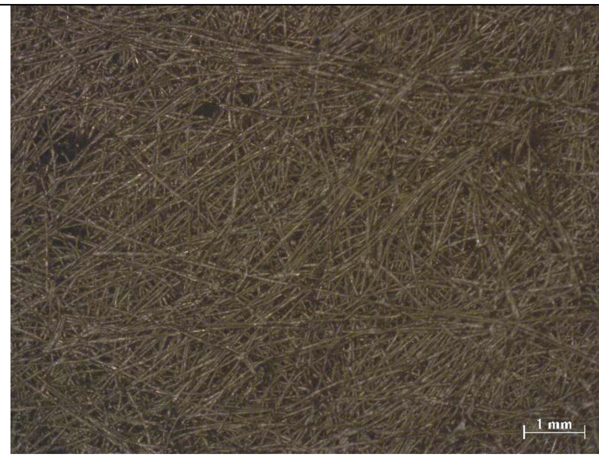

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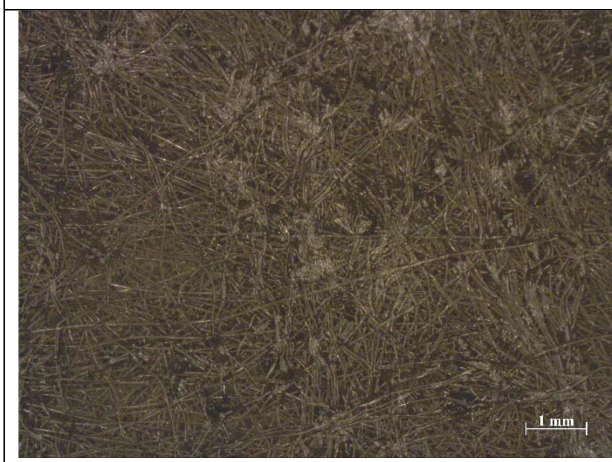

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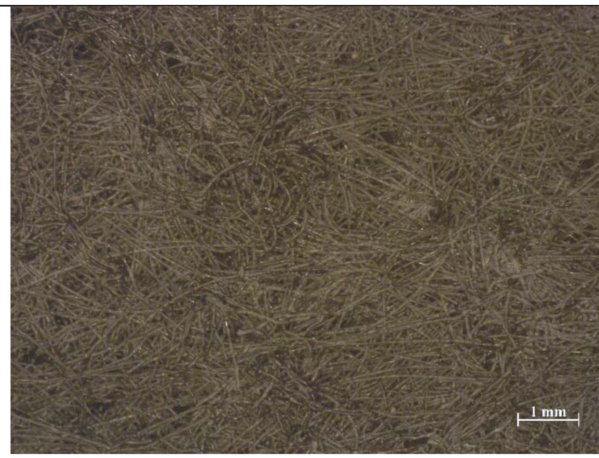

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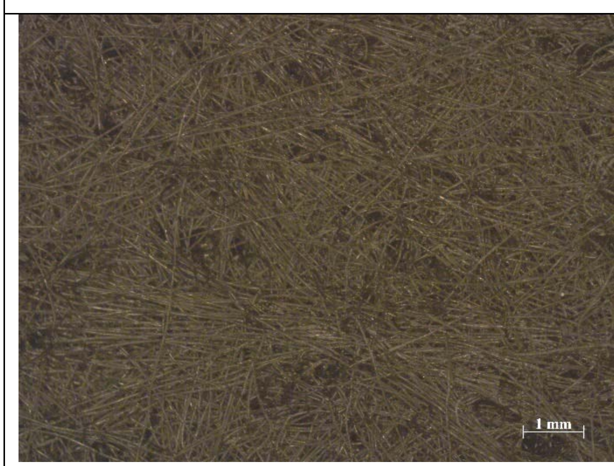

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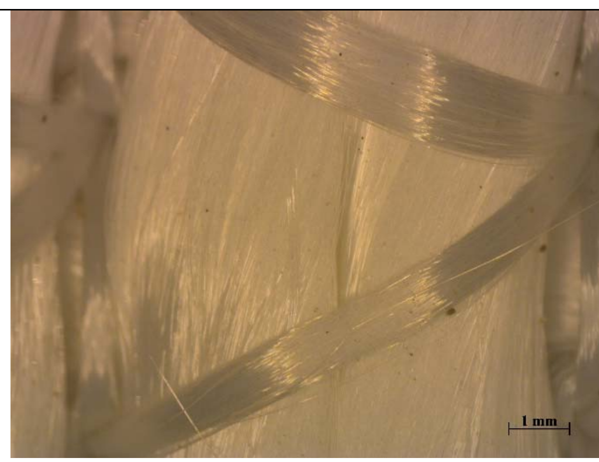
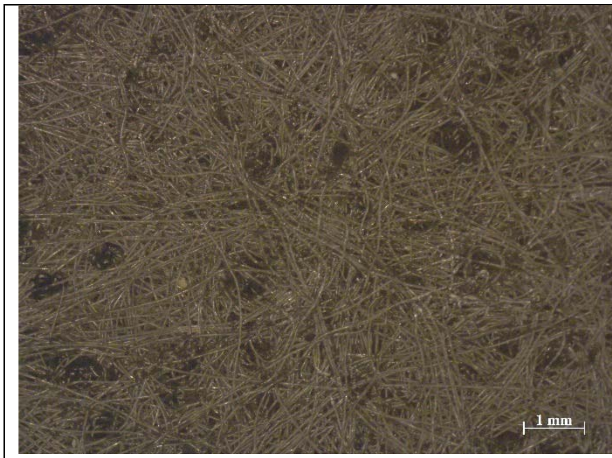
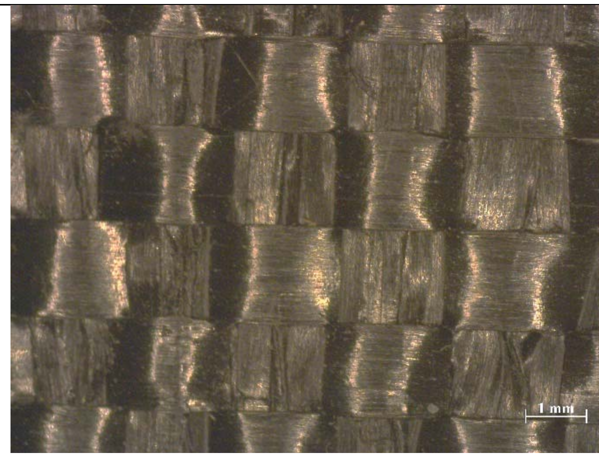


Fabric ES – 1133-11-74

Cont. Figure 3.2: Pictures taken by optical microscope of geotextiles tested in Phase II.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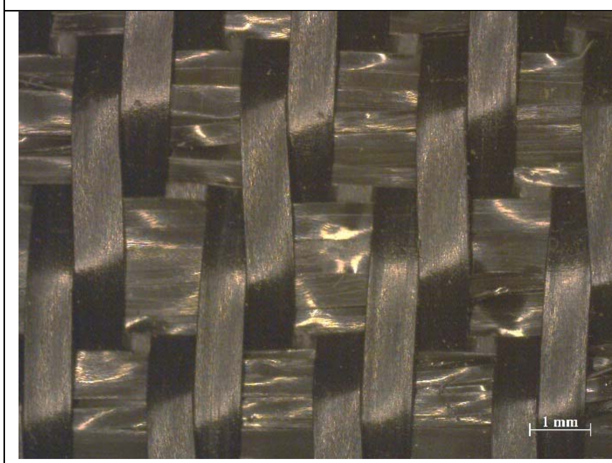	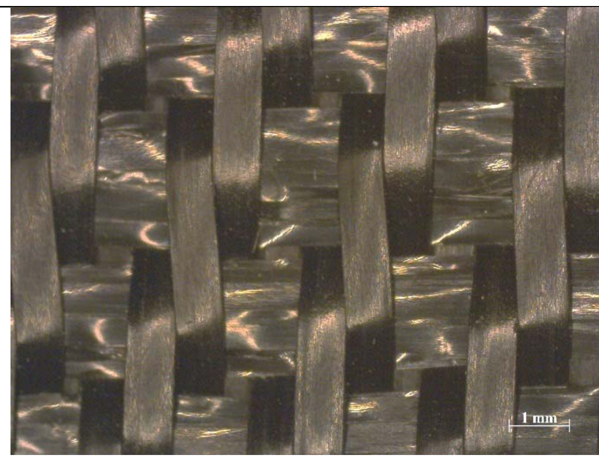
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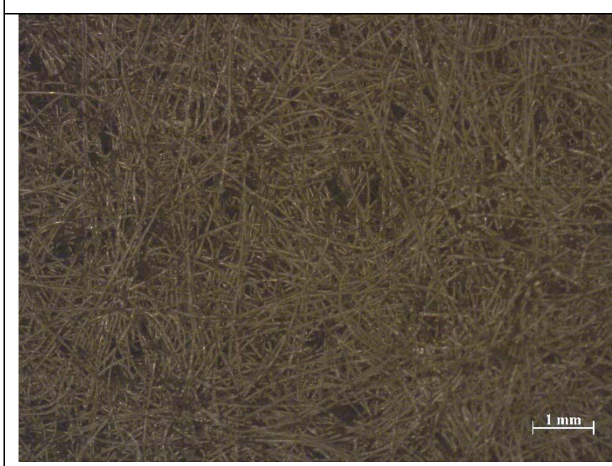	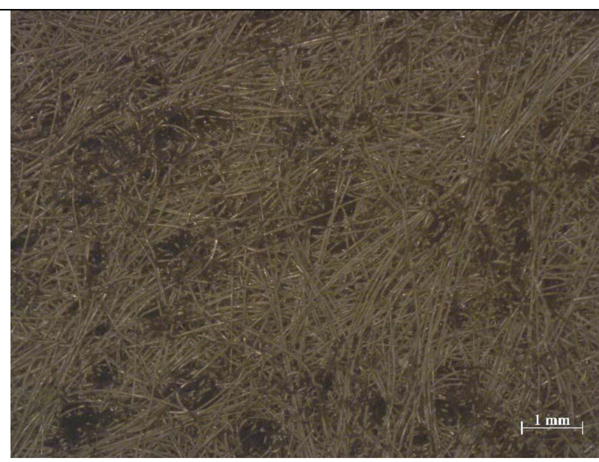
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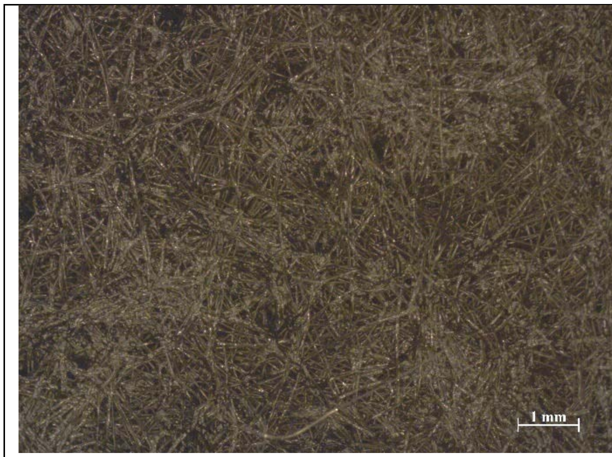
Cont. Figure 3.2: Pictures taken by optical microscope of geotextiles tested in Phase II.



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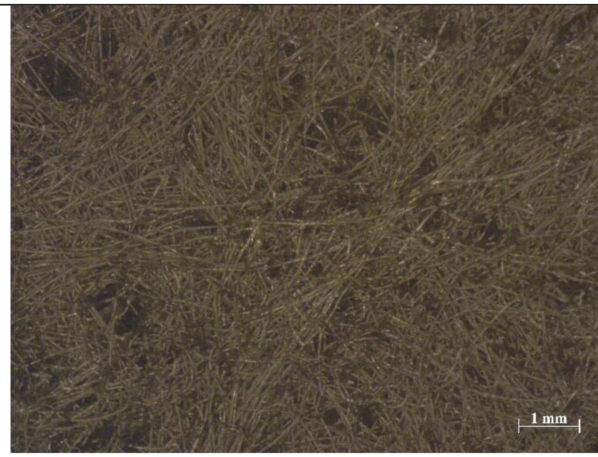

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Fabric SAS – 8160-14-71

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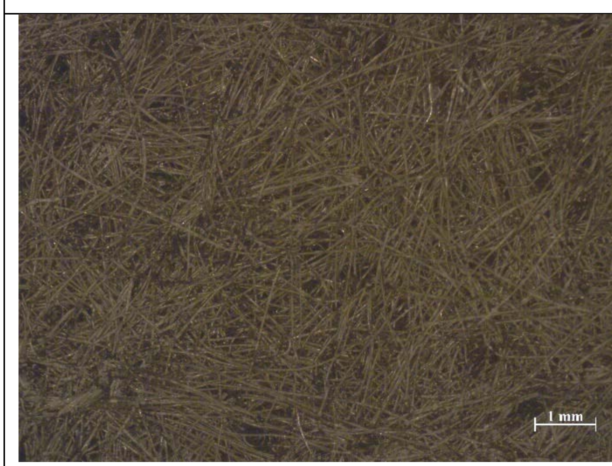

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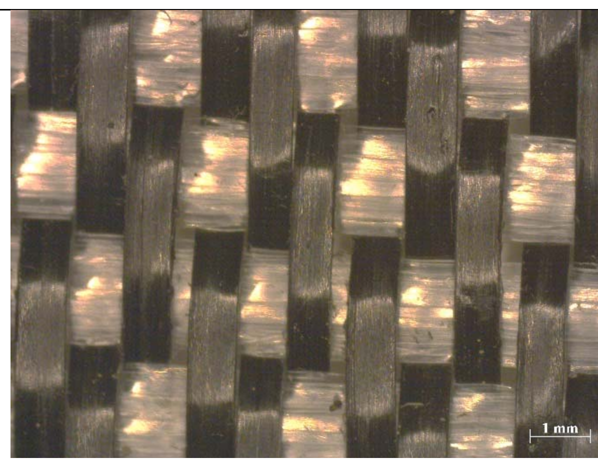
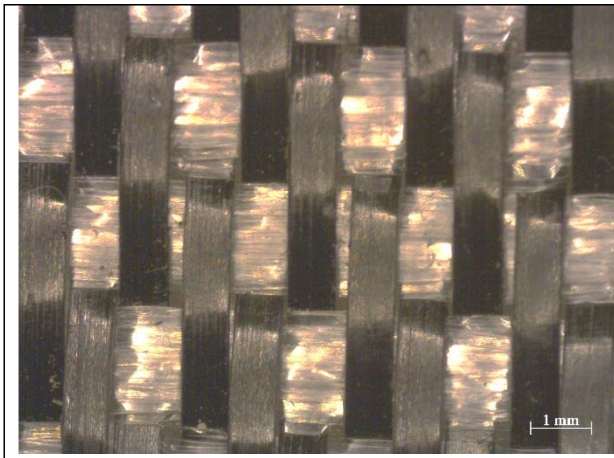


Fabric SR – 5994-00-72

Cont. Figure 3.2: Pictures taken by optical microscope of geotextiles tested in Phase II.

	
Fabric SR – 5994-00-72 (2)	

Cont. Figure 3.2: Pictures taken by optical microscope of geotextiles tested in Phase II.

3.2 Puncture Strength Standard Test Methods

ASTM D4833 (pin) and ASTM D6241 (CBR) standards were followed to evaluate the puncture strength of the various geotextile specimens.

Sample Preparation

For Phase I, most geotextile materials were supplied in approximately 12 ft by 12 ft sections. Ten 120 mm-diameter samples were cut along the material diagonal for testing using the ASTM D4833 standard. Fifteen 240 mm-diameter samples were prepared for testing using the ASTM D6241 standard and were taken along a parallel diagonal over approximately the same width of material. For Phase II (Table 3.2, geotextile materials were provided by WisDOT and in this phase five test specimens were prepared for each strength puncture test. The sample selection layout is illustrated in Figure 3.3. The diagonal sampling captures maximum material variability in both manufacturing directions. The samples were taken parallel to one another and over the same material width to reduce the impact of variability in material location on the results of the two test methods. Samples were neither taken closer than six in. to the edge for ASTM D6241 testing nor closer than 16 in to the edge for ASTM D4833 to meet all requirements. Additionally, any crushed or deformed areas were excluded. In the event of a deformed area, best efforts were made to select samples from nearby areas as shown in Figure 3.4. Notice that the samples follow the general diagonal, but do not include the crushed material.

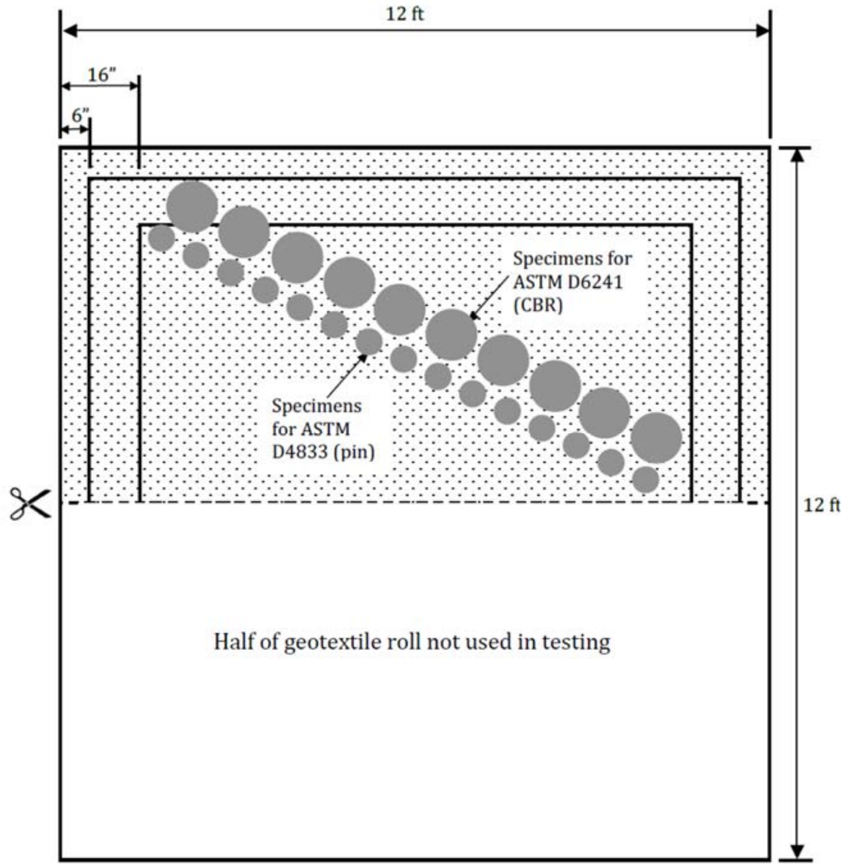


Figure 3.3 Layout of samples used for testing.

The samples were labeled for later identification, as needed. Bolt holes were cut in each specimen using a small "cross" cut of a scissors. Figure 3.5 shows the samples prepared to be tested. Note that woven geotextile (material B in Figure 3.2) easily lost fibers during handling because it was a woven material. To prevent changes in mass and loss of material, all woven geotextile samples were outlined with a thin glue layer. Note that this glue layer was close enough to the perimeter of the sample to never make contact with the clamping fixture.

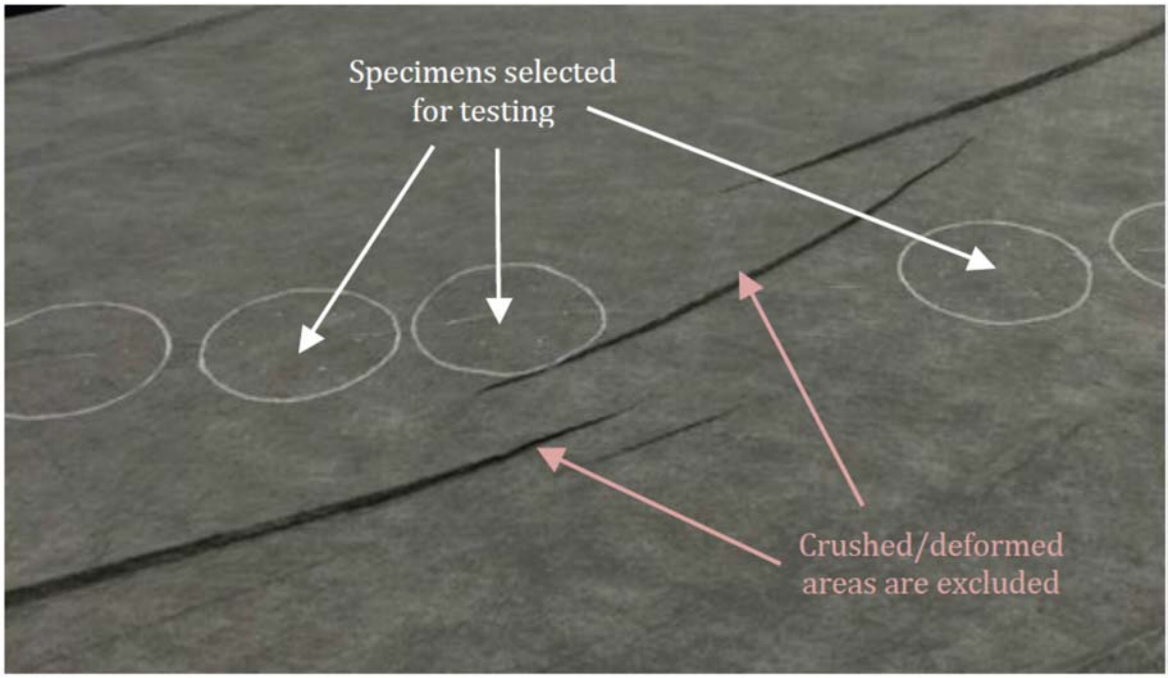


Figure 3.4 Sample selections near a deformed area.

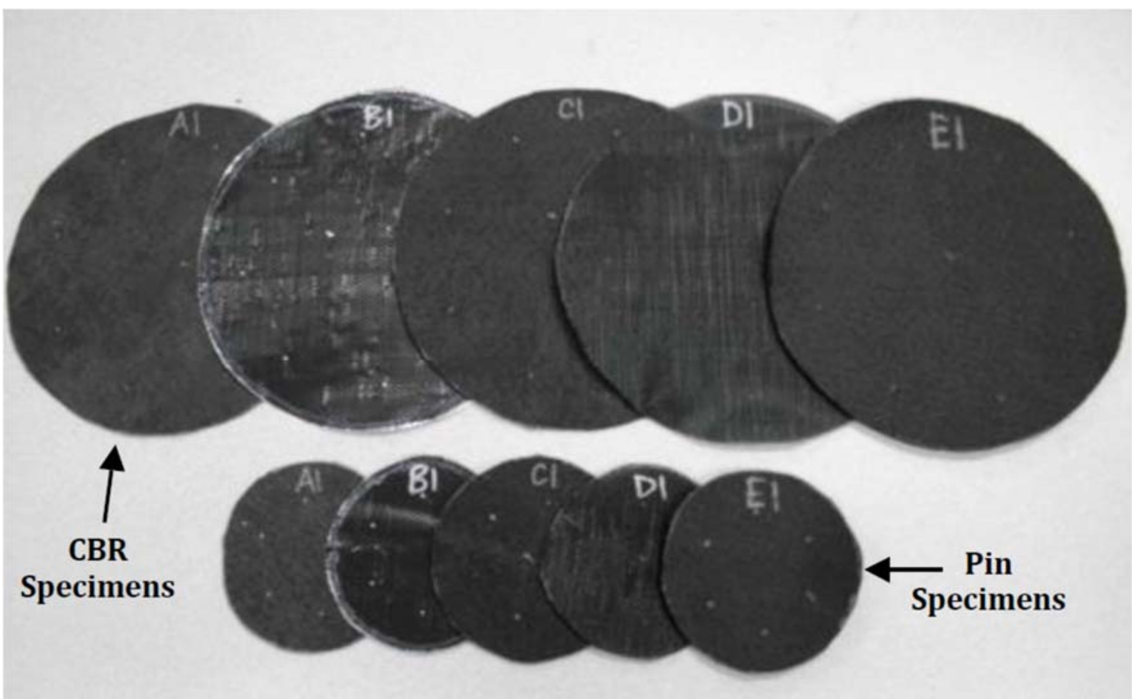


Figure 3.5 Woven and nonwoven geotextile specimens prepared for pin and CBR puncture strength tests.

Clamping Fixtures

As stated above, the testing fixtures met all ASTM requirements. The fixtures are shown in Figure 3.6 and dimensions were given previously in Table 2.3. Both ASTM D4833 and ASTM D6241 standards suggested either grooves with O-rings or coarse sandpaper bonded to opposing sides as a means to prevent slippage. For this study, sandpaper was selected and adhered to the inside surfaces of the clamps as shown in Figure 3.7.

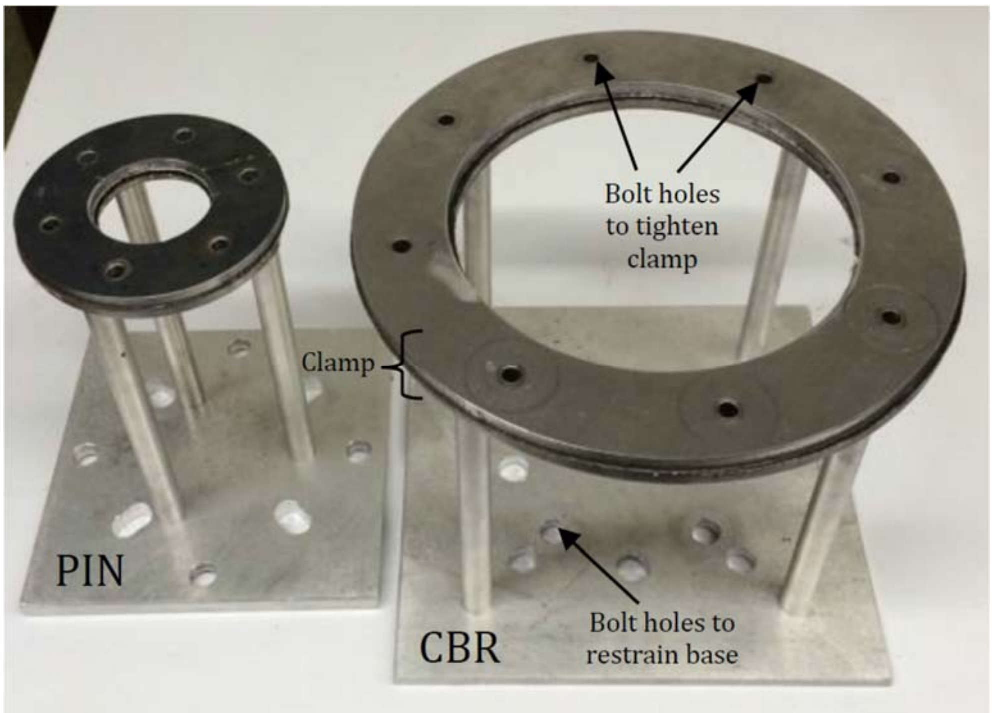


Figure 3.6 Clamping fixtures used for puncture testing at the UW-Milwaukee Mechanics and Composites Lab.

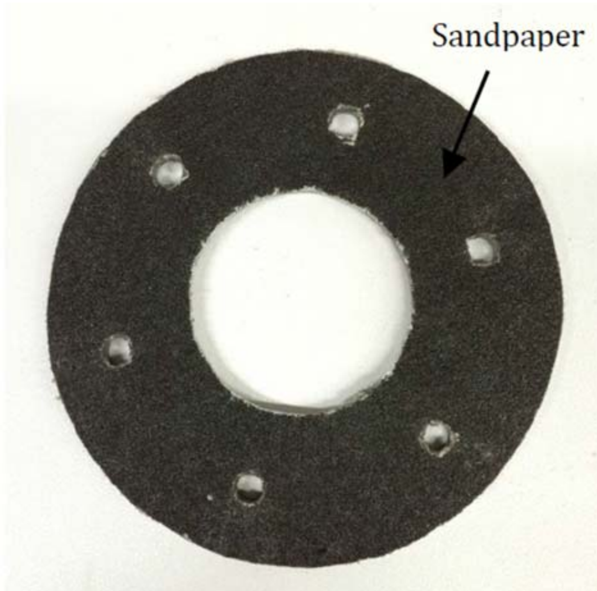


Figure 3.7 Sandpaper used to prevent geotextile slippage (shown on ASTM D4833 (pin) clamp).

Testing Procedure

Each geotextile sample was affixed to the corresponding ASTM test fixture. The sample was then marked along the inside circumference of the clamp. This marking was used to determine if slippage had exceeded the maximum allowed per ASTM requirements. Using the universal testing machine located in the UW-Milwaukee Engineering Mechanics and Composites Research Lab as shown in Figure 3.8, the puncture rod was lowered at a constant rate of extension (CRE) until it completely ruptured the test sample. The time, load, and displacement were recorded for all samples using R-Controller Version 2.00.09. Geotextile materials sometimes display a double peak in the load-displacement graph. Per ASTM standards, the initial puncture strength value was reported even if the second peak was higher. *All* data recorded, including loading after the maximum puncture resistance value had been reached, will be reported in Chapter 4 and the appendix.

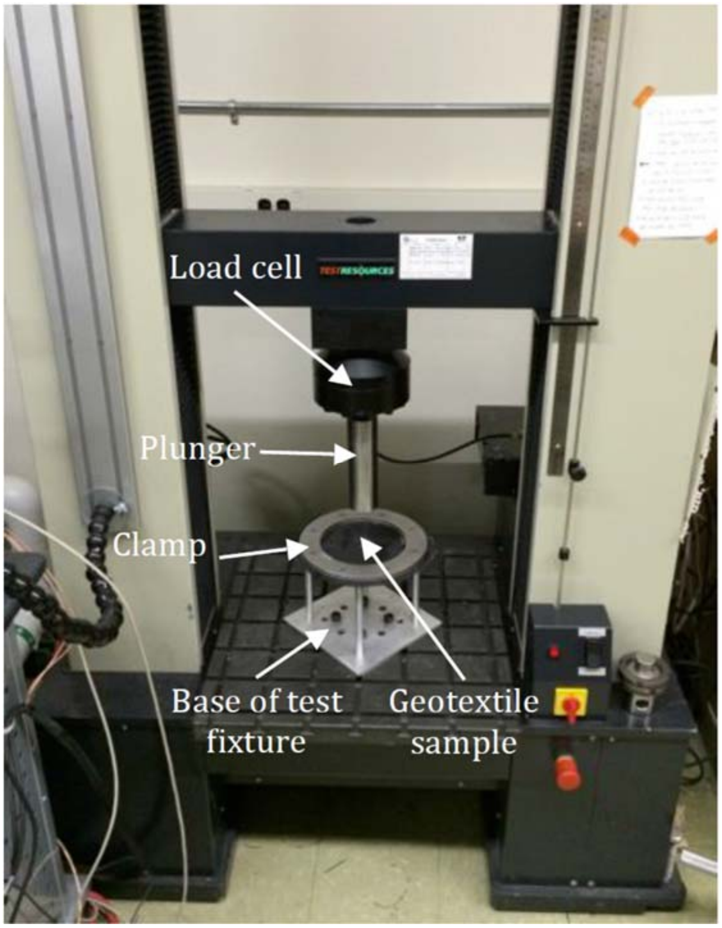


Figure 3.8 Testing Machine at the UW-Milwaukee Engineering Mechanics and Composites Research Lab.

3.3 UV and Environmental Exposure Testing (Phase III)

Subsets of the specimens provided by WisDOT are evaluated for effects on puncture strength from exposure to UV and environmental effects. The reason for this study is that the fabrics maybe sitting exposed on the work site before actually being put to use. Few state agencies provide guidance for UV testing. For example, State of Washington requires 50% stability strength using ASTM D4355 after exposure to certain hours. In this study we expose the specimens in a specially designed chamber under UV light (UVA340B with typical radiation of 0.89 $W/m^2/nm$) and temperature of 140°F. Thus assuming 12 hours/per day (assuming 2 weeks in the field) this will amount to a total exposure 168 hours interrupted with exposures of water spray every 24 hours. After the exposure, the specimens are tested for puncture resistance. The relationship between irradiance and wavelength for sunlight is closest to the UVA340B lamps used. The UVA 340B lamps are the best available simulation of sunlight in the critical short-wave UV region (Q-Labs Corporation, Westlake, Ohio). The sunlight in the critical short wavelength region from 365 nm down to the solar cutoff of 295 nm. The lamps peak emission is at 340 nm and correlates with intensity to noon summer sunlight levels. These lamps are typically recommended for correlation with outdoor results for most plastics, textiles, coatings, pigments and UV stabilizers and are thus suited for this application. Five specimens from each group were tested to provide a representative value for the puncture strength after exposure to environmental factors. A geotextile UV testing chamber was built according to ASTM specifications at UWM to perform conditioning for test specimens as shown in Figure 3.9. Geotextile specimens were subjected to UV light conditi0oning as described earlier then subjected to CBR puncture strength test. Figure 3.10 depicts geotextile specimens being subjected to UV light as conditioning for pre-puncture strength.

Figure 3.9 Photograph showing geotextile testing chamber and PID Controller for UV and heat controls.

Figure 3.10 Geotextile specimens in UV chamber at UW-Milwaukee with UV340B lamps and pair of 500W ceramic heaters.

Freeze-Thaw Conditioning

In order to investigate the effect of climate conditions on puncture strength of geotextiles, specimens were subjected to various cycles of freeze-thaw conditioning. Nine samples of material E were cut at the larger diameter (for testing using ASTM D6241). Three samples each were subjected to 15, 30, and 45 freeze-thaw conditioning cycles at the UW-Milwaukee Structural Lab. The freeze-thaw conditioning was accomplished by fully submerging the samples in water within an insulated drawer (Figure 3.11) and running them through the designated number of cycles. A cycle is considered cooling the samples from room temperature to 15°F (-9.4°C) and up to 45°F (7.2°C). The cycles continue between 15°F (-9.4°C) and 45°F (7.2°C) until completed. ASTM specified that all samples must be brought to “moisture equilibrium in the atmosphere for testing” using mass determination as a measure. Because all samples, excluding those subjected to freeze-thaw cycles, were subjected to the same conditions and stored in the same room for several days, weights were not taken. Samples subjected to freezing, however, were weighed until successive weights, made at 2-hour increments, differed by less than 0.1%, per ASTM requirements. The weight values for all conditioned samples were made at least 24 hours after conditioning had completed. The results are summarized in Table 3.3. Approximately three hours had passed between their final two weight measurements.

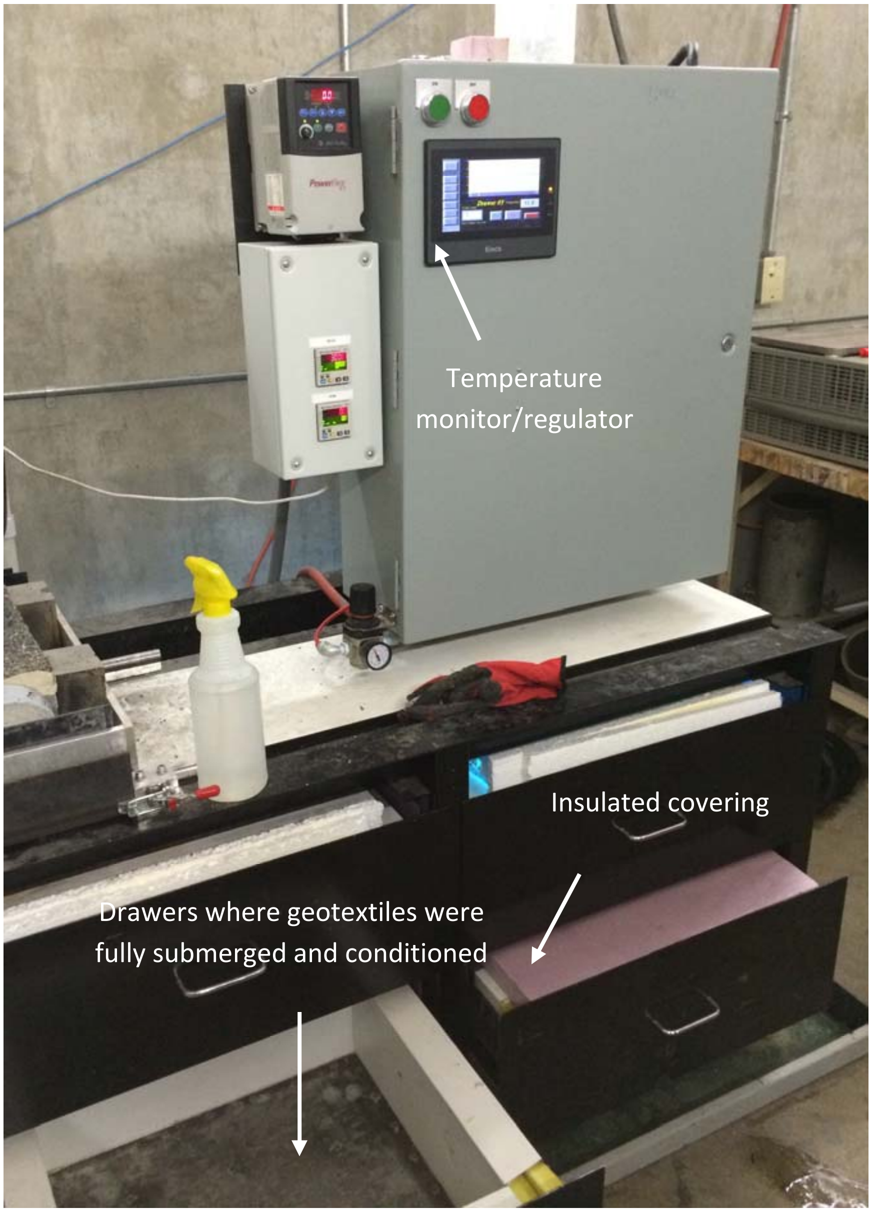


Figure 3.11 Freeze-Thaw Conditioning Machine at the UW-Milwaukee Structural Lab

Table 3.3 Final Conditioned Sample Weights

Freeze-Thaw Conditioned Sample Number	Initial Weight (g)	Final Weight (g)	Change (g)	ASTM D6241 Allowable Change (g)
1	20.95	20.95	0.00	±0.02
2	18.40	18.40	0.00	±0.01
3	20.33	20.34	0.01	±0.02
4	21.54	21.54	0.00	±0.02
5	21.59	21.59	0.00	±0.02
6	21.65	21.65	0.00	±0.02
7	22.61	22.62	0.01	±0.02
8	21.13	21.13	0.00	±0.02
9	21.23	21.24	0.01	±0.02

Chapter 4

Test Results and Analyses

This chapter presents geotextile test results and accompanying detailed analyses conducted. In addition, quantification and evaluation of the various investigated geotextiles are presented based on their puncture resistance. Moreover, statistical analysis was conducted to correlate investigated geotextile CBR and pin puncture strengths.

4.1 Phase – I Testing Rogram

The results of pin and CBR puncture strength tests on geotextile samples are summarized in Table 4.1. A selection of puncture strength load-displacement curves will serve as representative examples for reference in Chapter 4.

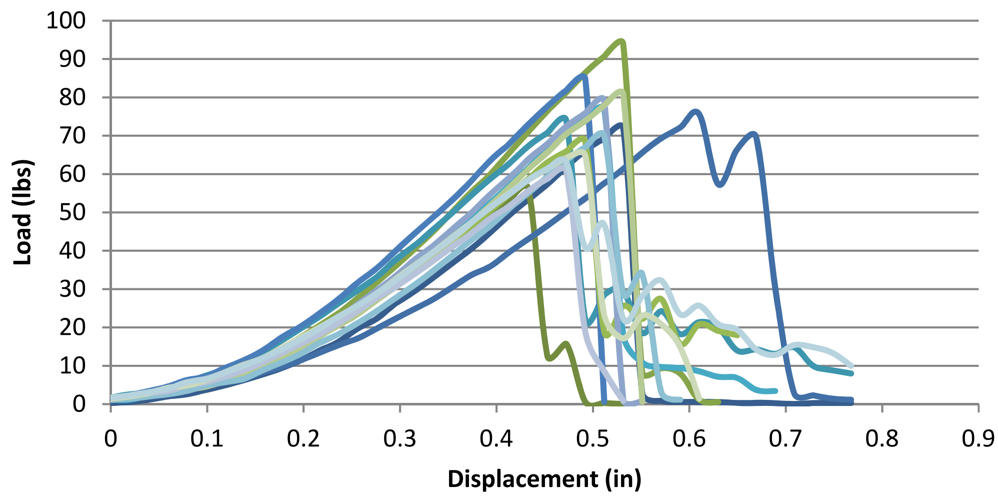
Table 4.1 Summary of pin and CBR puncture strength tests for Phase I

Geotextile Material Type	ASTM Test	Number of Test Samples	Average Puncture Load, lbs (N)	Standard Deviation in Puncture Load, lbs (N)	Coefficient of Variation in Puncture Load (%)	Average Elongation, in (mm)
A (nonwoven)	D4833	15	73 (324)	10 (43)	13.3	0.50 (12.7)
	D6241	10	362 (1611)	41 (184)	11.4	1.89 (48.0)
B (woven)	D4833	15	100 (443)	7 (29)	6.6	0.35 (8.9)
	D6241	10	733 (3261)	20 (92)	2.8	1.40 (35.6)
C (nonwoven)	D4833	15	115 (510)	21 (93)	18.3	0.46 (11.7)
	D6241	15	595 (2648)	57 (255)	9.6	1.88 (47.8)
D (woven)	D4833	10	178 (790)	18 (81)	10.3	0.46 (11.7)
	D6241	15	1392 (6190)	151 (673)	10.9	1.44 (36.6)
E (nonwoven)	D4833	10	240 (1069)	16 (73)	6.8	0.59 (15.0)
	D6241	15	1268 (5642)	101 (451)	8.0	2.47 (62.7)

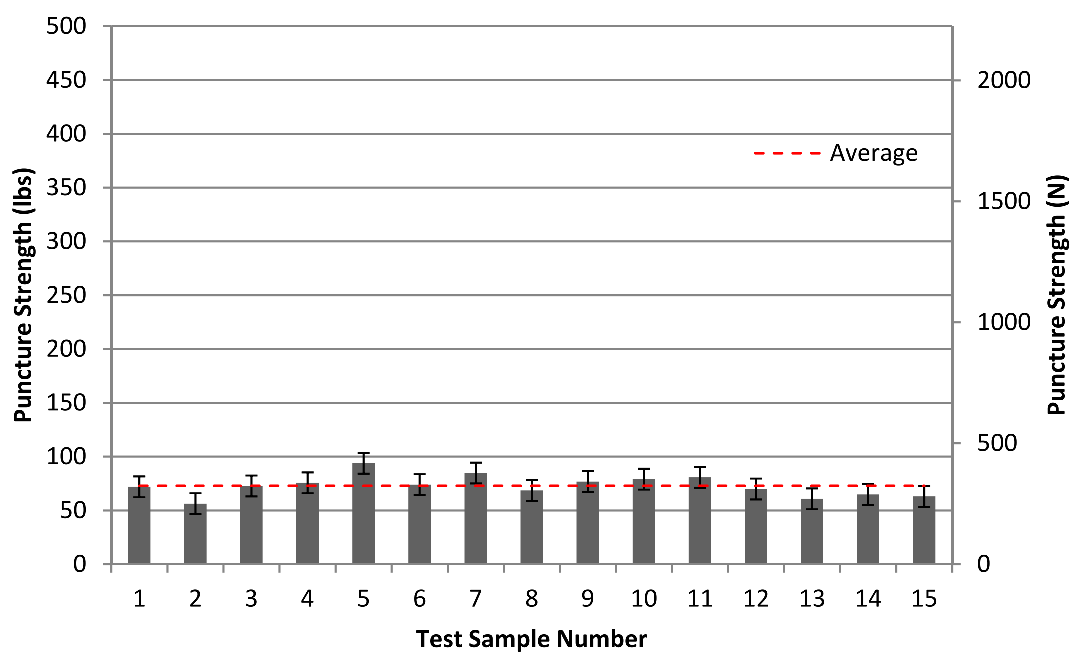
4.1.1 Behavior of Nonwoven Geotextiles under CBR Puncture Failure Load

Figure 4.1 depicts the puncture strength of 15 individual material A geotextile samples tested using the pin puncture test. The puncture load versus displacement is shown in Figure 4.1a. Inspection of Figure 4.1a demonstrates that all geotextile samples tested exhibited consistent behavior. Figure 4.1b depicts the bar chart of pin puncture strengths for all geotextile material A samples. The pin puncture load at failure varied from 56 lbs (250 N) to 94 lbs (418 N) with an average of 73 lbs (324 N) and coefficient of variation of 13.3%.

Figure 4.2a depicts the puncture load versus displacement for material A samples using the CBR puncture test. Figure 4.2b shows the bar chart of CBR puncture strengths for all geotextile material A samples. The CBR puncture load at failure varied from 324 lbs (1,441 N) to 457 lbs (2,033 N) with an average of 362 lbs (1,611) and coefficient of variation of 11.4%.

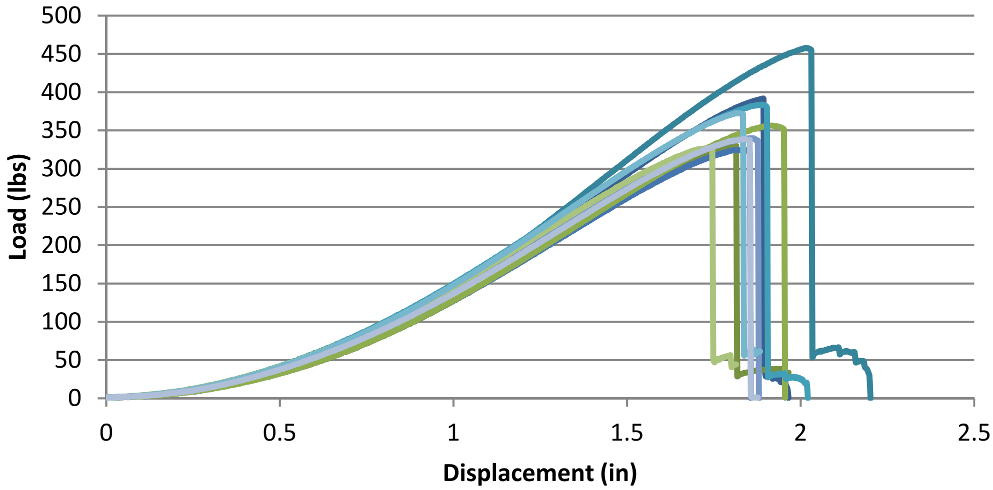


(a) Load-displacement curve

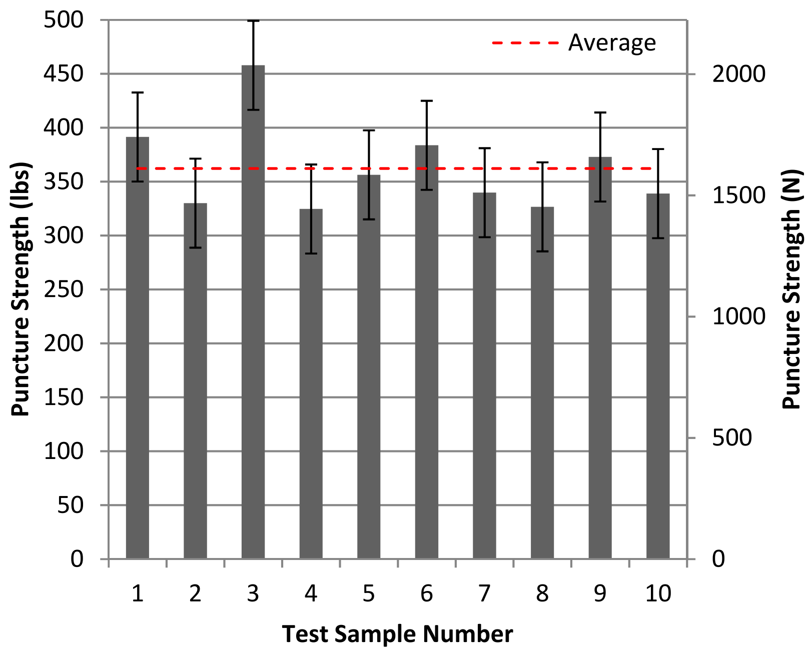


(b) Bar chart (error bars indicate standard deviations)

Figure 4.1 Pin puncture strengths for geotextile material A samples



(a) Load-displacement curve



(b) Bar chart (error bars indicate standard deviations)

Figure 4.2 CBR puncture strengths for geotextile material A samples

A representative CBR puncture strength failure curve of material A, one of the nonwoven materials tested, is shown in Figure 4.3. The curve consists of four phases: fiber rearrangement, load resistance, maximum resistance, and puncture failure. The curve begins with a slight slope as the plunger makes contact with the sample. Because the fibers still contain voids, they are free to rearrange without resisting the probe motion. As the fibers lose their ability to move relative to one another, they begin to develop internal material stresses as the fiber to fiber interaction increases. The load resistance increases due to the fiber-fiber interaction resulting in the region of increased slope. Eventually the material develops new voids as the fiber-fiber interaction fails. When the pressure on the material extends beyond the load that the fiber-fiber interaction can withstand, the material punctures.

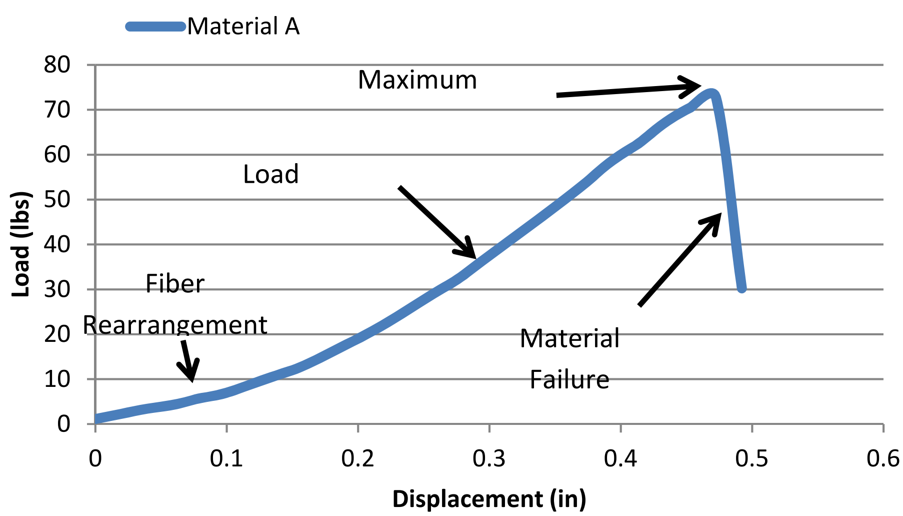
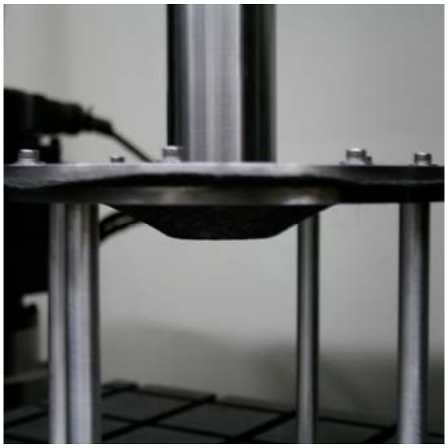


Figure 4.3 Nonwoven geotextile puncture strength failure curve demonstrated using a representative material A load vs. displacement curve

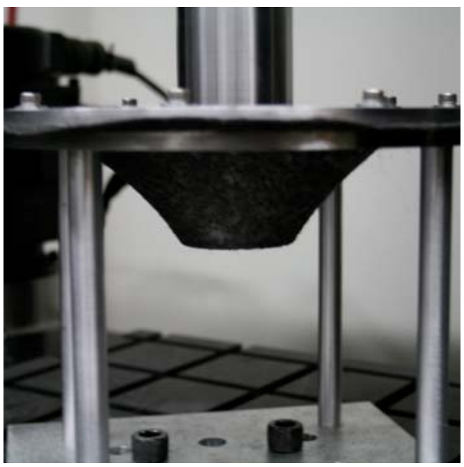
Images of the CBR puncture failure of a material A specimen is shown in Figure 4.4. Initially, the fibers rearrange while only developing a minimal load resistance (4.4a). The fibers then begin to resist the load (4.4b) using the fiber-fiber surface interaction. The fiber-fiber connection remains intact, but the relative distance between contact points increases as the probe is displaced. The fibers have not failed, but they are lengthened, resulting in large voids within the material as shown in the transition from (4.4c) to (4.4d). Eventually the fiber-fiber connections fail at puncture loading when they can no longer resist the probe (4.4e) and recoil along the length of the probe (4.4f) due to the sudden reduction in material internal stresses and release of potential energy. A load aural indication of rupture was observed as material failure was of several fibers at the same moment.

Koerner and Koerner (2010) demonstrated that geotextiles made from staple fibers or continuous filaments (with the same base material and mass per unit area) will have similar puncture resistances. This is likely true because the increase in load resistance is due to the fiber-fiber *interaction* in nonwoven materials. If two geotextiles have the same material content per unit area, the fibers contained within each will have a similar number of contact points regardless of fiber length. Elongation of the material may, however, be increased for an increased fiber length even if the puncture strength is not.

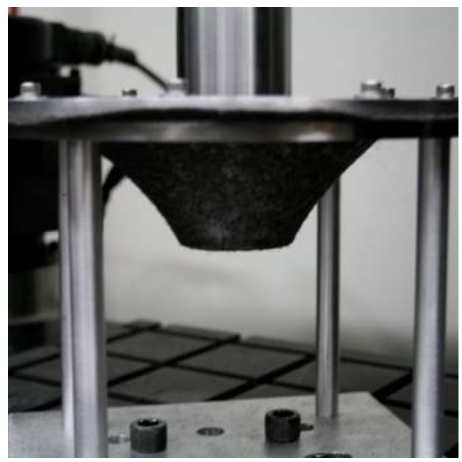


(a) Fiber rearrangement

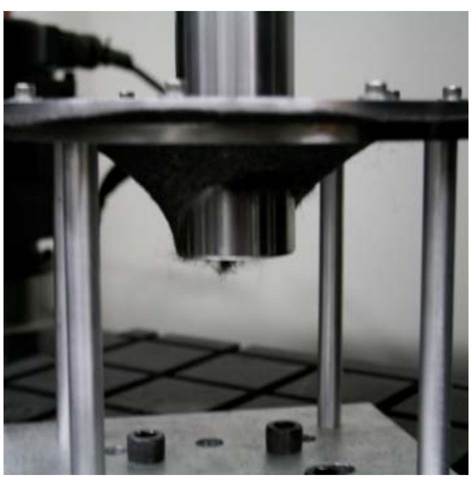
(b) Load resistance begins



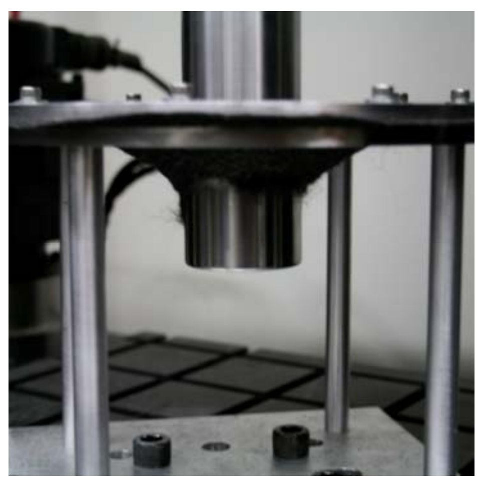
(c) Fiber extension



(d) Material voids become apparent



(e) Puncture

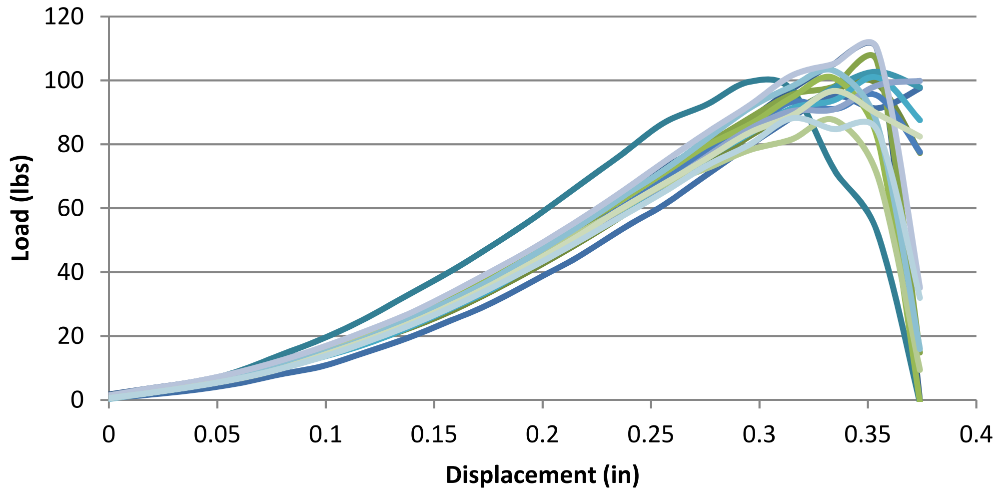


(f) Recoil

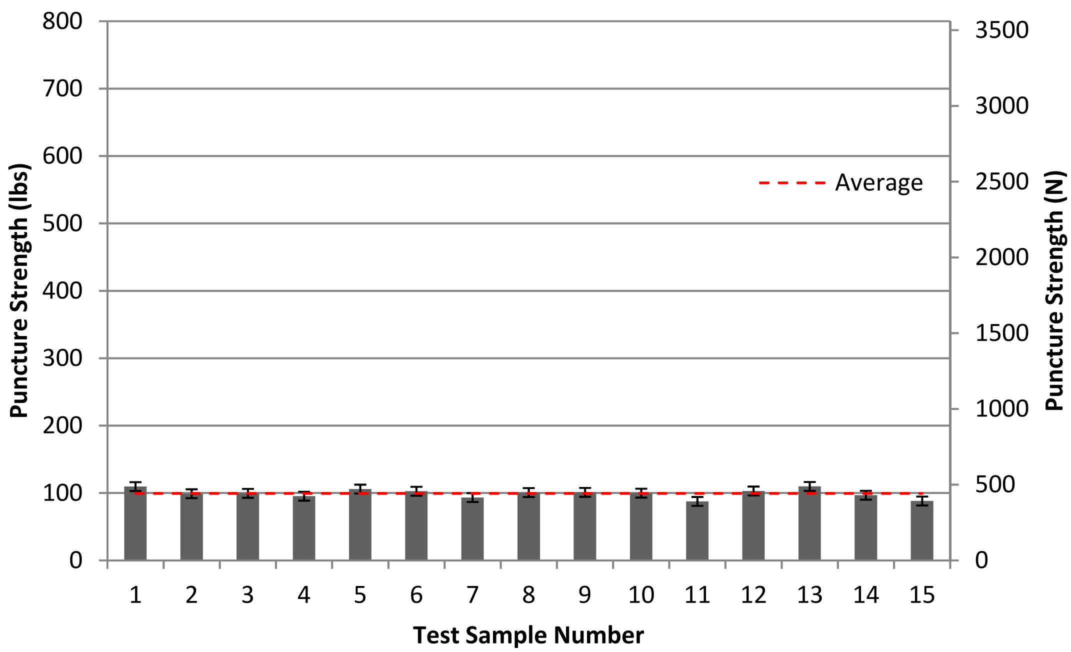
Figure 4.4 Failure stages of nonwoven geotextile (material A is pictured subjected to the CBR puncture strength test)

4.1.2 Behavior of Woven Geotextiles under CBR Puncture Failure Load

Figure 4.5 depicts the puncture strength of 15 individual material B geotextile samples tested using the pin puncture test. The puncture load versus displacement is shown in Figure 4.5a. Inspection of Figure 4.5a demonstrates that all geotextile samples tested exhibited consistent behavior. Figure 4.5b depicts the bar chart of pin puncture strengths for all geotextile material B samples. The pin puncture load at failure varied from 88 lbs (391 N) to 110 lbs (489 N) with an average of 99 lbs (440 N) and coefficient of variation equal to 6.6%. Figure 4.6a depicts the puncture load versus displacement for material B samples using the CBR puncture test. Figure 4.6b shows the bar chart of CBR puncture strengths for all geotextile material B samples. The CBR puncture load at failure varied from 693 lbs (3,083 N) to 762 lbs (3,390 N) with an average of 733 lbs (3,261) and coefficient of variation equal to 2.8%.

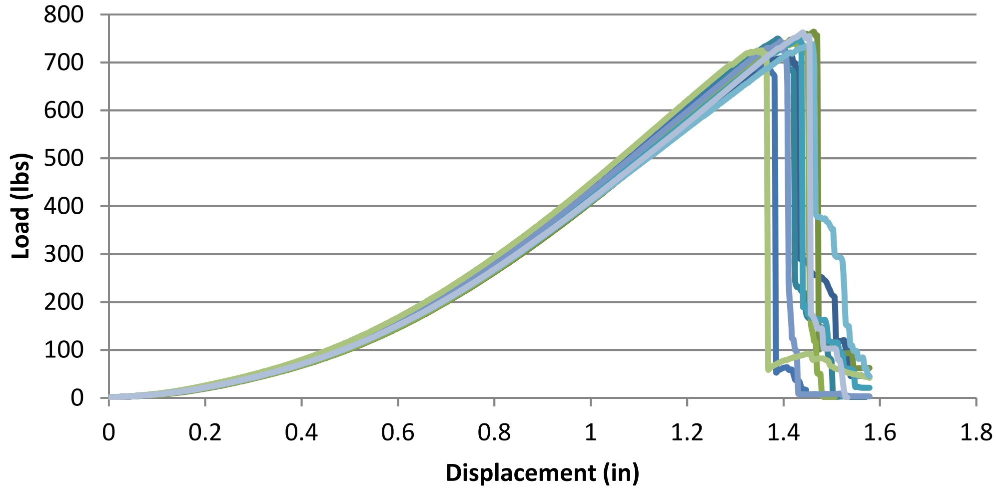


(a) Load-displacement curve

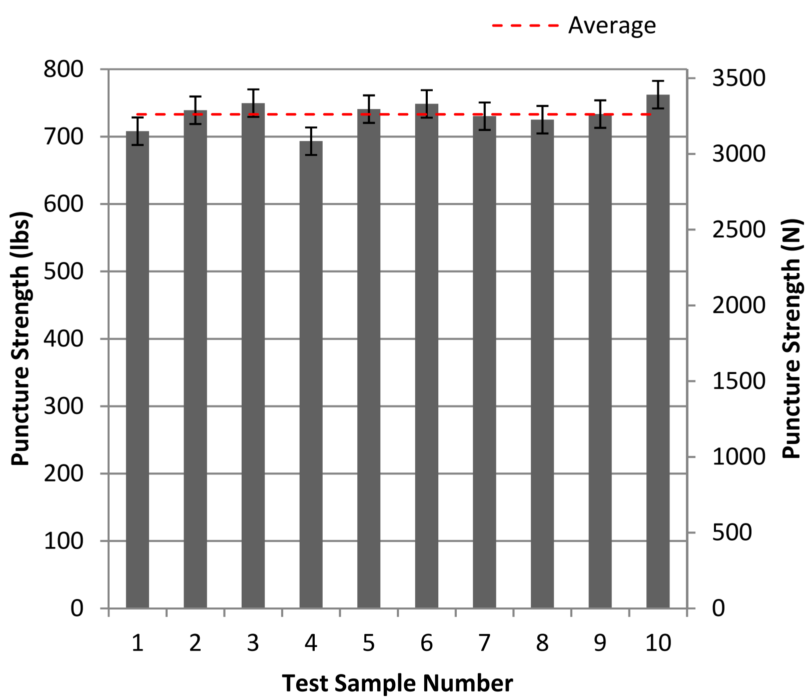


(b) Bar chart (error bars indicate standard deviations)

Figure 4.5 Pin puncture strengths for geotextile material B samples



(a) Load-displacement curve



(b) Bar chart

Figure 4.6 CBR puncture strengths for geotextile material B samples

A representative puncture strength failure curve of material B, one of the woven materials tested, is shown in Figure 4.7. The curve consists of six phases: fiber rearrangement, load resistance, monofilament failure (puncture resistance), secondary fiber rearrangement, and multifilament failure. Like nonwoven materials, the curve begins with a slight slope as the plunger makes contact with the sample. Because the geotextile weave still contains voids, the fibers are free to rearrange without resisting the probe motion. As the fibers lose their ability to move relative to one another, they begin to develop internal material stresses as the fiber-fiber interaction increases and respective filaments also develop tensile strains. Eventually the tensile strain increases until the displacement where *mono*filaments begin to rupture. Unlike nonwoven geotextiles, woven geotextiles may reach a secondary peak resistance greater than the puncture strength when the *multi*filaments fail. The dip between successive peak resistances occurs because the material fibers are again able to rearrange and fill newly formed voids within the geotextile weave. Additional peaks may be observed if extension of the probe is allowed to continue.

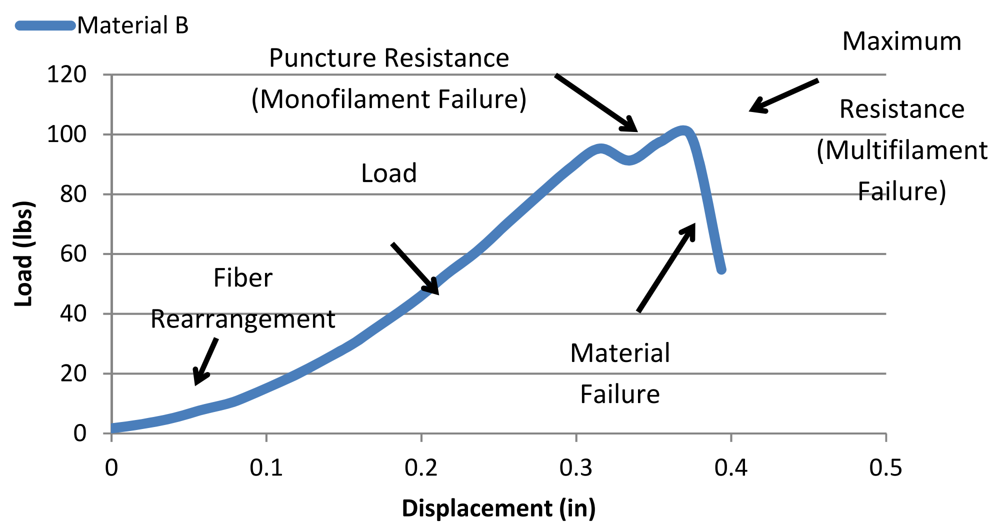
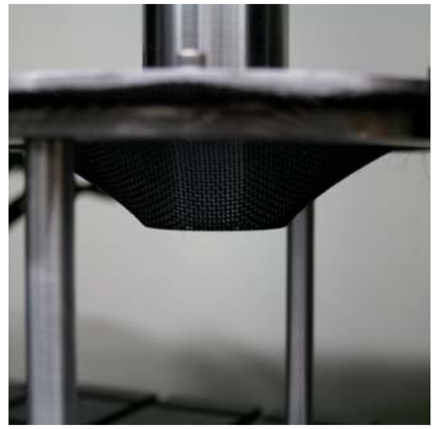


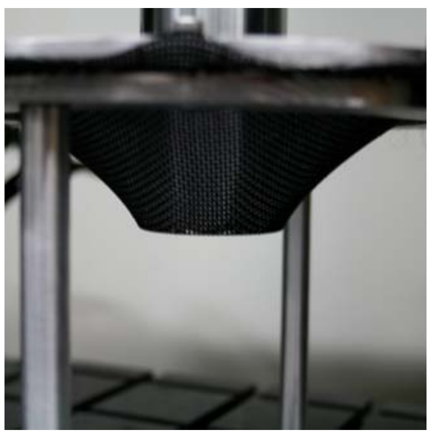
Figure 4.7 Woven geotextile puncture strength failure curve demonstrated using a representative material B load vs. displacement curve

The failure of a woven geotextile, material D, is shown in Figure 4.8. Initially, the fibers rearrange while only developing a minimal load resistance (4.8a). The fibers then begin to resist the load (4.8b) using the fiber-fiber interaction and tension within fibers develops. The fibers elongate (4.8c) until tension in the shorter monofilaments causes them to rupture (4.8d). The monofilament failures are characterized by quiet cracking noises. Because some of the monofilaments have failed, new voids are formed and the remaining monofilaments are free to rearrange within their multifilament groups (4.8e). Eventually, the longer monofilaments will develop resistance to the load resulting in the additional peak load until the overall multifilament has failed (4.8f). This is indicated by a long series of failure cracking sounds. The remaining geotextile materials pin and CBR load vs. displacement curves and bar charts are presented in Figures 4.9 through 4.14.

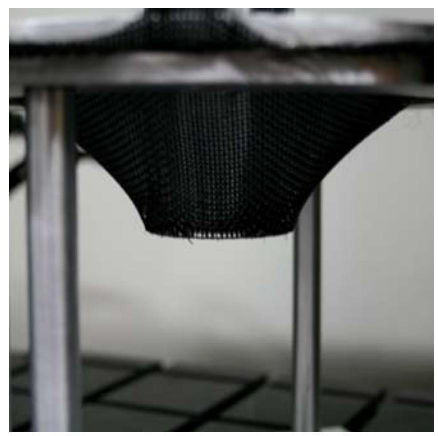
(a) Fiber rearrangement



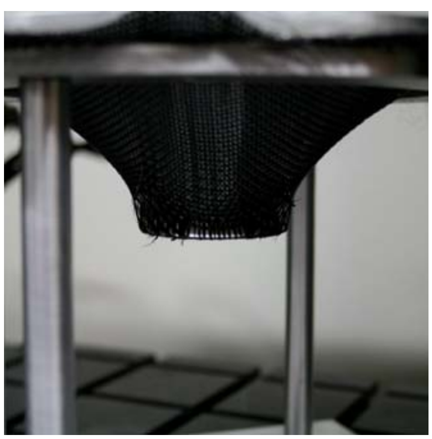
(b) Load resistance begins



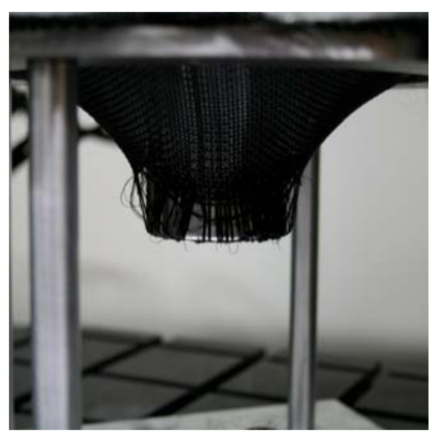
(c) Fiber elongation



(d) Monofilament failure

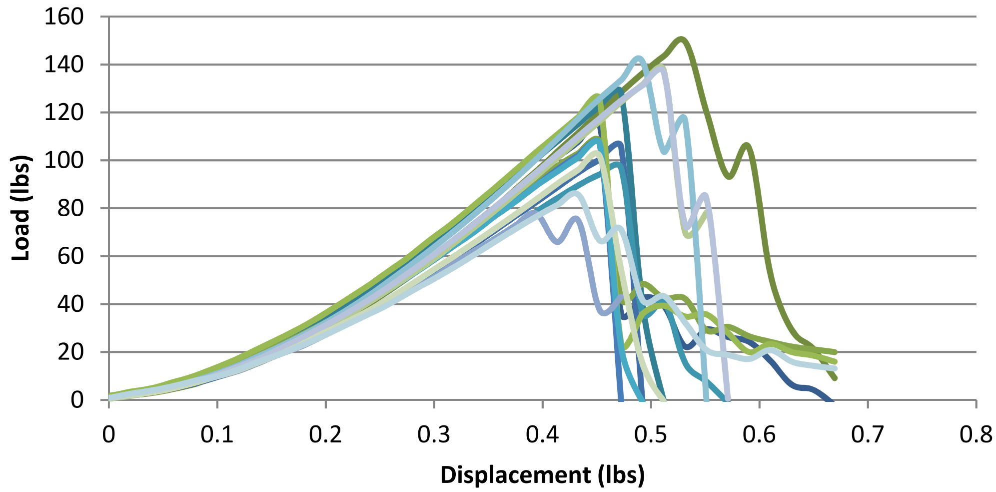


(e) Fiber rearrangement and continued multifilament load resistance

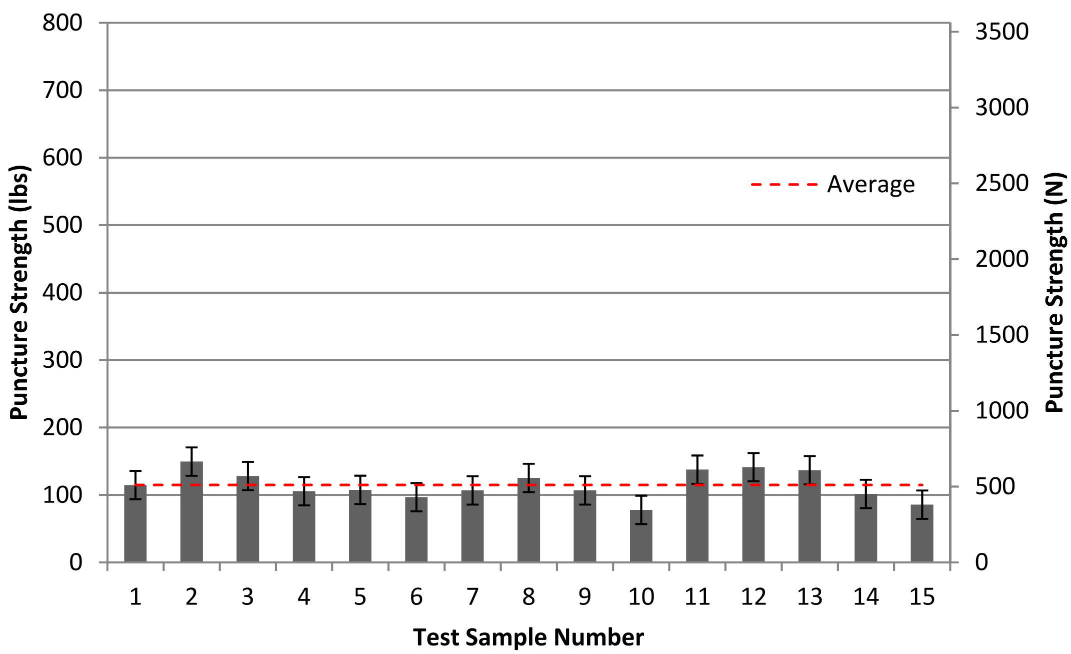


(f) Multifilament failure

Figure 4.8 Failure stages of woven geotextile (material D is pictured subjected to the CBR puncture strength test)

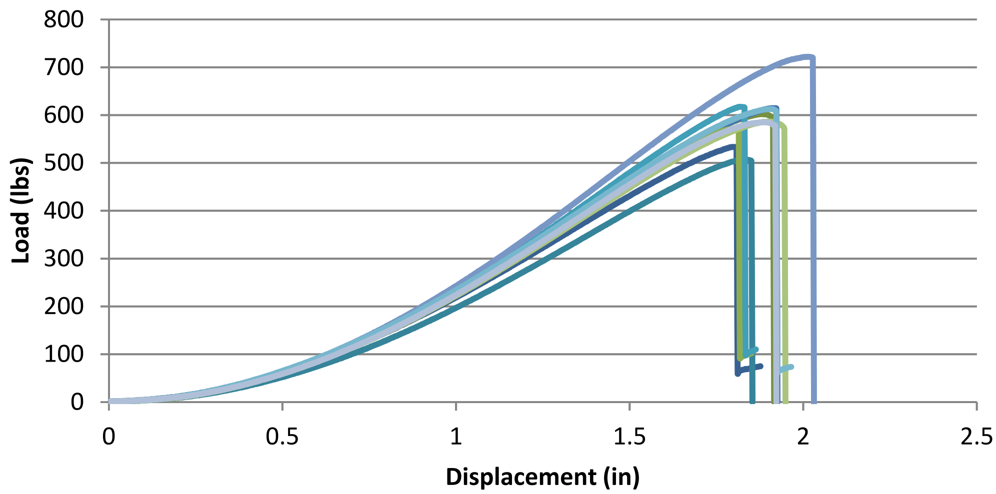


(a) Load-displacement curve

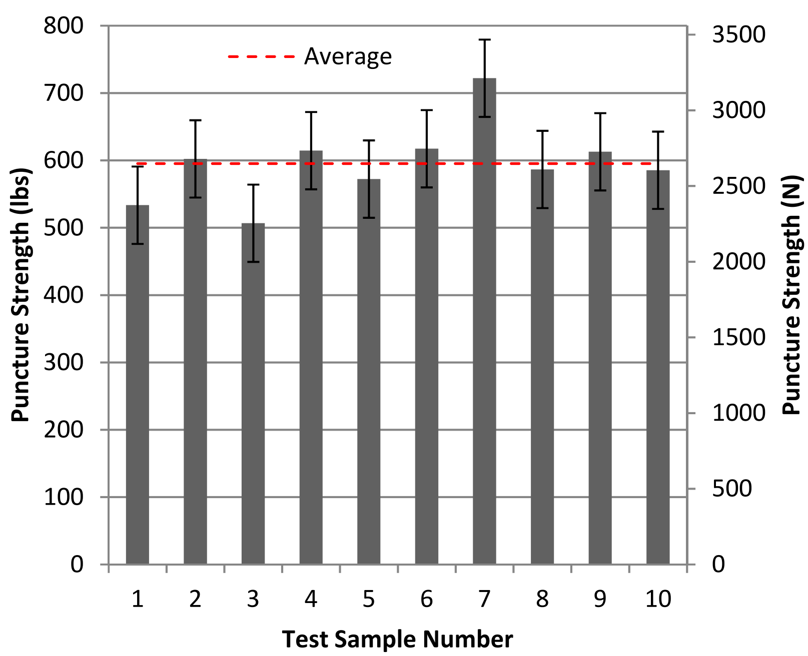


(b) Bar chart (error bars indicate standard deviations)

Figure 4.9 Pin puncture strengths for geotextile material C samples

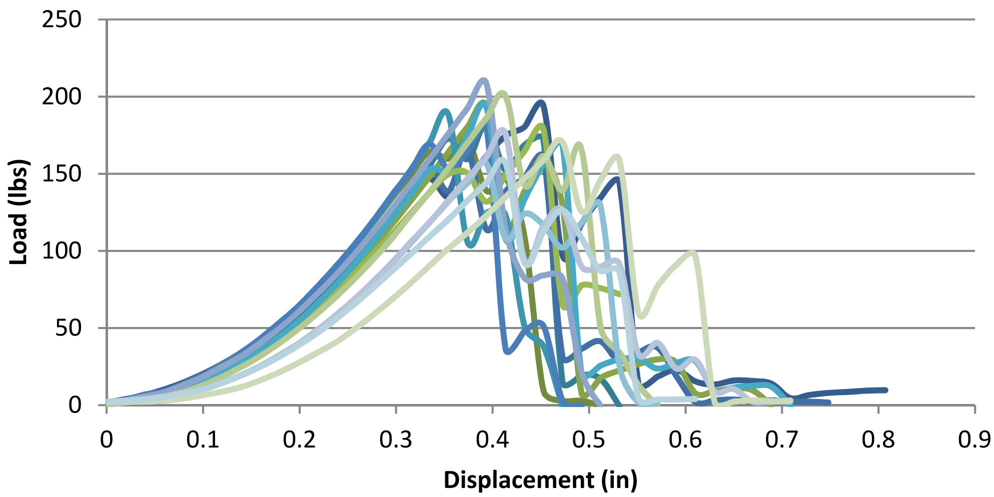


(a) Load-displacement curve

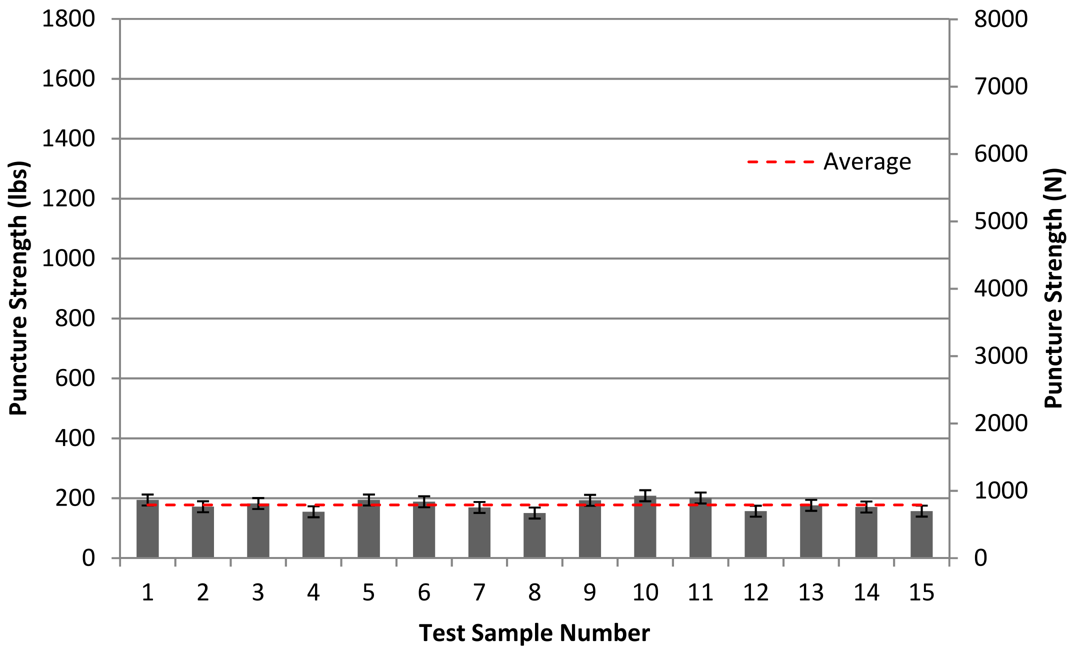


(b) Bar chart (error bars indicate standard deviations)

Figure 4.10 CBR puncture strengths for geotextile material C samples

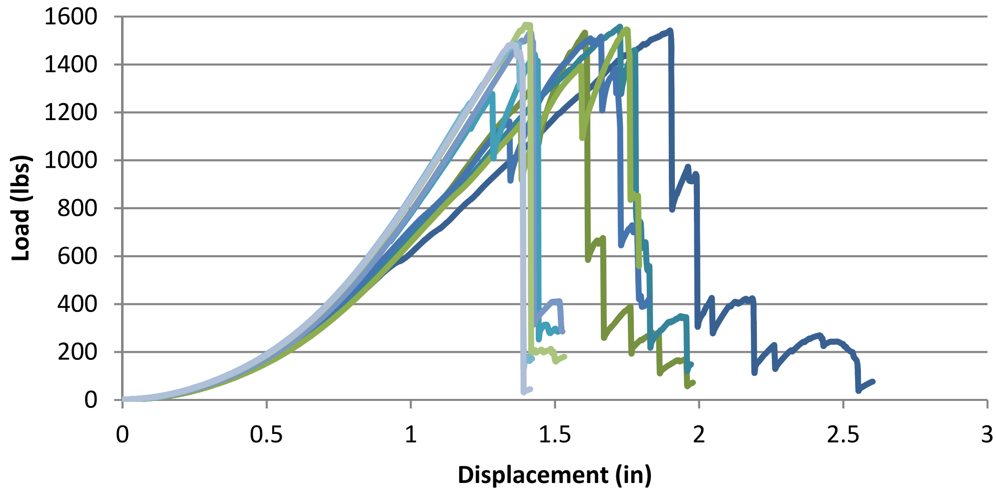


(a) Load-displacement curve

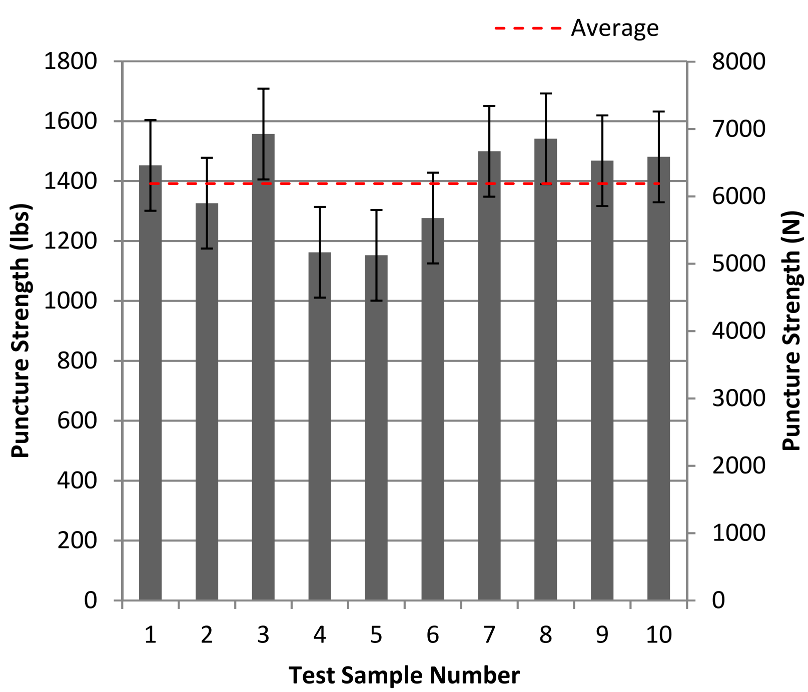


(b) Bar chart (error bars indicate standard deviations)

Figure 4.11 Pin puncture strengths for geotextile material D samples

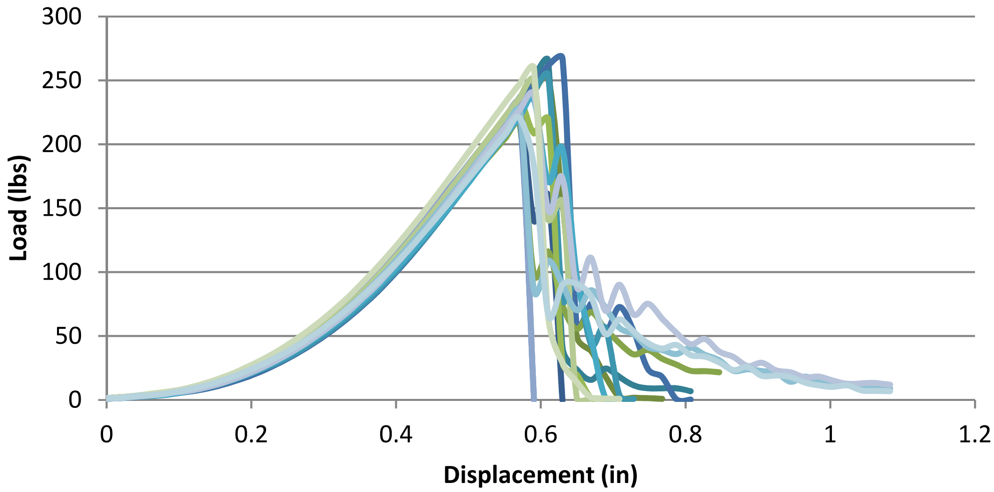


(a) Load-displacement curve

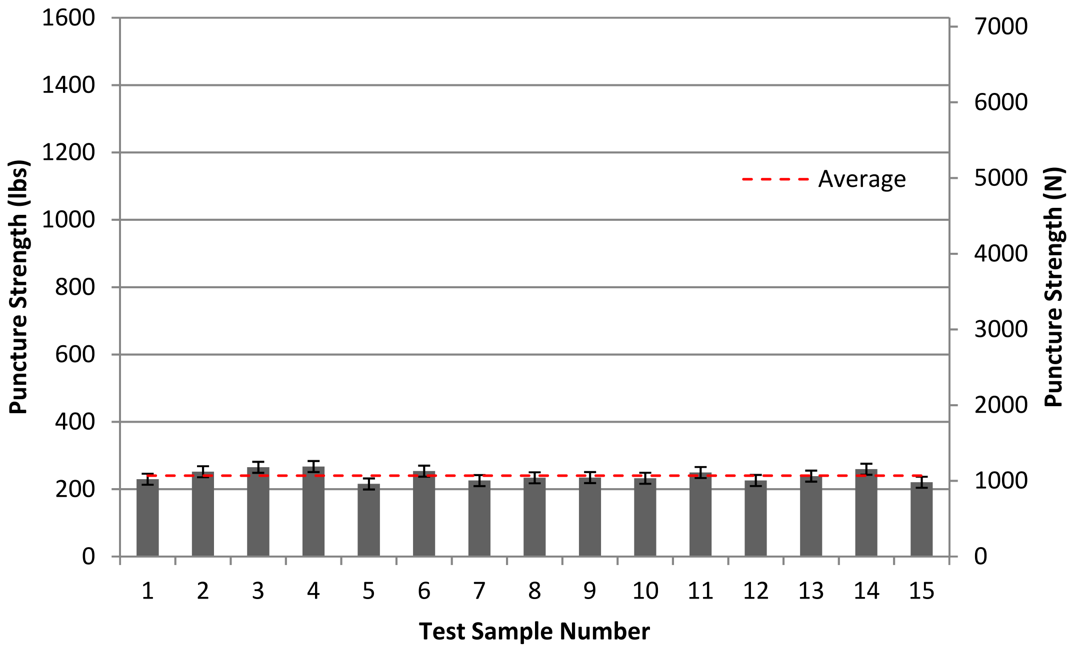


(b) Bar chart (error bars indicate standard deviations)

Figure 4.12 CBR puncture strengths for geotextile material D samples

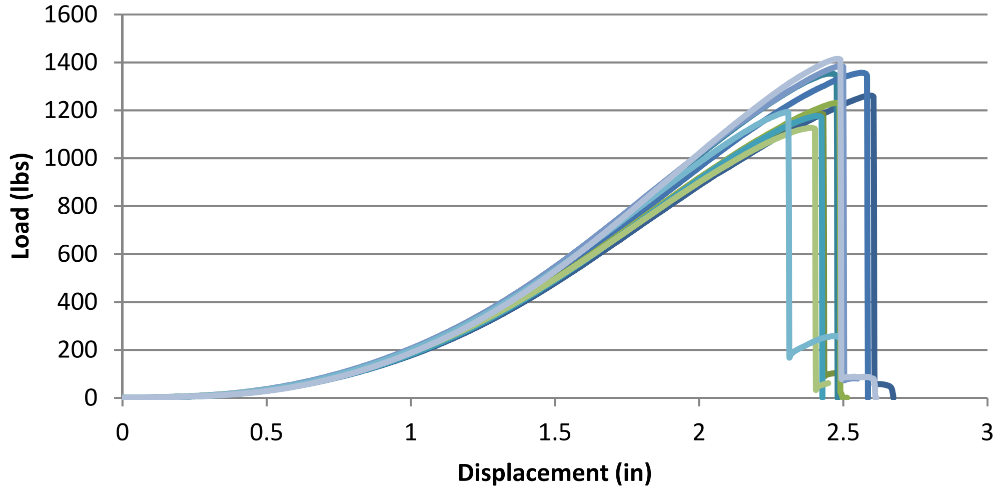


(a) Load-displacement curve

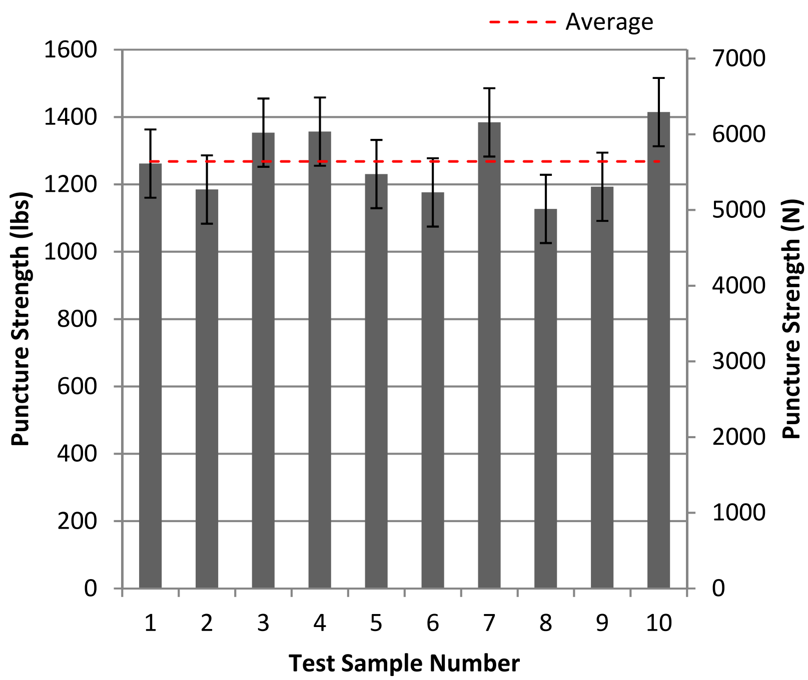


(b) Bar chart (error bars indicate standard deviations)

Figure 4.13 Pin puncture strengths for geotextile material E samples



(a) Load-displacement curve



(b) Bar chart (error bars indicate standard deviations)

Figure 4.14 CBR puncture strength for geotextile material E samples

The results of all pin and CBR puncture strength tested geotextile samples are plotted in Figure 4.15 to compare the two test puncture strength values. It is important to note that geotextile samples tested using ASTM D6241 showed a lower coefficient of variation compared with ASTM D4833 for materials A, B, and C but a higher coefficient of variation for D and E. Thus, one test is not preferred over the other on the basis of testing variability.

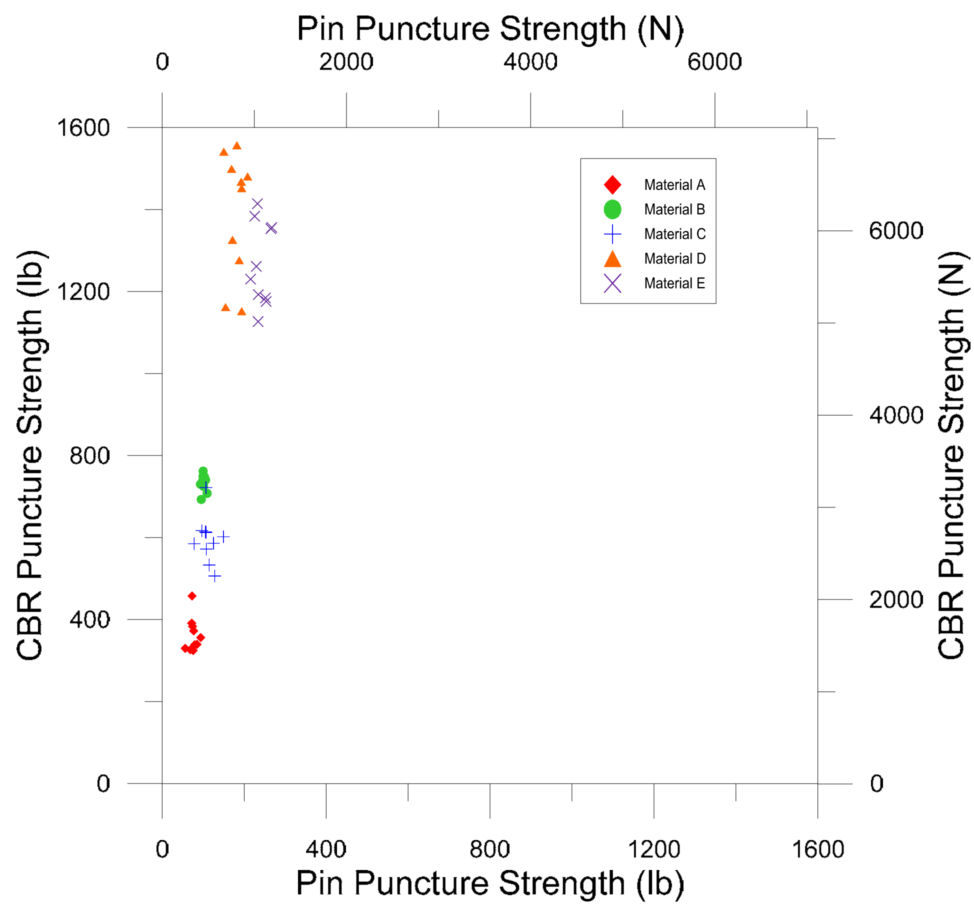


Figure 4.15 Pin and CBR puncture strength for all materials tested plotted with their average value

4.1.3 CBR Puncture Testing Failure Characteristics

A summary of CBR puncture failure characteristics in woven and nonwoven PP geotextiles is presented in Table 4.2. Further discussion of elongation and effects of weave type on puncture resistance are discussed in section 4.3.1 of this report.

Table 4.2 Puncture strength failure comparison of nonwoven and woven PP geotextiles

Puncture Strength Failure Characteristic	Nonwoven	Woven
Initial Load Failure Cause	Fiber-fiber contact points	Monofilament rupture
Secondary Load Failure Cause	None	Additional monofilament rupture or multifilament rupture
Elongation at failure	Greater than woven	Less than nonwoven
Aural indicator	Single “pop”	Series of “cracking”

4.2 Correlation of CBR and Pin Puncture Strength

A means to determine the CBR puncture strength based on a known pin puncture strength was developed. Askari et al. (2012) previously studied the effects of test speed on the puncture resistance of polyester needle punched nonwoven geotextiles using ASTM D6241. Although the material tested was polyester rather than polypropylene, results of their tests were used in the current study to develop the general relationship between test speed and puncture resistance. A ratio of increase in puncture strength due to an increase in speed was determined to be 1 to 4, or 0.25. Using this ratio, the ratios of probe and sample areas, and the compression rates shown in Table 4.3, Equation 1 was developed to correlate the CBR puncture strength based on preexisting pin values.

Table 4.3 Parameters used in developing CBR and pin puncture strength correlation

Measure	**D4833 (pin)**	**D6241 (CBR)**
Probe Diameter, mm (in)	8 (0.315)	50 (1.968)
Probe Area, mm^2 (in^2)	50.3 (0.078)	1963.5 (3.043)
Inner Sample Diameter, mm (in)	45 (1.772)	150 (5.906)
Inner Sample Area, mm^2 (in^2)	1590.4 (2.465)	17671.5 (27.390)
Probe Area / Sample Area	0.032	0.111

This equation is for the estimation of *nonwoven* material puncture strengths only.

$$Strength_{CBR,estimated} = 0.25 \times Strength_{pin,measured} \left(\frac{Area_{p,CBR}}{Area_{p,pin}} \right) \left(\frac{Area_{s,pin}}{Area_{s,CBR}} \right) \left(\frac{Rate_{pin}}{Rate_{CBR}} \right) \qquad (1)$$

where:

$Area_{p,CBR}$ = area of the CBR probe

$Area_{s,CBR}$ = area of the CBR inner clamp diameter/sample unsupported diameter

$Area_{s,pin}$ = area of the pin inner clamp diameter/sample unsupported diameter

$Area_{p,pin}$ = area of the pin probe

$Rate_{CBR}$ = constant rate of compression of CBR puncture testing

$Rate_{pin}$ = constant rate of compression of pin puncture testing

Substituting Table 4.3 values into Equation 1 and using constant rates of compression to be 300 mm/min and 50 mm/min for pin and CBR tests, respectively, the following equation to determine the estimated CBR puncture strength for nonwoven geotextiles is described by:

$$Strength_{CBR,estimated} = 5.270 \times Strength_{pin,measured} \qquad (2)$$

The results of this testing indicated that the change in compression rate has a different effect on puncture resistance for *woven* materials. This rate has a relationship of approximately 0.35. The adjusted equation to estimate CBR puncture resistance then becomes:

$$Strength_{CBR,estimated} = 0.35 \times Strength_{pin,measured}\left(\frac{Area_{p,CBR}}{Area_{p,pin}}\right)\left(\frac{Area_{s,pin}}{Area_{s,CBR}}\right)\left(\frac{Rate_{pin}}{Rate_{CBR}}\right) \quad (3)$$

Substituting the standard ASTM values into Equation 3, the following equation is developed, which can be used to estimate the CBR punctures strength for woven materials.

$$Strength_{CBR,estimated} = 7.378 \times Strength_{pin,measured} \quad (4)$$

Equation 2 and 4 were then used to estimate the CBR puncture strength from the pin puncture test results as depicted in Figure 4.16.

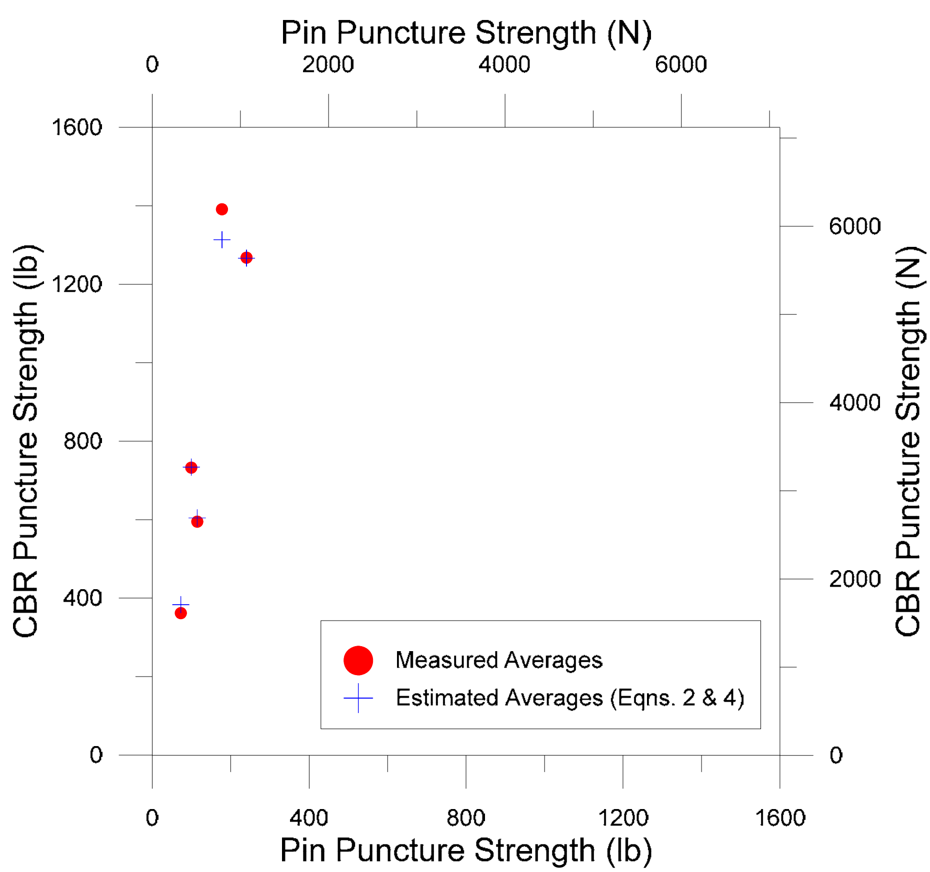


Figure 4.16 Estimated CBR puncture strength using separate equations to describe woven and nonwoven materials

In an attempt to find general formula for all samples, the empirical Equations 5 and 6 are proposed:

$$Strength_{CBR,estimated} = 0.30 \times Strength_{pin,measured} \left(\frac{Area_{p,CBR}}{Area_{p,pin}} \right) \left(\frac{Area_{s,pin}}{Area_{s,CBR}} \right) \left(\frac{Rate_{pin}}{Rate_{CBR}} \right) \qquad (5)$$

$$Strength_{CBR,estimated} = 6.324 \times Strength_{pin,measured} \qquad (6)$$

Equation 6 was then used to estimate the CBR puncture strength from the pin puncture test results as depicted in Figure 4.17. For comparison, Figure 4.18 shows the line obtained from Equation 6 as well as the line of best fit for the measured test results. The line of best fit equation for measured puncture strength averages is described by Equation 7 and has a coefficient of determination R^2=0.789. Equation 6 simplifies to Equation 8 for the samples tested and has an R^2=0.781. The statistical results show a reasonable correlation between the measured and estimated puncture strength values using pin and CBR tests based on the suggested Equation 6.

$$Strength_{CBR} = 50.17 + 5.82 \times Strength_{pin} \quad \text{(all values in lb)} \qquad (7)$$

$$Strength_{CBR} = 6.33 \times Strength_{pin} \quad \text{(all values in lb)} \qquad (8)$$

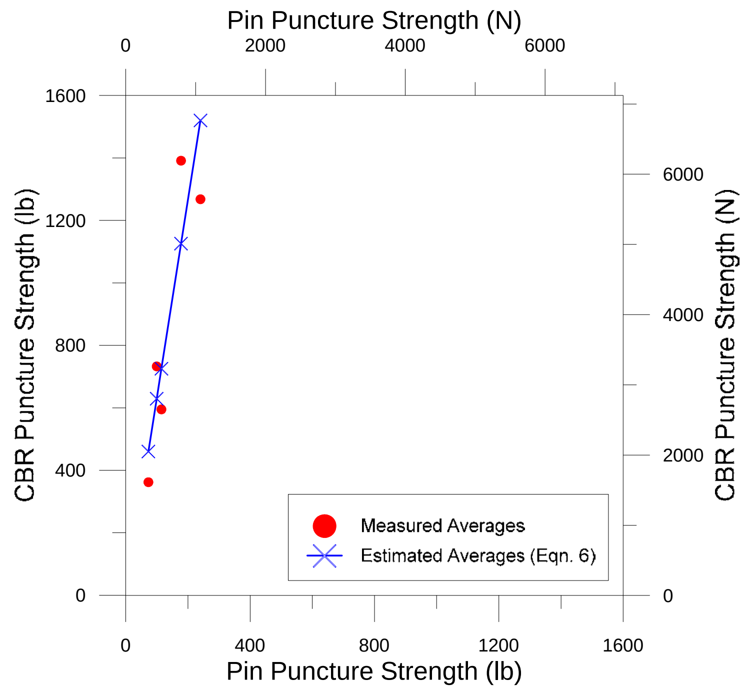


Figure 4.17 Estimated CBR puncture strength using Equation 6

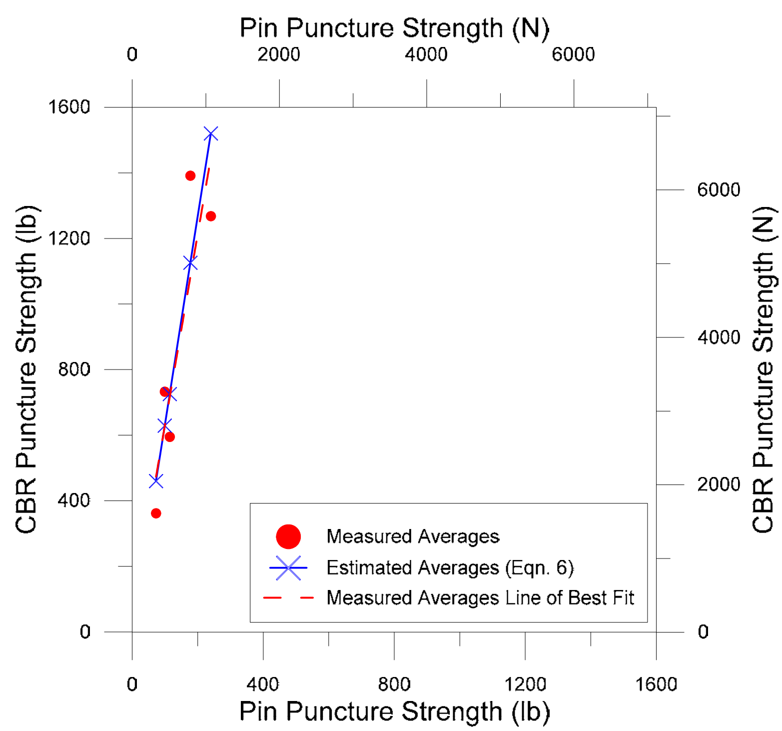


Figure 4.18 Comparison of the estimated CBR puncture strength using Equation 6 and the line of best fit for measured results

4.3 Mass per Unit Area used to Select Geotextiles

Jones et al. (2000) determined unit weight is not a good indicator for geotextile performance. In this study, two sets of materials were tested with the same unit weight. Materials A and B were made of the same material and had unit weights of 4 oz/yd^2, but A was needlepunched and B was woven. Likewise, materials C and D were of like materials, had a unit weight of 8 oz/yd^2 and were needlepunched and woven, respectively.

Effect of Weave Type on CBR Puncture Strength

To examine the effects that weave play on maximum puncture resistance, typical CBR puncture results for Materials A and B, which have the same mass per unit area of 4 oz/yd^2 and base material, are plotted in Figure 4.19. Likewise, Materials C and D, which have the same mass per unit area of 8 oz/yd^2 are plotted in Figure 4.20. Again, the only difference in the two sets of materials was whether they were woven or nonwoven.

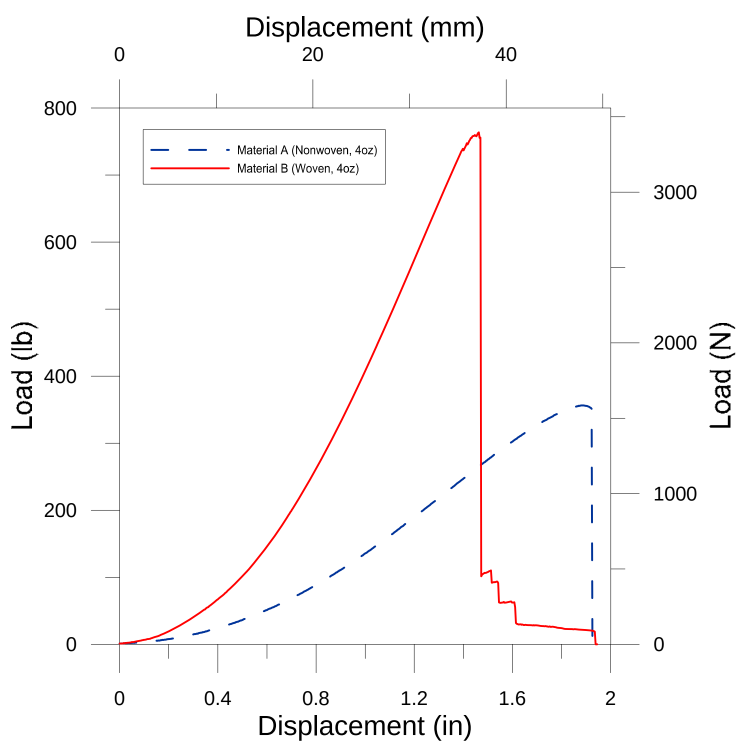


Figure 4.19 CBR loading curves for material A (PP, nonwoven, 4 oz/yd^2) and material B (PP, woven, 4 oz/yd^2)

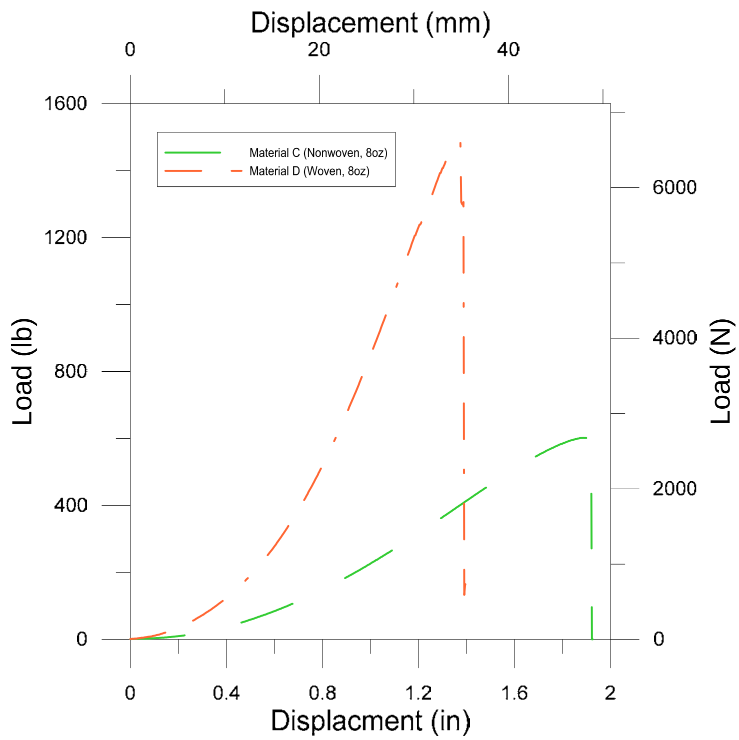


Figure 4.20 CBR loading curves for material C (PP, nonwoven, 8 oz/yd^2) and material D (PP, woven, 8 oz/yd^2)

The CBR puncture resistance of material C (8 oz/yd^2) was approximately double that of material A (4 oz/yd^2). material D (8 oz/yd^2) showed a puncture resistance approximately double that of material B (4 oz/yd^2). This indicates that woven materials (with the same base material and mass per unit area as a nonwoven material) will exhibit a CBR puncture strength approximately double the nonwoven strength. Remember that further insight to the puncture strength of nonwoven materials is supported by Koerner and Koerner (2010). Koerner and Koerner (2010) had determined that both staple fiber and continuous filament nonwoven materials will exhibit similar CBR puncture strengths. This is likely because the puncture resistance of nonwoven materials is dependent on the fiber-fiber contact points which is directly proportional to the mass per unit area.

The nonwoven materials (A and C) failed at the approximately the same displacement at failure as shown in Figure 4.21. The woven materials (B and D) also experienced similar displacements at puncture failure. This implies that the elongation at puncture failure is determined by weave type, rather than mass per unit area.

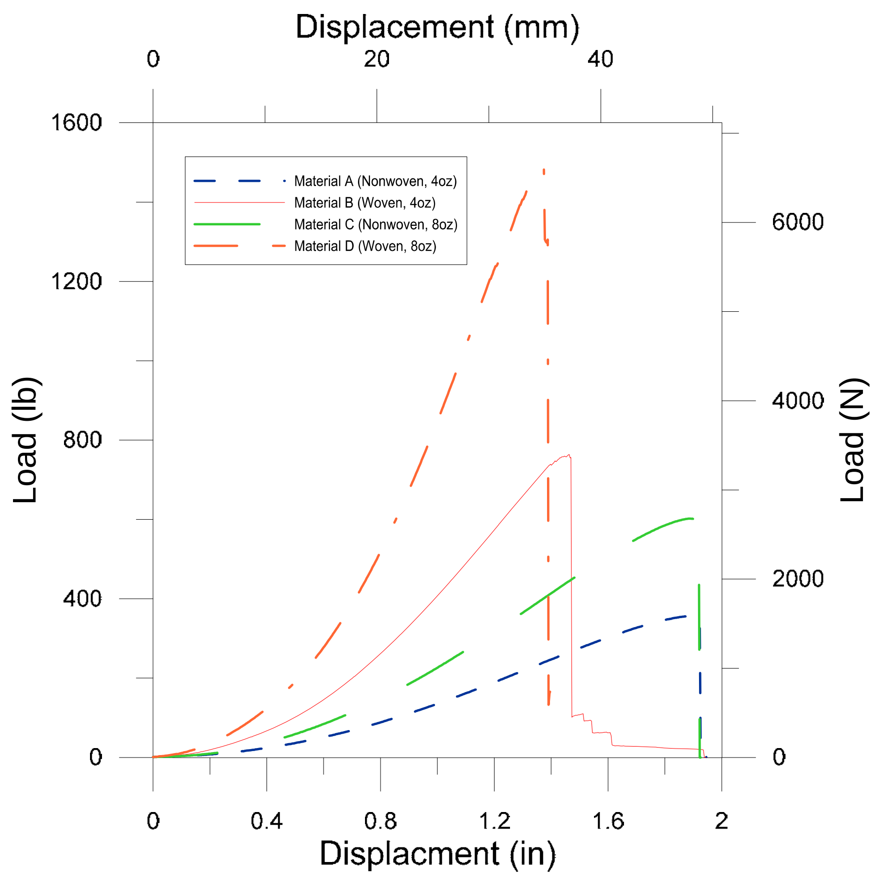


Figure 4.21 CBR loading curves for Materials A-D

A comparison of pin and CBR puncture tests are shown in Figure 4.22. Notice that material B (4 oz/yd^2) had a lower puncture resistance than material C (8 oz/yd^2) during pin testing, yet had a higher puncture resistance during CBR testing. Because CBR testing has a larger probe size, small material variations become less apparent. By comparing multiple materials of the same unit weight, this research supports the theory that CBR puncture strength values better indicate field performance.

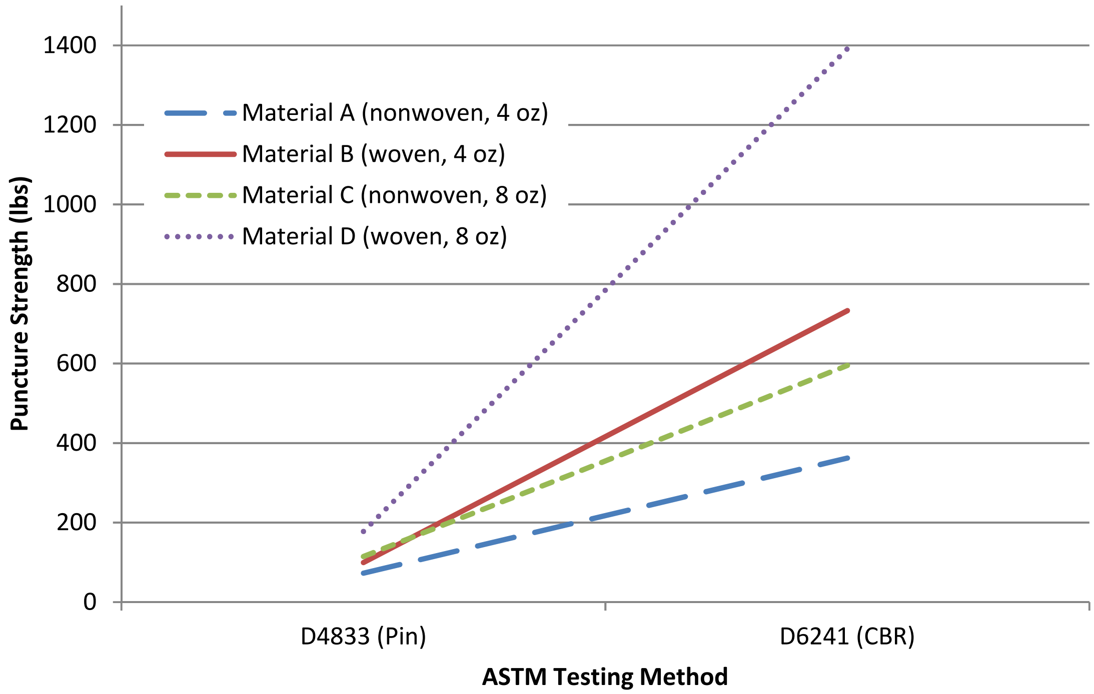


Figure 4.22   Puncture strength of materials with two mass per unit areas

4.4 Susceptibility of Nonwoven Geotextiles to Freeze/Thaw Deterioration

As stated previously, nine samples of material E were tested to investigate the effects of freeze/thaw on the puncture strength of geotextiles. The material selected was a nonwoven, needle punched fabric with a mass per unit area of 12 oz/yd^2. The results of the testing are summarized in Table 4.4. and shown in Figure 4.23.

Table 4.4 Summary of Conditioned Sample Testing

Material Type	Condition Cycle Count	Sample Number	Puncture Load, lbs (N)	Average Puncture Load, lbs (N)	Standard Deviation, lbs (N)	Coefficient of Variation (%)
E	15	1	1130 (5026)	1064 (4733)	141 (627)	13.3
		2	902 (4012)			
		3	1159 (5155)			
E	30	4	1063 (4728)	1260 (5605)	85 (378)	6.8
		5	1191 (5298)			
		6	1355 (6027)			
E	45	7	1449 (6445)	1303 (5796)	171 (761)	13.1
		8	1116 (4964)			
		9	1346 (5987)			

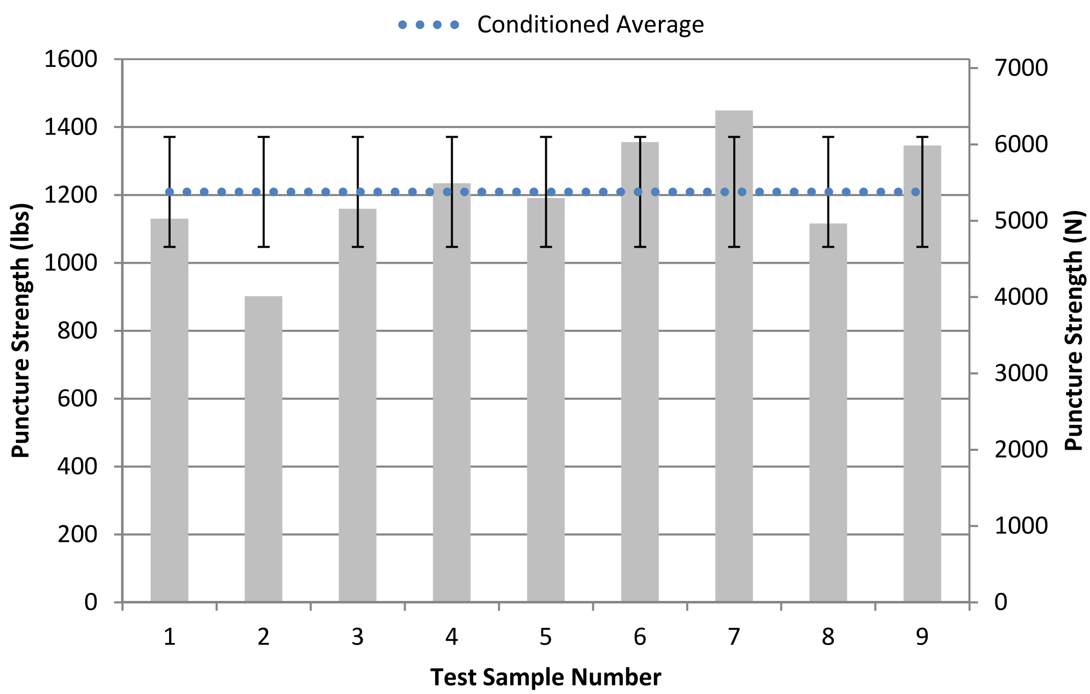


Figure 4.23 Bar chart of puncture strength of freeze/thaw conditioned test samples (error bars indicate standard deviations)

The puncture resistances of conditioned and unconditioned material E were compared. The average puncture resistance and standard deviation of the unconditioned samples are added in Figure 4.24. An unpaired, two tail, type three *t*-test was run in excel on the conditioned vs. unconditioned samples of material E. The resulting *p* value was p=0.347, which is much higher than the α=0.05 significance level. There is no evidence that the puncture resistance of nonwoven geotextiles is significantly impacted when the material is subjected to up to 45 cycles of freeze-thaw conditioning.

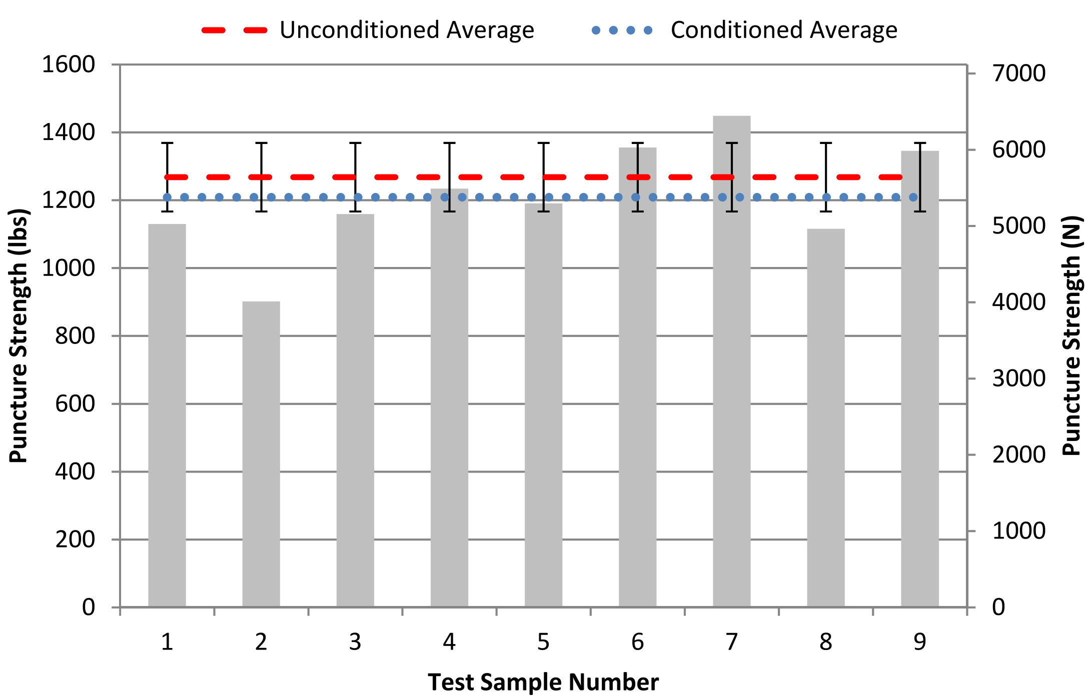


Figure 4.24 Puncture strength of freeze/thaw conditioned test samples plotted with the unconditioned material average (error bars indicate standard deviation of unconditioned samples)

The puncture resistances of the first nine unconditioned material E samples are plotted with the conditioned samples in Figure 4.25. The diagonal line represents the line of equality where the CBR puncture resistance for both conditioned and unconditioned would remain the same for each sample. Because the average of the tested samples is below this line, the CBR puncture resistance for conditioned samples was, on average, higher than that of unconditioned samples. This implies that the freeze-thaw cycling may reduce puncture strength resistance over time. Although the statistical analysis described previously implies there is no significant difference between conditioned and unconditioned samples, the small sampling size and limited number of freeze-thaw cycles may not accurately represent material deterioration, should there be any. Because of this, future research is necessary to describe any trends related to freeze-thaw deterioration in nonwoven PP geotextiles.

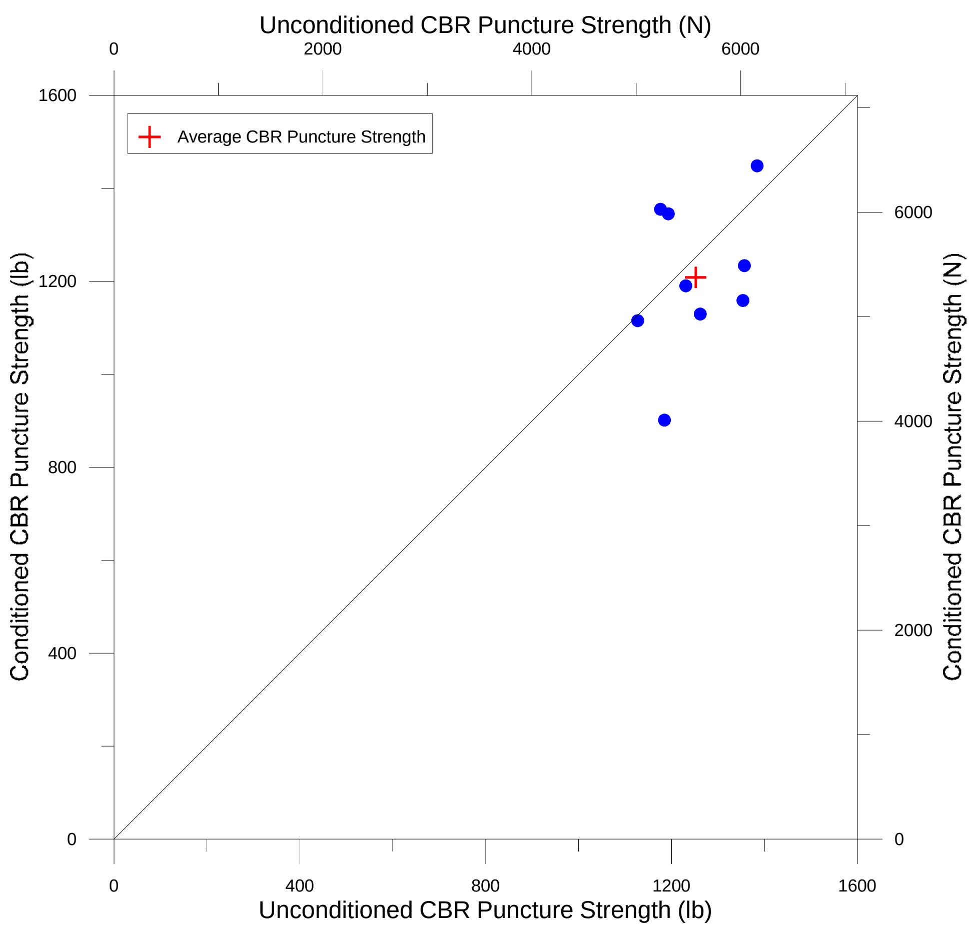
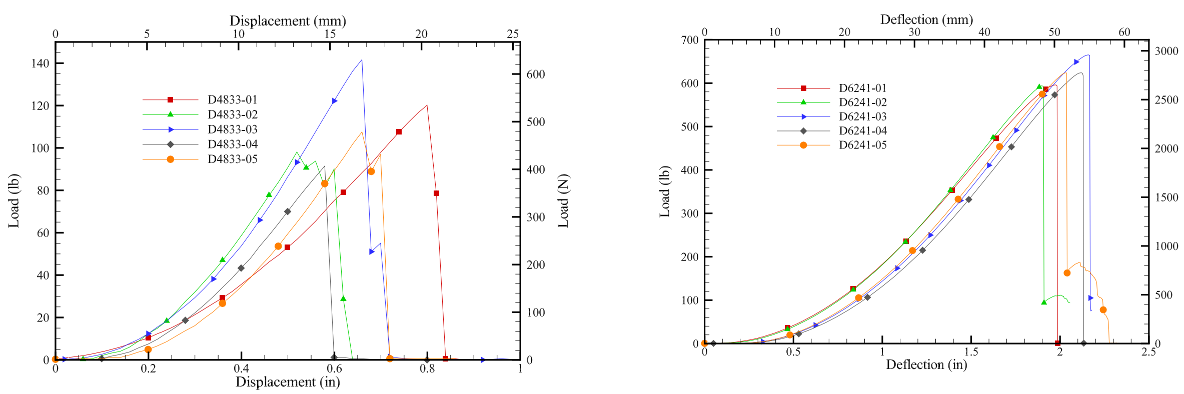


Figure 4.25 Conditioned vs. unconditioned CBR puncture strengths of material E

4.5 Phase – II Testing Program

The results of pin and CBR puncture strength tests on nonwoven drainage/filtration (DF) geotextile specimens are depicted in Figure 4.26. Load displacement curves are consistent with typical nonwoven geotextile trends discussed earlier in phase I. The puncture loads for both pin and CBR tests are obtained from these load-displacement curves and summarized in Table 4.5. In addition, the puncture loads for pin test on specimens conducted by WisDOT are presented in the same table. The puncture loads from WisDOT pin test vary from 88 to 119 lbs. with an average value of 102 lbs. and a coefficient of variation of 11%., while the results of the pin puncture test conducted on specimens from the same geotextile at UWM composite materials lab range between 91 and 143 lbs. with an average value of 112 lbs. and a coefficient of variation of 18%. On the other hand, the results of the CBR puncture test on samples from the same geotextile materials show that the puncture loads vary from 594 to 665 lbs. with an average value of 620 lbs. and a coefficient of variation of 5%. Inspection of the load displacement curves in Figure 4.25 and the coefficient of variation results shows a good repeatability and less variability in the CBR puncture test results for this geotextile material. The pin and CBR puncture strength values for all specimens of this geotextiles from WisDOT and UWM labs tests are compared in Figure 4.27.



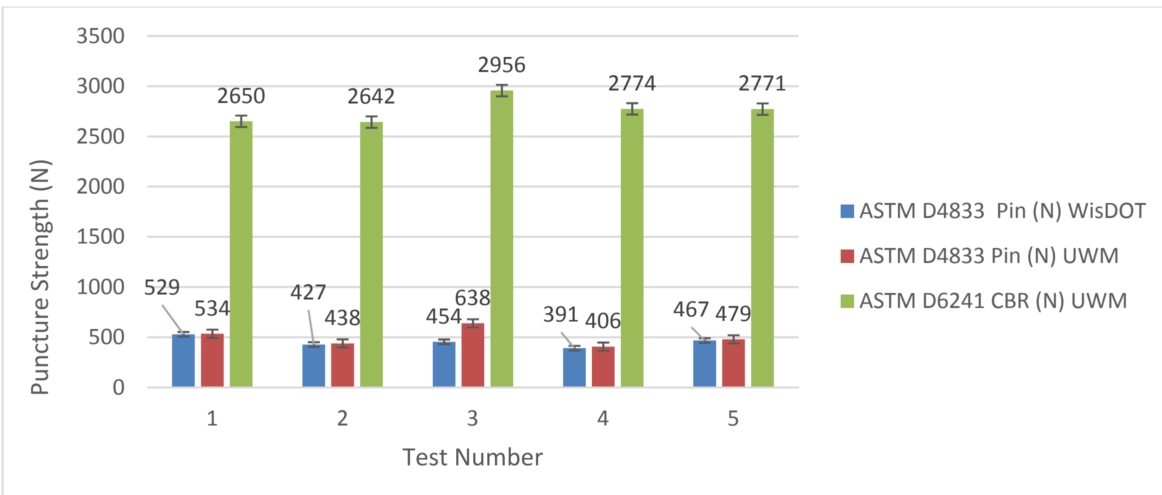
(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

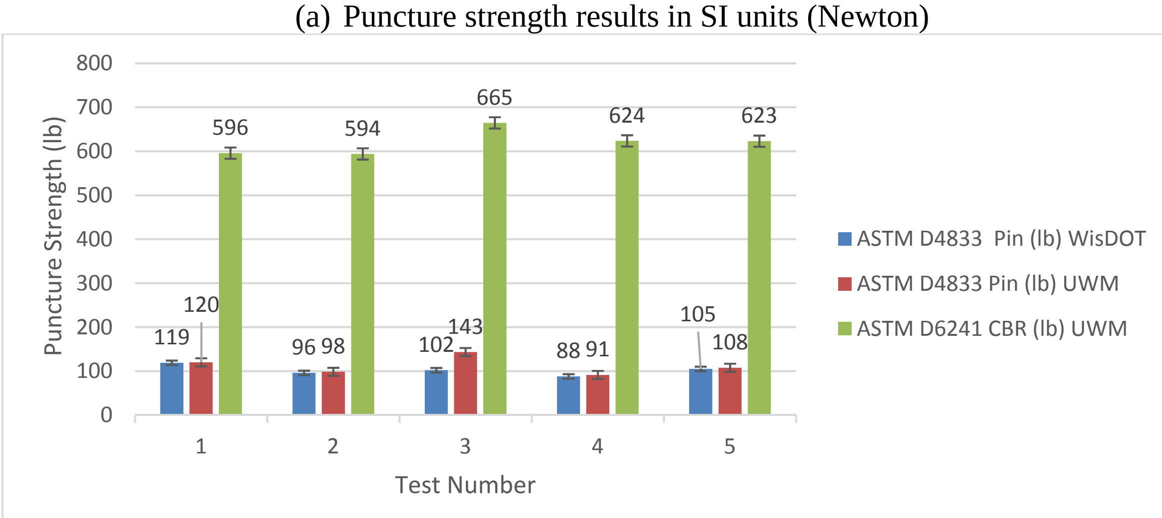
Figure 4.26: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 9200-04-71– manufactured by HONES GEO Component

Table 4.5: Summary of puncture loads for geotextile specimens – fabric type DF, project number – 9200-04-71 manufactured by HONES GEO Component

Test number	ASTM D4833 (Pin)				ASTM D6241 (CBR)	
	WisDOT		UWM		UWM	
	N	lb	N	lb	N	lb
1	529	119	534	120	2650	596
2	427	96	438	98	2642	594
3	454	102	638	143	2956	665
4	391	88	406	91	2774	624
5	467	105	479	108	2771	623
Average	**454**	**102**	**499**	**112**	**2759**	**620**
Standard Deviation	**51**	**11**	**91**	**20**	**127**	**29**
CV%	**11%**	**11%**	**18%**	**18%**	**5%**	**5%**



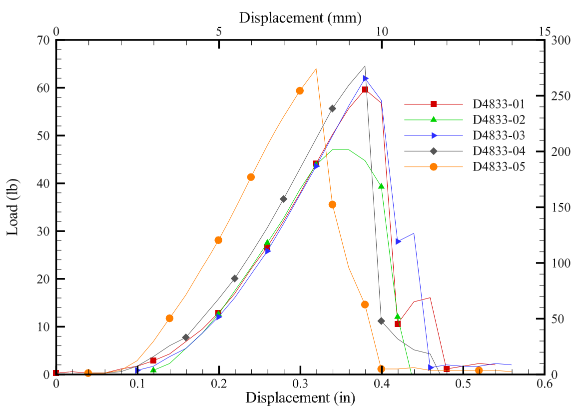
(a) Puncture strength results in SI units (Newton)



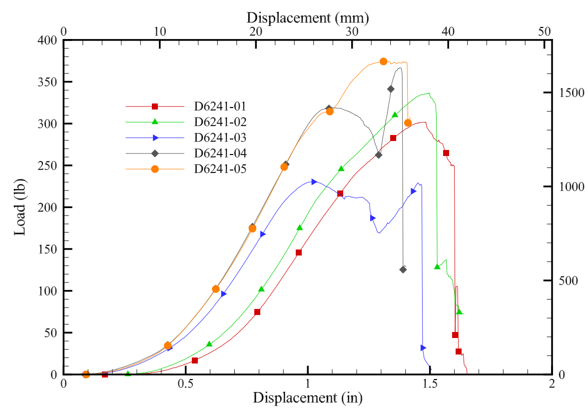
(b) Puncture strength results in U.S. units (Pound)

Figure 4.27: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 9200-04-71– manufactured by HONES GEO Component

The results of pin and CBR puncture tests on woven heavy riprap (HR) geotextile specimens are depicted in Figure 4.28. Load displacement curves are consistent with typical woven geotextile trends discussed earlier in phase I. The puncture loads for both pin and CBR tests are obtained from these load-displacement curves and summarized in Table 4.6. In addition, the puncture loads for pin test on specimens conducted by WisDOT are presented in the same table. The puncture loads from WisDOT pin test vary from 49 to 109 lbs. with an average value of 71 lbs. and a coefficient of variation of 32%., while results of the pin puncture test conducted on specimens from the same geotextile at UWM composite materials lab range between 47 and 64 lbs. with an average value of 59 lbs. and coefficient of variation of 12%. On the other hand, the results of the CBR puncture test on samples from the same geotextile materials show that the puncture loads vary from 230 to 335 lbs. with an average value of 300 lbs. and a coefficient of variation of 14%. Inspection of the load displacement curves in Figure 4.28 and the coefficient of variation results shows reasonable repeatability in both the pin and CBR puncture test results for this woven geotextile material. The pin and CBR puncture strength values for all specimens of this geotextiles from WisDOT and UWM labs tests are compared in Figure 4.29.



(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test



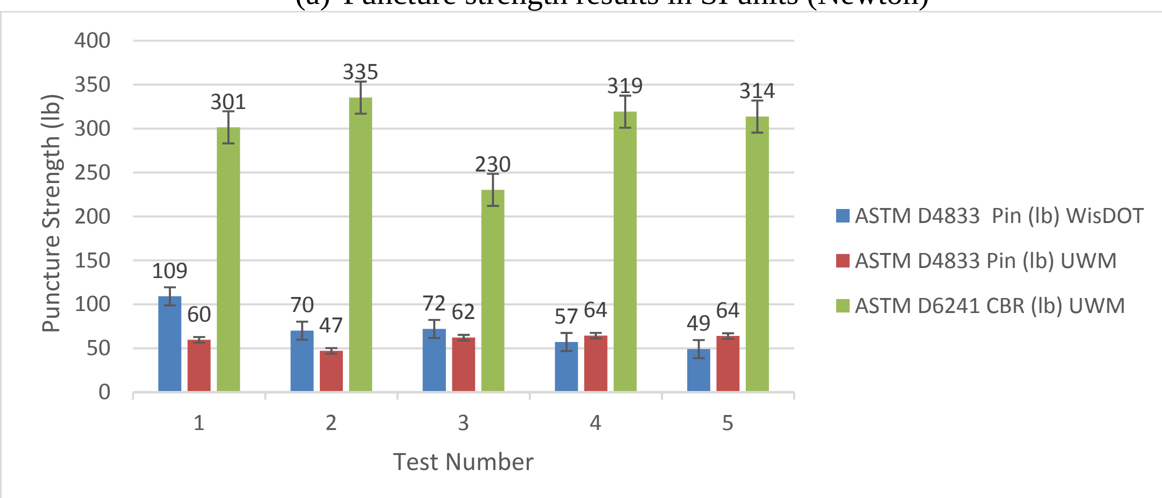
(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure 4.28: Pin and CBR puncture strength tests for geotextile specimens – fabric type HR, project number– manufactured by X1

Table 4.6: Summary of puncture loads for geotextile specimens – fabric type HR, project number – manufactured by X1

Test number	ASTM D4833 (Pin)				ASTM D6241 (CBR)	
	WisDOT		UWM		UWM	
	N	lb	N	lb	N	lb
1	485	109	265	60	1341	301
2	311	70	209	47	1491	335
3	320	72	276	62	1024	230
4	254	57	286	64	1420	319
5	218	49	284	64	1395	314
Average	**318**	**71**	**264**	**59**	**1334**	**300**
Standard Deviation	**103**	**23**	**32**	**7**	**181**	**41**
CV%	**32%**	**32%**	**12%**	**12%**	**14%**	**14%**

(a) Puncture strength results in SI units (Newton)



(b) Puncture strength results in U.S. units (Pound)

Figure 4.29: Pin and CBR puncture strength tests for geotextile specimens – fabric type HR, project number– manufactured by X1

The results of all pin and CBR puncture tests conducted at UWM during phase II are compiled and presented in Appendix A. A summary of the average values and coefficient of variation is shown Table 4.7a in U.S. customary units and in Table 4.7b in SI units. In addition, pin puncture test results provided by WisDOT for the same materials are presented in the same table. The results presented in Table 4.7 are the average values of the pin and CBR puncture tests conducted at UWM as well as average values for test results obtained from WisDOT records. Each average values in general represent five puncture strength tests conducted. Details of each individual test conducted at UWM is presented below in Appendix A in which the load versus displacement curves for each individual geotextile are shown. In addition, the puncture strength (puncture load at failure) for each geotextile type/sample is depicted in a bar chart with the error bar is presented for all test.

4.6 Statistical Analysis – Correlation and Modeling

Statistical analysis was conducted on pin and CBR puncture test results from phase I and II on both nonwoven and woven geotextiles to explore correlation/association between the pin and CBR puncture tests. Figures 4.30 to 4.35 compare the CBR with pin puncture strength and depict the correlations for all geotextiles investigated in this study. For example, in Figure 4.30 the CBR puncture strength is correlated to the pin puncture strength for woven geotextiles investigated in Phase I by a constant of 7.46 and coefficient of determination of 0.98.

Table 4.7a: Summary of test results for Phase II testing program (in U.S. customary units)

Geotextile		Project Number	Puncture Strength (lbs.)				Coefficient of Variation		
Function	Type		WisDOT Specification Min. Value	Average Laboratory Tests D4833 (Pin)		D6241 (CBR)	D4833 (Pin)		D6241 (CBR) UWM
				WisDOT	UWM	UWM	WisDOT	UWM	
DF-A	NW	1195-13-71	40	67	19	214	-	15%	20%
DF-A	NW	1030-11-70	40	128	36	410	11%	30%	5%
DF-A	NW	1195-13-71	40	48	33	214	27%	36%	17%
DF-A	NW	1170-01-70	40	51	36	141	33%	17%	7%
DF-B	NW	1206-07-77	70	100	59	294	2%	17%	3%
DF-A	NW	NA/Tencate	40	105	83	430	23%	21%	11%
DF-A	NW	NA/Tencate	40	123	62	453	14%	10%	5%
DF-A	NW	1060-33-70	40	105	94	189	17%	17%	16%
DF-C	NW	9200-04-71	70	102	112	620	11%	18%	5%
DF-A	NW	1030-11-70	40	108	104	585	32%	19%	10%
DF-B	NW	1206-07-77	70	107	45	417	1%	7%	5%
DF-A	NW	1030-11-70	40	66	67	445	2%	21%	5%
DF-B	NW	2753-06-71	70	102	66	244	6%	9%	25%
DF-A	NW	1060-33-73	40	112	62	198	13%	29%	15%
ES	K	1133-11-74	NA	56	57	465	40%	38%	17%
HR	W	NA/Adv GS	100	71	59	300	32%	12%	14%
HR	W	NA/Adv GS	100	194	113	307	13%	15%	10%
MS	W	6968-01-70	NA	143	71	290	9%	14%	41%
MS	W	NA/Tencate	NA	76	106	553	17%	21%	10%
SAS	NW	1133-03-71	70	114	77	389	27%	12%	9%
SAS	NW	8160-14-71	70	105	67	295	23%	19%	9%
SAS	NW	5658-00-75	70	91	89	210	21%	11%	10%
SAS	NW	NA	70	107	69	318	15%	29%	12%
SAS	NW	1030-11-70	70	127	74	199	20%	11%	6%
SAS	NW	NA/West Ex	70	95	131	719	11%	18%	5%
SAS	NW	9240-10-61	70	88	76	327	10%	26%	13%
SAS	NW	1060-33-75	70	122	88	415	7%	12%	12%
SR	W	5994-00-72	146*	188	102	406	-	11%	23%
SR	W	5994-00-72	146*	173	37	264	-	39%	14%

W: Woven, NW: Non-woven, K: Knitted, A: Schedule A, B: Schedule B, and C: Schedule C.
*Values are obtained from WisDOT documents other than specifications

Table 4.7b: Summary of test results for Phase II testing program (in SI units)

Geotextile		Project Number	Puncture Strength (N)				Coefficient of Variation		
Function	Type		WisDOT Specification Min. Value	Average Laboratory Tests			D4833 (Pin)		D6241 (CBR) UWM
				D4833 (Pin)		D6241 (CBR)			
				WisDOT	UWM	UWM	WisDOT	UWM	
DF-A	NW	1195-13-71	175	299	84	953	-	15%	20%
DF-A	NW	1030-11-70	175	568	160	1824	11%	30%	5%
DF-A	NW	1195-13-71	175	212	148	950	27%	36%	17%
DF-A	NW	1170-01-70	175	227	158	627	33%	17%	7%
DF-B	NW	1206-07-77	300	443	264	1310	2%	17%	3%
DF-A	NW	NA/Tencate	175	465	371	1912	23%	21%	11%
DF-A	NW	NA/Tencate	175	546	276	2016	14%	10%	5%
DF-A	NW	1060-33-70	175	466	416	840	17%	17%	16%
DF-C	NW	9200-04-71	311	454	499	2759	11%	18%	5%
DF-A	NW	1030-11-70	175	480	463	2600	32%	19%	10%
DF-B	NW	1206-07-77	300	478	199	1857	1%	7%	5%
DF-A	NW	1030-11-70	175	294	300	1980	2%	21%	5%
DF-B	NW	2753-06-71	300	452	295	1084	6%	9%	25%
DF-A	NW	1060-33-73	175	497	274	880	13%	29%	15%
ES	K	1133-11-74	NA	249	254	2068	40%	38%	17%
HR	W	NA/Adv GS	440	318	264	1334	32%	12%	14%
HR	W	NA/Adv GS	440	865	503	1364	13%	15%	10%
MS	W	6968-01-70	NA	638	315	1288	9%	14%	41%
MS	W	NA/Tencate	NA	339	473	2460	17%	21%	10%
SAS	NW	1133-03-71	300	509	342	1731	27%	12%	9%
SAS	NW	8160-14-71	300	465	300	1312	23%	19%	9%
SAS	NW	5658-00-75	300	407	398	932	21%	11%	10%
SAS	NW	NA	300	475	308	1416	15%	29%	12%
SAS	NW	1030-11-70	300	564	328	887	20%	11%	6%
SAS	NW	NA/West Ex	300	423	582	3199	11%	18%	5%
SAS	NW	9240-10-61	300	390	337	1456	10%	26%	13%
SAS	NW	1060-33-75	311	541	391	1845	7%	12%	12%
SR	W	5994-00-72	650*	838	455	1806	-	11%	23%
SR	W	5994-00-72	650*	768	163	1174	-	39%	14%

W: Woven, NW: Non-woven, K: Knitted, A: Schedule A, B: Schedule B, and C: Schedule C.
*Values are obtained from WisDOT documents other than specifications

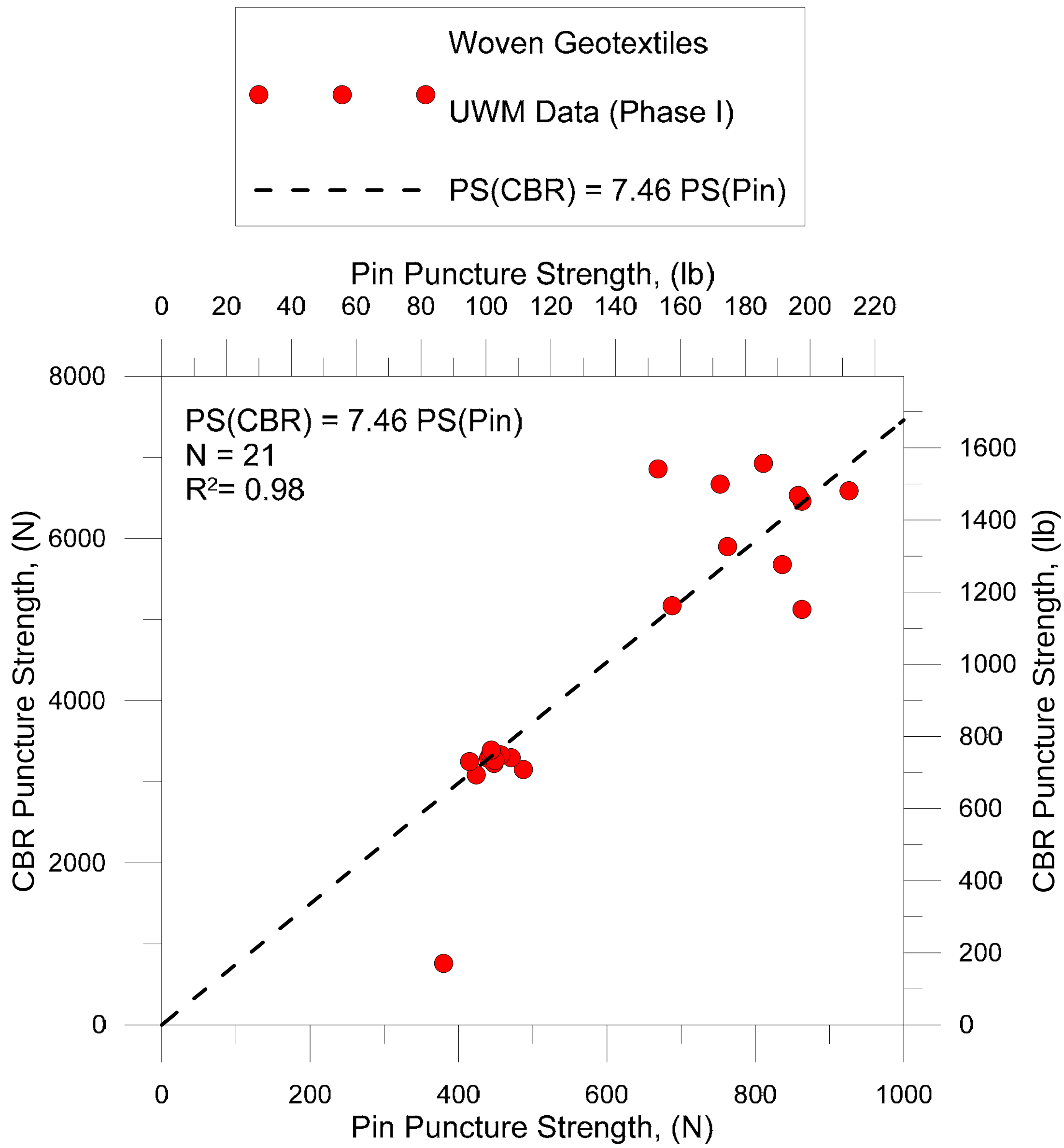


Figure 4.30: Comparison of measured CBR and pin puncture strength for woven geotextiles investigated in Phase I.

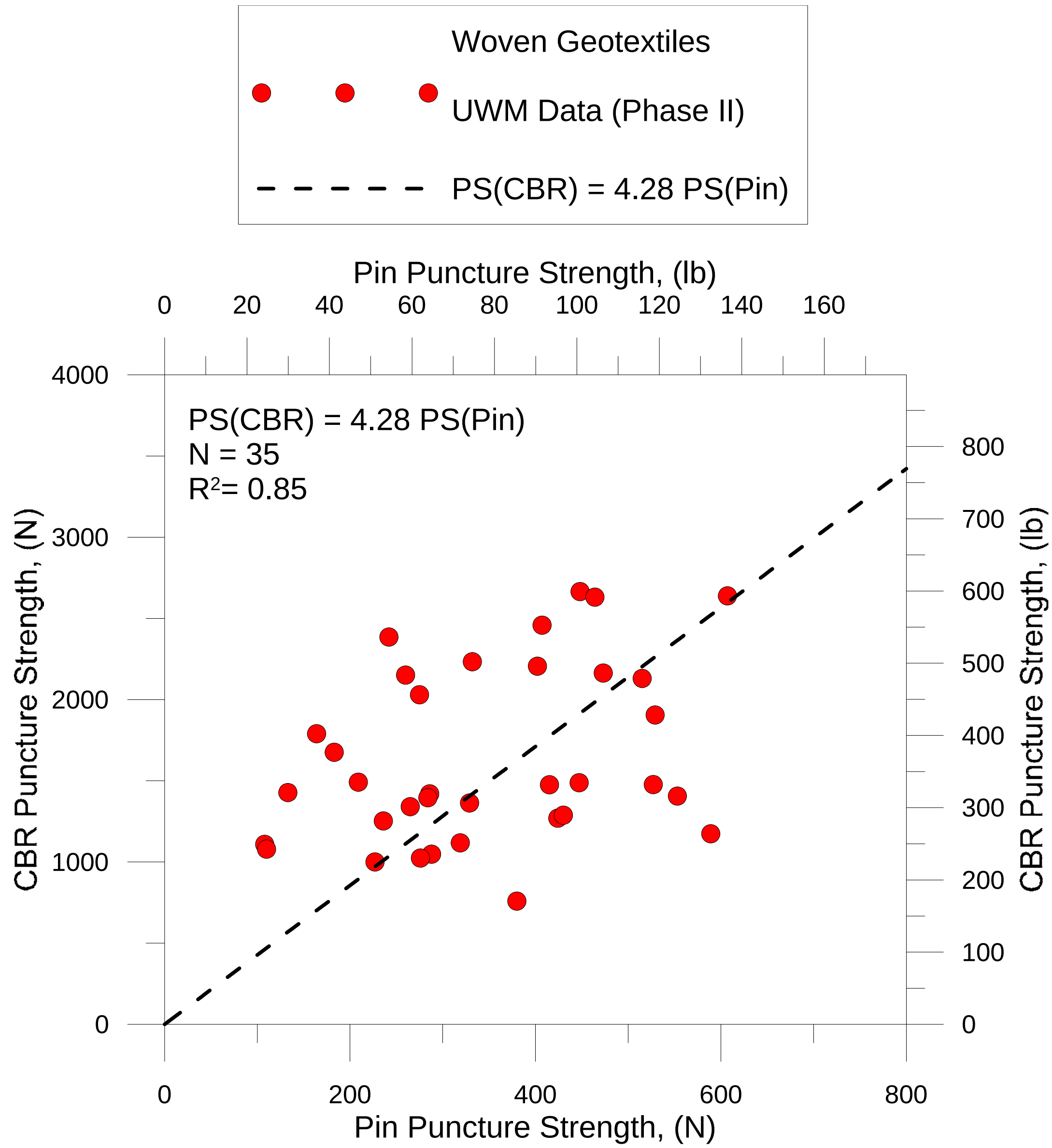


Figure 4.31: Comparison of measured CBR and pin puncture strength for woven geotextiles investigated in Phase II.

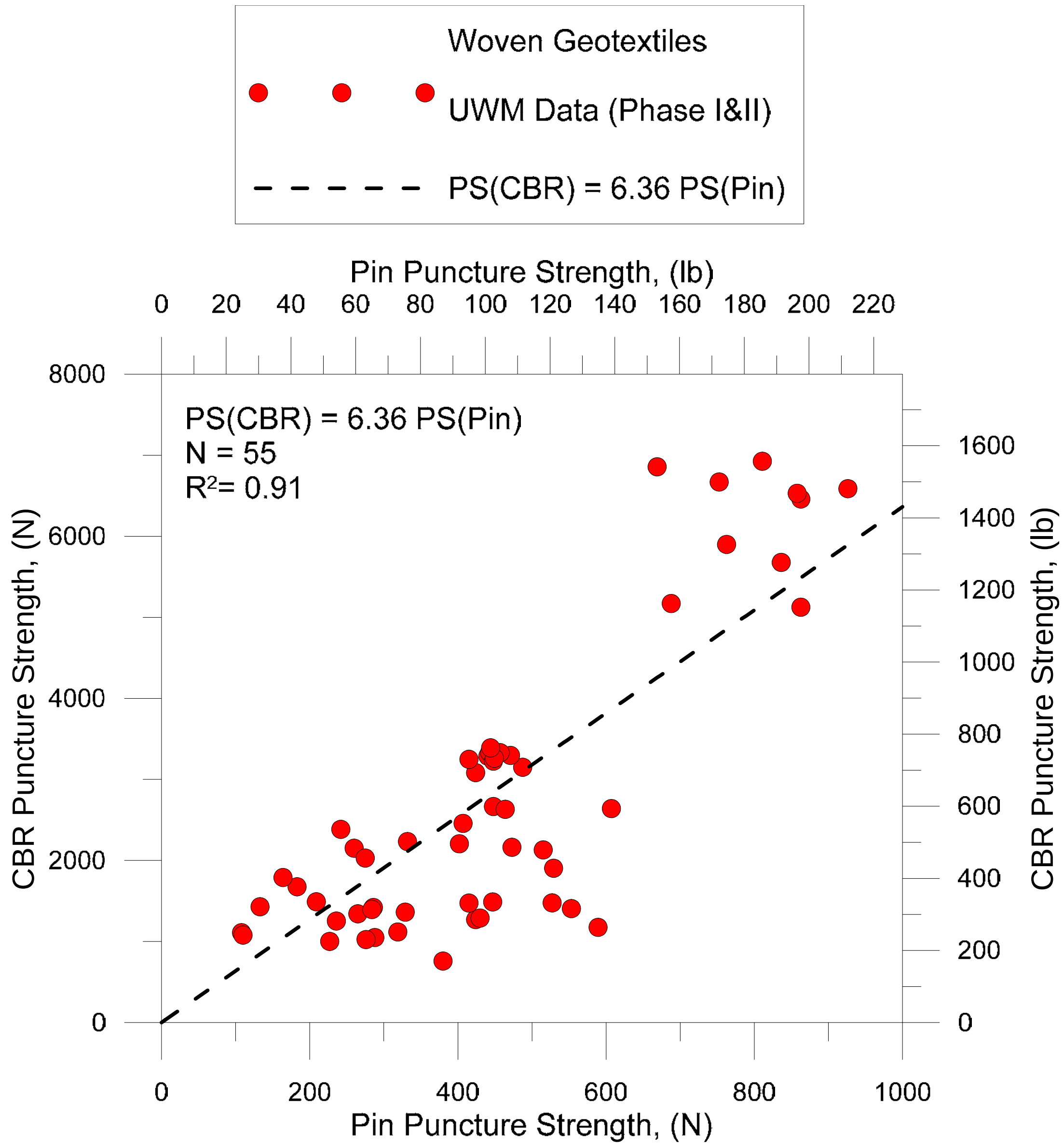


Figure 4.32: Comparison of measured CBR and pin puncture strength for woven geotextiles investigated in Phases I&II.

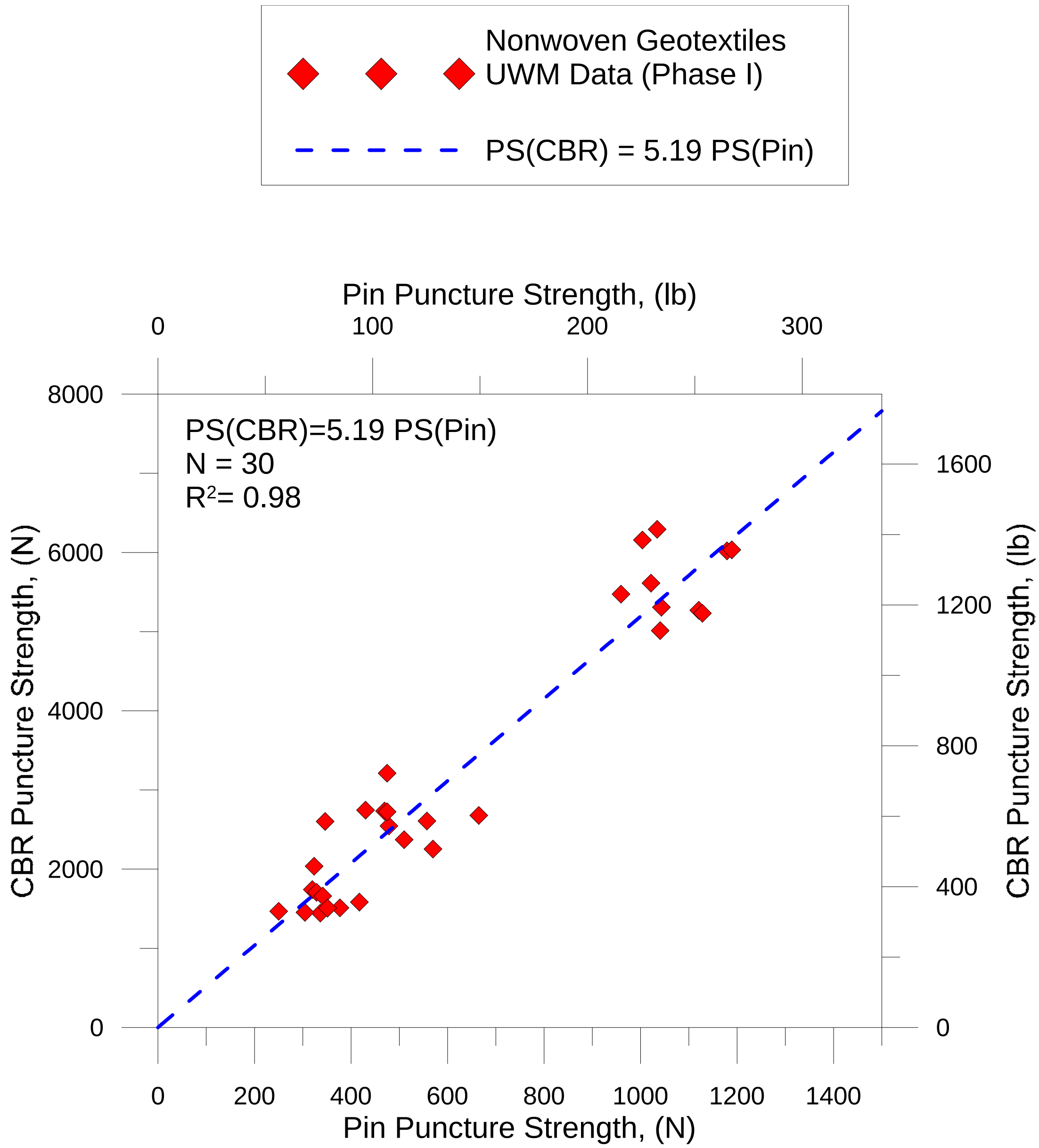


Figure 4.33: Comparison of measured CBR and pin puncture strength for nonwoven geotextiles investigated in Phase I.

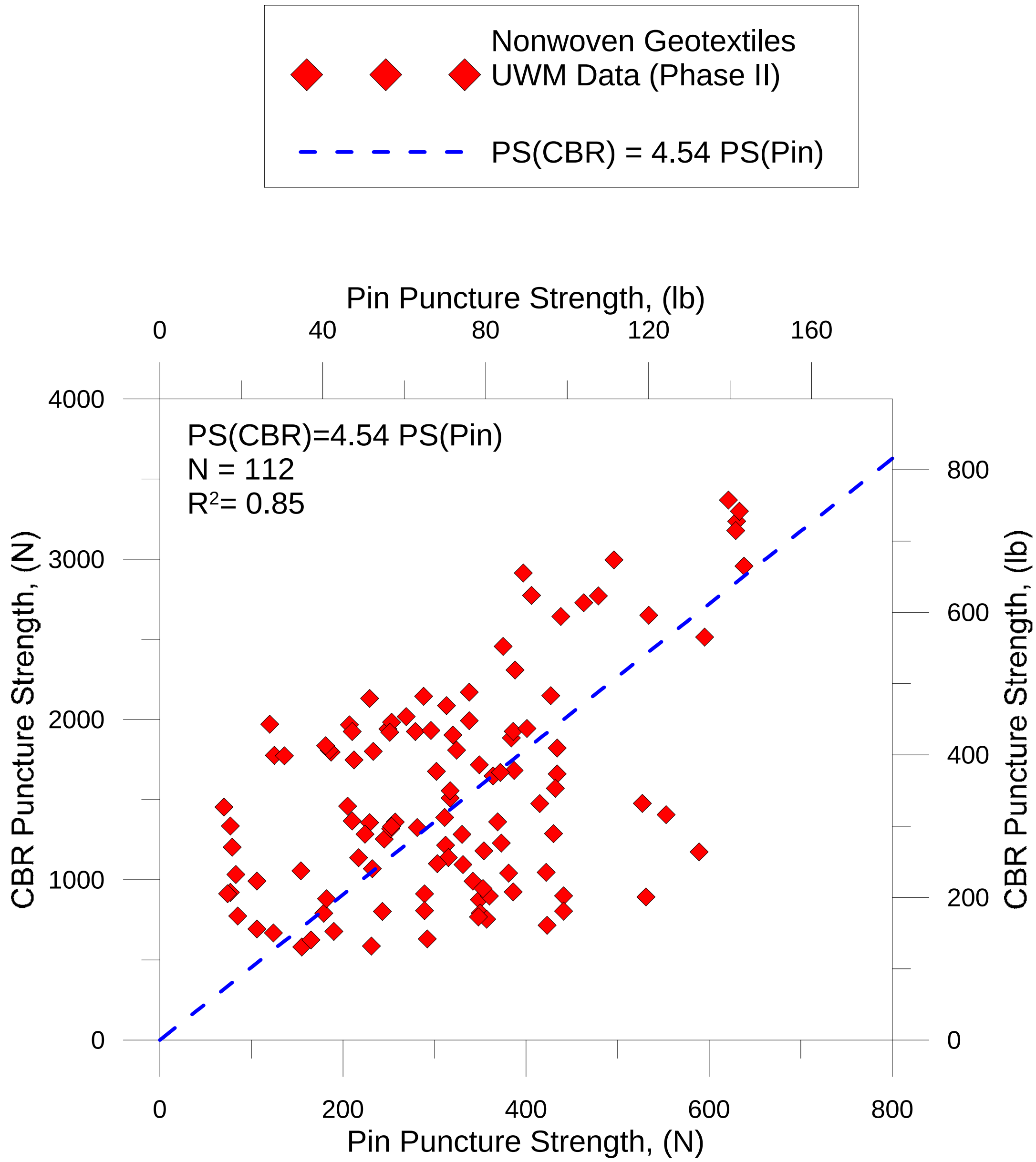


Figure 4.34: Comparison of measured CBR and pin puncture strength for nonwoven geotextiles investigated in Phase II.

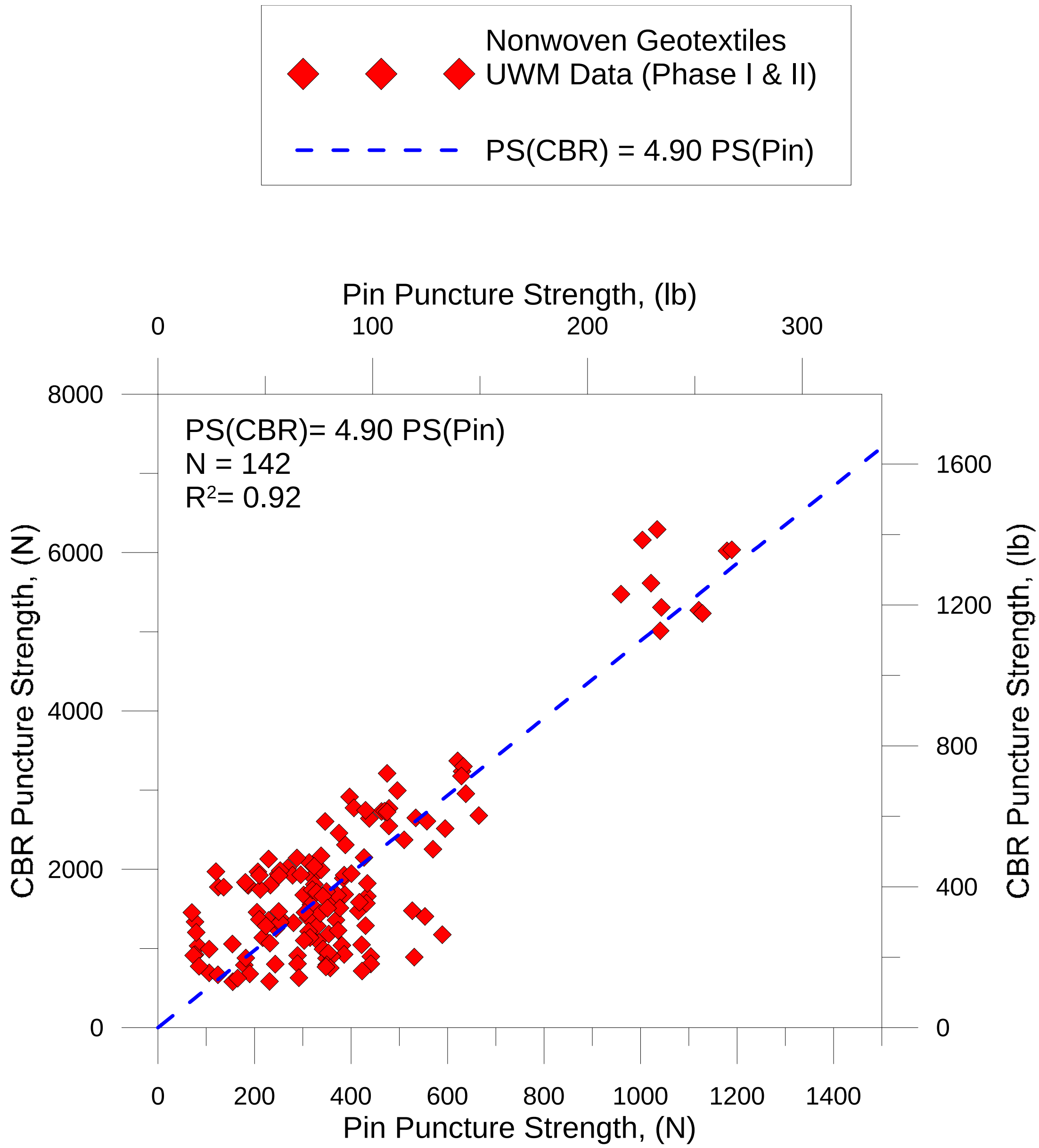


Figure 4.35: Comparison of measured CBR and pin puncture strength for nonwoven geotextiles investigated in Phase I&II.

4.7 Phase III: UV Testing Results

Significant degradation of greater than 50% was observed after UV weathering in many of the geotextiles tested. Significant degradation in SAS, DF and ES puncture strength were the most impacted by the weathering tests. All the woven geotextiles tested (HR, MS, SR) retained greater than 70% of their RTA puncture strength. The common denominator in the weak performing geotextiles was that they were all non-woven.

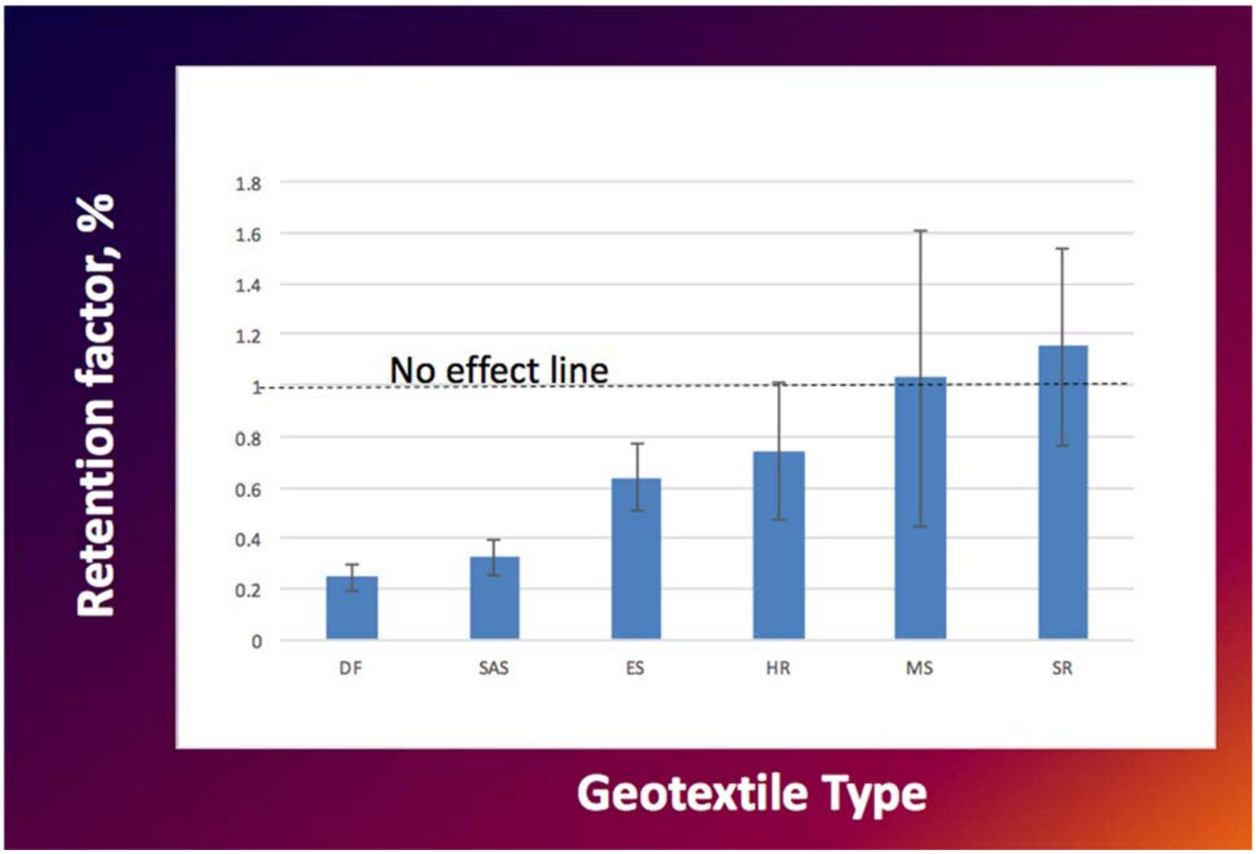


Figure 4.36: Retention factor for puncture tests as a function of geotextile type after UV/moisture weathering

Chapter 5

Puncture Test Specifications from U.S. State DOTs

In this chapter we review the puncture test specifications from the various DOT standard specification manuals. In some cases reference is made to the AASHTO M288, which for puncture testing is defined in the table below.

Table 5.1. AASHTO M288 specifications for geotextile puncture testing

			class 1		class 2		class 3	
Test	Test Methods	Units	Elongation < 50%	Elongation > 50%	Elongation < 50%c	Elongation > 50%	Elongation < 50%	Elongation > 50%
Puncture strength	ASTM D 6241	N	2750	1925	2200	1375	1650	990

Table 5.2. Summary of geotextile specifications from the State of Arizona

		Low Survivability Fabric		Moderate Survivability Fabric		High Survivability Fabric		Very High Survivability Fabric	
Test	Method								
		Non-woven	Woven	Non-woven	Woven	Non-woven	Woven	Non-woven	Woven
Puncture Strength: lbs	ASTM D4833	30	50	50	75	75	110	110	130
Ultraviolet Stability: %	ASTM D 4355	70	70	70	70	70	70	70	70

Table 5.3. Summary of geotextile specifications from the State of Arkansas

			Type 1 &6&8		Type 2 & 9		Type 3 &4		Type 5 &10	
			class 2		class 3		Slit fence		class 1	
	Test Method	Units	Elongation		Elongation		Elongation		Elongation	
			< 50%	> 50%	< 50%	> 50%	< 50%	> 50%	< 50%	> 50%
Grab strength	ASTM D4632	N	1100	700	800	500	550	550	1400	900
Sewn seam strength	ASTM D4632	N	990	630	720	450			1260	810
Tear strength	ASTM D4533	N	400	250	300	180			500	350
Puncture strength	ASTM D6241	N	2200	1375	1650	990			2750	1925

Type 1 shall comply with the requirements for Subsurface Drainage, Class 2. This geotextile is used by placing against a soil to allow for long-term passage of water into a subsurface drain system retaining the in-situ soil.

Type 2 shall comply with the requirements for Subsurface Drainage, Class 3. This geotextile is used by placing against a soil to allow for long-term passage of water into a subsurface drain system retaining the in-situ soil.

Type 3 shall comply with the requirements for Temporary Silt Fence, Supported Silt Fence. This geotextile is used as a vertical, permeable interceptor designed to remove suspended soil from overland water flow and shall be supported between posts with wire or polymeric mesh.

Type 4 shall comply with the requirements for Temporary Silt Fence, Unsupported Silt Fence(Self-Supporting). This geotextile is used as a vertical, permeable interceptor designed to remove suspended soil from overland water flow.

Type 5 shall comply with the requirements for Permanent Erosion Control, Class 1. This geotextile is used between energy absorbing armor systems and in the in-situ soil to prevent soil loss resulting in excessive scour and to prevent hydraulic uplift pressures causing instability of the permanent erosion control system.

Type 6 shall comply with the requirements for Permanent Erosion Control, Class 2. This geotextile is used between energy absorbing armor systems and in the in-situ soil to prevent soil loss resulting in excessive scour and to prevent hydraulic uplift pressures causing instability of the permanent erosion control system.

Type 7 shall comply with the requirements for Paving. This geotextile is used as a paving fabric, saturated with asphalt cement, between pavement layers.

Type 8 shall comply with the requirements for Separation, Class 2. This geotextile is used to prevent mixing of a subgrade soil and an aggregate cover material (subbase, base, select material, etc.). May also be used beneath pavements where separation of two dissimilar materials is required but water seepage through the geotextile is not a critical function.

Type 9 shall comply with the requirements for Separation, Class 3. This geotextile is used to prevent mixing of a subgrade soil and an aggregate cover material (subbase, base, select material, etc.). May also be used beneath pavements where separation of two dissimilar materials is required but water seepage through the geotextile is not a critical function.

Type 10 shall comply with the requirements for Stabilization, Class 1. This geotextile is used in wet, saturated conditions to provide the coincident functions of separation and filtration. In some installations, the geotextile can also provide the function of reinforcement.

Table 5.4. Summary of geotextile specifications from the State of California

Test	Test Method	Class A1	Class A2	Class B1	Class B2	Class B3
Puncture strength, lb min	ASTM D6241	500	310	620	620	430
Ultraviolet resistance, percent min retained grab breaking load, 500 hours	ASTM D4355	70	70	70	70	70

Table 5.5. Summary of geotextile specifications from the State of Delaware

	Test Methods	Unit	class 2		class 3	
			Elongation		Elongation	
			< 50%	> 50%	< 50%	> 50%
Grab Strength	ASTM D4632	N	1100	700	800	50
Seam Strength	ASTM D4632	N	990	630	720	450
Tear Strength	ASTM D4533	N	400	250	300	180
Puncture Strength	ASTM D6241	N	2200	1375	1650	990

Table 5.6. Summary of geotextile specifications from the State of Florida

	Fabric type	Application Description	Test Method, Puncture test (KN), ASTM D 4833
Drainage (D)	D-1	Revetment (Special)	0.5
	D-2	Revetment (Standard) Articulating block Gabions	Woven monofilament 0.25, Other Geotextile elongation<50%=0.5 elongation>50%=0.35
	D-3	Under drain, French drain	elongation<50%=0.4 elongation>50%=0.25
	D-4	Slope pavement (Sand cement) Ditch pavement (Sand cement)	0.22
	D-5	Mechanical stabilized retaining wall	0.22
	D-6	Slope pavement (Concrete)	0.22

Table 5.7. Summary of geotextile specifications from the State of Hawaii

	Test Methods	Unit	a	b	c	d	e	f	g
Grab strength	ASTM D4632	lb	180	180	110	250	315	110	315
Sewn seam strength	ASTM D4884	lb	160	160	70	225	285	NA	285
Tear strength	ASTM D4533	lb	75	75	70	60	115	40	115
Puncture strength	ASTM D 4833	lb	80	80	70-120	90	115	55	115
Ultraviolet Degradation, 500 hours.	ASTM D4355	lb	50	50		50	50	70	50

a: Geotextiles For Permeable Separator Applications, **b**: Geotextiles for Underdrain Applications, **c**: Geotextiles for Geocomposite Drain Applications, **d**: Geotextiles for Permanent Erosion Control Applications. (A) Woven Monofilament Geotextiles, **e**: Geotextiles for Permanent Erosion Control Applications. (B) All Other Geotextiles, **f**: Geotextiles for Temporary Silt Fence Applications, **g**: Geotextiles for Stabilization Applications.

Table 5.8. Summary of geotextile specifications from the State of Idaho

			a		b		C		
	Test Methods	Units	Type I	Type II	Type I	Type II	Type I	Type II	Type III
Grab strength	ASTM D4632	lb	80	180	130	200	180/115	270/180	170/180
Grab elongation	ASTM D4632	%			15	15			
Puncture strength	ASTM D6241	lb	300	500	400	600	500/300	600/450	600/450

a: Drainage Geotextile Criteria(Type I refers to protected conditions. Protected conditions include trench depth < 10 ft, rounded aggregate or crushed aggregate less than 4 in size, and relatively smooth trench walls. Type II refers to unprotected conditions. All other conditions are unprotected.), **b**: Riprap/Erosion Geotextile Criteria (Type I refers to low to moderate survivability geotextiles. The Contractor may use Type I behind gabions less than 10 fthigh without an aggregate cushion. Type II refers to higher survivability geotextiles. Use a Type II geotextile in severe conditions, where stones will be larger than 250 lb or drop heights cannot be practically reduced.), **c**: Subgrade Separation Geotextile Criteria (Type I refers to moderate survivability conditions. Moderate survivability is low to moderate ground pressure equipment, < 40 psi with 12 in to 18 in initial lift thickness or high ground pressure equipment, > 40 psi with more than 18 in initial lift thickness. Type II and Type III refers to high survivability conditions. High survivability is low to moderate ground pressure equipment with 6 in to 12 in initial lift thickness or high ground pressure equipment with 12 in to 18 in initial lift thickness. Subgrade condition is assumed cleared of rocks, stumps & large limbs, and graded reasonably smooth. If subgrade preparation or clearing is not as stated, or cover material is angular shot rock, even higher survivability geotextiles may be necessary. Type III is used when subgrade separation geotextile will also function in a drainage application.

Table 5.9. Summary of geotextile specifications from the State of Indiana

	Test Method	Unit	Geotextile for Use with Underdrains	Geotextile for Use under Riprap
Grab Strength	ASTM D4632	lb	80	200
Seam Strength	ASTM D4632	lb	70	180
Puncture Strength	ASTM D4833	lb	25	80
Ultraviolet Degradation at 150 h	ASTM D4355	%	70	70

Table 5.10. Summary of geotextile specifications from the State of Kentucky

Type I Fabric Grotextiles for Slope Protection and Channel Lining			
	Test Methods	Unit	Value
Grab Strength	ASTM D4632	lb	200
Sewn Seam Strengthd	ASTM D4632	lb	180
Tear Strength	ASTM D4533	lb	50
Puncture Strength	ASTM D4833	lb	80
Ultraviolet Degradation, 500 hours.	ASTM D4355	%	70

Type II Fabric Geotextiles for Underdrains			
	Test Methods	Unit	Value
Grab Strength	ASTM D4632	lb	80
Sewn Seam Strength	ASTM D4632	lb	70
Tear Strength	ASTM D4533	lb	25
Puncture Strength	ASTM D4833	lb	25
Ultraviolet Degradation, 500 hours.	ASTM D4355	%	70

Type III Fabric Geotextiles for Subgrade or Embabkment Stabilization			
	Test Methods	Unit	Value
Grab Strength	ASTM D4632	lb	180
Sewn Seam Strength	ASTM D4632	lb	160
Tear Strength	ASTM D4533	lb	67
Puncture Strength	ASTM D4833	lb	67
Ultraviolet Degradation, 500 hours.	ASTM D4355	%	70

Type IV Fabric Geotextiles for Embankment Drainage Blankets and Pavement Edge Drains			
	Test Methods	Unit	Value
Grab Strength	ASTM D4632	lb	180
Sewn Seam strength	ASTM D4632	lb	160
Tear Strength	ASTM D4533	lb	50
Puncture Strength	ASTM D4833	lb	80
Ultraviolet Degradation, 500 hours.	ASTM D4355	%	70

Type V High Strength Geotextiles Fabric and Pavement Edge Drains			
	Test Methods	Unit	Value
Grab Strength	ASTM D4632	lb	500
Sewn Seam Strength	ASTM D4632	lb	500
Tear Strength	ASTM D4533	lb	180
Puncture Strength	ASTM D6241	**lb**	**1250**
Ultraviolet Degradation, 500 hours.	ASTM D4355	%	70

Table 5.11. Summary of geotextile specifications from the State of Louisiana

	Test Method	A	B	C	D	S	F	G
Grab Tensile, N,	ASTM D4632	330	400	580	800	800	400	400
Puncture, N,	ASTM D4833	110	130	180	330	330		
Tear Strength, N,	ASTM D4533	110	130	180	220	220		

Use Classes	(2) Stabilization:
(1) Drainage:	Bulkheads C or D
Underdrains A, B, C or D	Flexible Revetments C or D
Pipe and Precast Manhole Joints A, B, C or D	Rip Rap D
Weep Holes A, B, C or D	Railroad Crossings D
Bedding Fabric B, C, or D	Base Course D

Approach Slabs B, C, or D	Subgrade Layer D
Fabric for Geocomposite Drainage	Soil Stabilization C, D, or S
Systems1 B, C, or D	(3) Paving Fabric2: B or C (modified)
	(4) Silt Fencing:
	Wire Supported F
	Self Supported G

Table 5.12. Summary of geotextile specifications from the State of Maine

		Stabilization/Reinforcement Geotextile		Drainage Geotextile	
	Test Method	Elongation		Elongation	
		< 50%	≥ 50%	< 50%	≥ 50%
Grab Strength - N	D4632	1400	900	1100	700
Sewn Seam Strength - N	D4632	1260	810	990	630
Tear Strength - N	D4533	500	350	400	250
Puncture Strength - N	D4833	500	350	400	250
Ultraviolet Stability	D4355	50% after 500h		50% after 500h	

Table 5.13. Summary of geotextile specifications from the State of Maryland

		SD			
		Type1		Type 2	
	Method	Nonwoven	Woven	Nonwoven	Woven
Grab Strength - lb	D4632	160	250	160	250
Puncture Strength - lb	D6241	56	90	56	90
Tear Strength - lb	D4533	55	90	55	90

		PE					
		Type I		Type II		Type III	
	Method	Nonwoven	Woven	Nonwoven	Woven	Nonwoven	Woven
Grab Strength - lb	D4632	200	250	200	250	200	250
Puncture Strength - lb	D6241	80	90	80	90	80	90
Tear Strength - lb	D4533	80	90	80	90	80	90

		SE		ST	F	E
	Method	Nonwoven	Woven	Woven	Woven	Nonwoven
Grab Strength - lb	D4632	200	250	300	100	90

Puncture Strength - lb	D6241	80	90	110		30
Tear Strength - lb	D4533	80	90	110		30

Table 5.14. Summary of geotextile specifications from the State of Michigan

	Method	Geotextile Blanket	Geotextile Liner	Heavy Geotextile Liner	Silt Fence
Grab Strength - lb	D4632	90	200	270	100
Tear Strength - lb	D4533	45	75	100	45
Puncture Strength - lb	D4833	45	75	100	
Puncture Strength - lb	D6241	230	440	620	

	Method	Woven Geotextile Separator(<50% elongation)	Non-Woven Geotextile Separator (>50% elongation)	Stabilization Geotextile	Drainage Geo-composites
Grab Strength - lb	D4632	270	200	270	90
Tear Strength - lb	D4533	100	75	100	45
Puncture Strength - lb	D4833	100	75	100	65
Puncture Strength - lb	D6241	620	440	620	230

Table 5.15. Summary of geotextile specifications from the State of Minnesota

		I					
	Method	Fabric	Knit Sock	II	III	IV	V
Grab Strength - KN	D4632	0.45		0.45	0.45	0.9	0.9
Seam Breaking Strength -KN	D4632	0.4		0.4	0.4	0.8	0.8
Puncture Strength - N	D6241		800				

Table 5.16. Summary of geotextile specifications from the State of Montana

		Geotextile Survivability			
		Moderate Survivability		High Survivability	
	Method	Woven	Nonwoven	Woven	Nonwoven
Grab Strength - N	D4632	1100	700	1400	900
Tear Strength - N	D4533	400	250	500	350
Swen Seam Strength - N	D4632	990	630	1260	810
Puncture Strength - N	D4833	400	250	500	350

Table 5.17. Summary of geotextile specifications from the State of New Hampshire

			Class 0	class 1	
	Test Methods	Units	extra high strength	Elongation < 50%c	Elongation > 50%
Grab Strength	ASTM D4632	N	1670	1400	900
Sewn seam Strengthd	ASTM D4632	N	1500	1260	810
Tear Strength	ASTM D4533	N	600	500	350
Puncture Strength	ASTM D6241	N	5500	2750	1925
Puncture Strength	ASTM D4833	N	1000		

			class 2		class 3	
	Test Methods	Units	Elongation < 50%c	Elongation > 50%	Elongation < 50%c	Elongation > 50%
Grab Strength	ASTM D4632	N	1100	700	800	500
Sewn Seam Strengthd	ASTM D4632	N	990	630	720	450
Tear Strength	ASTM D4533	N	400	250	300	180
Puncture Strength	ASTM D6241	N	2200	1375	1650	990

Table 5.18. Summary of geotextile specifications from the State of New York

			Bedding Geotextile			
			class 1		class 2	
	Test Methods	Units	Elongation < 50%c	Elongation > 50%	Elongation < 50%	Elongation > 50%
Grab Strength	ASTM D4632	lb	315	202	247	157
Tear Strength	ASTM D4533	lb	112	79	56	56
Puncture Strength	ASTM D6241	lb	618	433	495	309

			Separation Geotextile	
			class 2	
	Test Methods	Units	Elongation < 50%c	Elongation > 50%
Grab Strength	ASTM D4632	lb	247	157
Tear Strength	ASTM D4533	lb	90	56
Puncture Strength	ASTM D6241	lb	495	309

			Drainage Geotextile
			class 2

	Test Methods	Units	Elongation < 50%c	Elongation > 50%
Grab Strength	ASTM D4632	lb	247	157
Tear Strength	ASTM D4533	lb	90	56
Puncture Strength	ASTM D6241	lb	495	309

			Slope Protection Geotextile	
			class 1	
	Test Methods	Units	Elongation < 50%c	Elongation > 50%
Grab Strength	ASTM D4632	lb	315	202
Tear Strength	ASTM D4533	lb	112	79
Puncture Strength	ASTM D6241	lb	618	433

			Stabilization Geotextile	
			class 1	
	Test Methods	Units	Elongation < 50%c	Elongation > 50%
Grab Strength	ASTM D4632	lb	315	202
Tear Strength	ASTM D4533	lb	112	79
Puncture Strength	ASTM D6241	lb	618	433

Table 5.19. Summary of geotextile specifications from the State of North Carolina

			Type 1	Type 2	Type 3	Type 4
	Test Methods	Units	Shoulder Drains	Under Rip Rap	Temporary Silt Fence	Soil Stabilization
Grab Strength	ASTM D4632	lb	90	205	100	180
Tear Strength	ASTM D4533	lb	40	80		70
Puncture Strength	ASTM D6241	lb	220	440		370

Table 5.20. Summary of geotextile specifications from the State of North Dakota

			Separation			
	Test Methods	Units	S1	S2	Riprap RR	Reinforcement R1
Grab Strength	ASTM D4632	lb	180	180	200	350
Tear Strength	ASTM D4533	lb	50	50	50	100
Puncture Strength	ASTM D6241	lb	405	405	435	1000

Table 5.21. Summary of geotextile specifications from the State of Ohio

	Test Methods	Units	Type A Under drain and slope drain	Type B Filter blanket for rock chanel protection	Type C Sediment fences	Type D Subgrade-base seperation
Grab Strength	ASTM D4632	lb	80	200	120	180
Tear Strength	ASTM D4533	lb	25	50	40	70
Puncture Strength	ASTM D4833	lb	25	80	50	70
Puncture Strength	ASTM D6241	lb	140	440	275	385

Table 5.22. Summary of geotextile specifications from the State of Oregon

		Drainage Geotextile			
		Type 1		Type 2	
	Method	Woven	Nonwoven	Woven	Nonwoven
Grab Strength - lb	D4632	180	115	250	160
Tear Strength -lb	D4533	67	40	90	56
Puncture Strength - lb	D6241	320	220	495	310

		Riprap Geotextile			
		Type 1		Type 2	
	Method	Woven	Nonwoven	Woven	Nonwoven
Grab Strength - lb	D4632	250	160	315	200
Tear Strength -lb	D4533	90	56	110	80
Puncture Strength - lb	D6241	495	310	620	430

		Subgrade Geotextile (Separation)		Embankment Geotextile	
	Method	Woven	Nonwoven	Woven	Nonwoven
Grab Strength - lb	D4632	180	113	315	200
Tear Strength -lb	D4533	68	41	110	80
Puncture Strength - lb	D6241	371	223	620	430

Table 5.23. Summary of geotextile specifications from the State of Pennsylvania

		Subsurface	Erosion Control		Sediment Control	
	Method	Drainage	Type A	Type B	Type A	Type B
Grab Tensile Strength, kg	D4632	72	91	41	91	41
Burst Strength, kPa	D3786	1300	2200	965	2200	965
Puncture, kg	D4833	25	36	18	36	18

Trapezoid Tear Strength, kg	D4533	25	23	14	23	14
Seam Strength, kg	D4632	32	82	36		
Ultraviolet Resistance Strength Retention, %	D4355	70@150h	70@150h	70@150h	70@150h	70@150h

		Separation	Stabilization	Reinforcement
	Method	Type A	Type B	Type C
Grab Tensile Strength, kg	D4632	122	181	227
Burst Strength, kPa	D3786	2965		
Puncture, kg	D4833	45	64	91
Trapezoid Tear Strength, kg	D4533	45		
Seam Strength, kg	D4632	109	163	204
Ultraviolet Resistance Strength Retention, %	D4355	70@150h	70@150h	70@150h

Table 5.24. Summary of geotextile specifications from the State of South Carolina

			Strength Property Requirements (All Fabrics)	
	Method	Unit	Class 1 Fabric Protected	Class 2 Fabric Unprotected
Grab Strength	D4632	lb	90	200
Seam Strength	D4632	lb	80	180
Puncture Strength	D4833	lb	40	80
Burst Strength	D3786	lb	140	250
Tear Strength	D4533	lb	40	80
Ultraviolet Degradation at 500 Hours	D4355	%	50	50

Table 5.25. Summary of geotextile specifications from the State of South Dakota

		Drainage Fabric		Silt Fence	Geotexitile Separator		MSE Geotextile Fabric	Impermeable Plastic Membrane
	Method	Type A	Type B		Woven	NonWoven		
Grab Strength, Ibs	D4632			90				
Tear Strength, lbs	D4533	25	75		50	40	75	50
Puncture Strength, lbs	D4833	25	90		75	50	110	60

Table 5.26. Summary of geotextile specifications from the State of Vermont

	Method	Roadbed Separator		Under Railroad Ballast		Under Stone Fill	
Elongation	D4632	<50%	>50%	<50%	>50%	<50%	>50%
Grab Strength, Ibs	D4632	1100	700	1400	900	1400	900

Tear Strength, lbs	D4533	400	250	500	350	500	350
Puncture Strength, lbs	D6241	2200	1375	2750	1925	2750	1925

	Method	Underdrain Trench Lining	Silt Fence	Filter Curtains
Elongation	D4632	20% Min	*	20% Max
Grab Strength, Ibs	D4632	44	550MD 450XD	900
Tear Strength, lbs	D4533	110	180	225
Puncture Strength, lbs	D6241	625	1225	1925

*≥50%, post spacing shall not exceed 1.2 m. Where Elongation is <50%, post spacing shall not exceed 2 m

Table 5.27. Summary of geotextile specifications from the State of Washington

Geotextile for Underground Drainage Strength Properties for Survivability						
			Low Survivability		Moderate Survivability	
	Method	Unit	Woven	Nonwoven	Woven	Nonwoven
Grab Tensile Strength	D4632	lb	180	115	250	160
Puncture Resistance	D6241	lb	370	220	495	310
Tear Strength	D4533	lb	67	40	80	50
Ultraviolet (UV) Radiation Stability	D4355	%	50			

Geotextile for Separation or Soil Stabilization						
			Separation		Soil Stabilization	
	Method	Unit	Woven	Nonwoven	Woven	Nonwoven
Grab Tensile Strength	D4632	lb	250	160	315	200
Puncture Resistance	D6241	lb	495	310	620	430
Tear Strength	D4533	lb	80	50	112	79
Ultraviolet (UV) Radiation Stability	D4355	%	50			

Geotextile for Permanent Erosion Control and Ditch Lining								
			Permanent Erosion Control				Ditch Lining	
			Moderate Survivability		High Survivability			
	Method	Unit	Woven	Nonwoven	Woven	Nonwoven	Woven	Nonwoven
Grab Tensile Strength	D4632	lb	250	160	315	200	250	160
Puncture Resistance	D6241	lb	495	310	620	430	495	310
Tear Strength	D4533	lb	80	50	112	79	80	50
Ultraviolet (UV) Radiation Stability	D4355	%	70 after 500h					

Geotextile Reinforcement Used in Geosynthetic Reinforced Slopes and Retaining Walls				
	Method	Unit	Woven	Nonwoven

Grab Tensile Strength	D4632	lb	200	120
Puncture Resistance	D6241	lb	370	220
Tear Strength	D4533	lb	63	50
Ultraviolet (UV) Radiation Stability	D4355	%	70 after 500h	

Table 5.28. Summary of geotextile specifications from the State of Wisconsin

	Method	Unit	SAS (Subgrade Aggregate Separation)	DF (Drainage Filtration) [a]	R (Riprap)	HR (Heavy Riprap)	C (Modified SAS)
grab tensile strength	D4632	lb	170	110, 180, 180[b]	205	305	205
puncture strength	D4833	lb	70	40, 70, 70[c]	80	100	70

a: Furnish fabric conforming with the physical requirements of either schedule A, schedule B, or schedule C as the contract specifies, **b**: schedule A, schedule B, schedule C, **c**: schedule A, schedule B, schedule C

Table 5.29. Summary of geotextile specifications from the State of Wyoming

	Method	Drainage & Filtration	Erosion Control	Silt Fence	Separation & Stabilization (Non-Woven)
Grab Tensile Strength, lb	D4632	100	180	100	160
Tear Strength, lb	D4533	45	70	50	60
Puncture Strength, lb	D4833	60	90	50	85

	Method	Embankment & Retaining Wall Reinforcement	Impermeable Plastic Membrane	Subgrade Reinforcement
Grab Tensile Strength, lb	D4632	300	150	250
Tear Strength, lb	D4533	110	50	110
Puncture Strength, lb	D4833	110	60	120

Chapter 6

Proposed Geotextile Specification Limits

This chapter presents a summary of test results correlation and comparison from the geotextile industry data. In addition, a set of proposed specification limits are presented based on WisDOT geotextiles types.

6.1 Geotextile Industry Data

Minimum average roll values (MARV) for a subset of the geotextiles tested in this project were found through research and data collection of vendor specification sheets. Table 6.1 and 6.2 show the results in context of the vendor provided MARV numbers. The research team also obtained additional data and information from geotextile manufacturers that included both CBR and pin puncture strength test data as well as published values of CBR and pin puncture strength. These new data obtained are summarized in Tables B1 and B2 in Appendix B. In addition, the data values are used to provide a comparison to the models developed based on the experimental study conducted herein.

Table 6.1 Comparison of Phase 1 to Industry MARV

Geotextile Material Type	ASTM Test	No. of Tests	Average Puncture Load, lbs (N)	Standard Deviation in Puncture Load, lbs (N)	Coefficient of Variation in Puncture Load (%)	Average Elongation, in (mm)
A (nonwoven) 4 oz/yd^2	D4833	15	73 (324)	10 (43)	13.3	0.50 (12.7)
	D6241	10	362 (1611)	41 (184)	11.4	1.89 (48.0)
	D6241/D4833 Ratio: 4.9					
	MARV-D6241 Puncture load, lbs (N) : 250 (1113)					
B (woven) 4 oz/yd^2	D4833	15	100 (443)	7 (29)	6.6	0.35 (8.9)
	D6241	10	733 (3261)	20 (92)	2.8	1.40 (35.6)
	D6241/D4833 Ratio: 7.3					
	MARV-D6241 Puncture load, lbs (N) : 700 (3115)					
C	D4833	15	115 (510)	21 (93)	18.3	0.46 (11.7)

(nonwoven) 8 oz/yd^2	D6241	15	595 (2648)	57 (255)	9.6	1.88 (47.8)
	D6241/D4833 Ratio: 5.2					
	MARV-D6241 Puncture load, lbs (N) : 500 (2224)					
D (woven) 8 oz/yd^2	D4833	10	178 (790)	18 (81)	10.3	0.46 (11.7)
	D6241	15	1392 (6190)	151 (673)	10.9	1.44 (36.6)
	D6241/D4833 Ratio: 7.8					
	MARV-D6241 Puncture load, lbs (N) : 1250 (5563)					
E (nonwoven) 12 oz/yd^2	D4833	10	240 (1069)	16 (73)	6.8	0.59 (15.0)
	D6241	15	1268 (5642)	101 (451)	8.0	2.47 (62.7)
	D6241/D4833 Ratio: 5.3					
	MARV-D6241 Puncture load, lbs (N) : 900 (4005)					

Table 6.2: Comparison of Phase 2 test values to industry MARV

Fabric Type	Project Number and Date	Vendor/Type	MARV			Testing – Average Values			
			D4833 MARV	D6241 MARV	D6241/D4833 Ratio-MARV	D4833 (N) -WISDOT	D4833 (N) - UWM	D6241 (N) - UWM	D6241/D4833 Ratio-UWM
DF	1195-13-71	Propex Geotex 401 (non-woven)	289	1380	4.8	213	148	950	6.5
DF	1170-01-70	Willacochee Industrial Fabrics, Winfab 400N (non-woven)	289	1380	4.8	227	158	627	4.0
DF	9200-04-71	Hanes Geo Components Terra Tex N07 (non-woven)	467	2110	4.5	472	499	2759	5.5
DF	1030-11-70	Tencate – Mirafi 140N (non-woven)	300	1380	4.6	480	463	2600	5.6

DF	2753-06-71	Geosynthetics ST180N (non-woven)	467	-	-	452	295	1084	3.7
DF	1060-33-73	Propex Geotex 701 (non-woven)	445	2047	4.6	497	274	880	3.2
SAS	1133-03-71	Propex 701 (non-woven)	445	2113	4.7	509	342	1731	5.1
SAS	8160-14-71	Geosynthetics ST180N (non-woven)	467	-	-	465	300	1312	4.4
SAS	1060-33-75	Tencate Mirafi 170N (non-woven)	460	2003	4.4	540	391	1845	4.7

6.2 Experimental Data Based Models

The results of the experimental data obtained from Phase I and II for both woven and nonwoven geotextiles are summarized in Table 6.3 (see Figures 4.30 to 4.35 in Chapter 4).

Table 6.3: Correlations between CBR and pin puncture strength based on the experimental test results.

Geotextile Test Result		**Correlation: PS(CBR) = α × PS(Pin)**	**R^2**
Phase I	Woven	PS(CBR) = 7.46 × PS(Pin)	0.98
	Nonwoven	PS(CBR) = 5.19 × PS(Pin)	0.98
Phase II	Woven	PS(CBR) = 4.28 × PS(Pin)	0.85
	Nonwoven	PS(CBR) = 5.57 × PS(Pin)	0.85
Combined (Phase I and Phase II)	Woven	PS(CBR) = 6.36 × PS(Pin)	0.91
	Nonwoven	PS(CBR) = 4.90 × PS(Pin)	0.92

PS(CBR): CBR Puncture Strength (N, lbs) from ASTM D6241
PS(Pin): Pin Puncture Strength (N, lbs) from ASTM D4833
α: Correlation Constant

These models have a good coefficient of correlation values and will be used to propose the average minimum limits for geotextile CBR puncture strength for WisDOT. The current pin puncture strength based WisDOT specifications are summarized in Table 6.4.

The results of the nonwoven geotextiles in Phase I & II (***PS(CBR) = 4.90 × PS(Pin)***) are selected to propose for the specifications. These results have a 0.92 coefficient of determination, which is a good correlation with the largest number of test points of 142. Further, using this set of data does not bias the factor to the woven specimens which achieve the highest benefit from moving to the CBR standard. The data obtained from the geotextile industry tests/specifications are compiled and presented in Figure 6.1. The results show that the data compiled from the industry is within a reasonable agreement of the models presented in this report. The analysis of geotextile industry data for the nonwoven geotextiles showed the following correlations: ~ ***PS(CBR) = 4.75 × PS(Pin)***, which is a reasonable outcome compared with the model obtained from the experimental test results. Additionally as a result of the phase III additional tests conducted, we include a recommendation to include a minimum UV stability for the geotextiles based on possible exposure in the field.

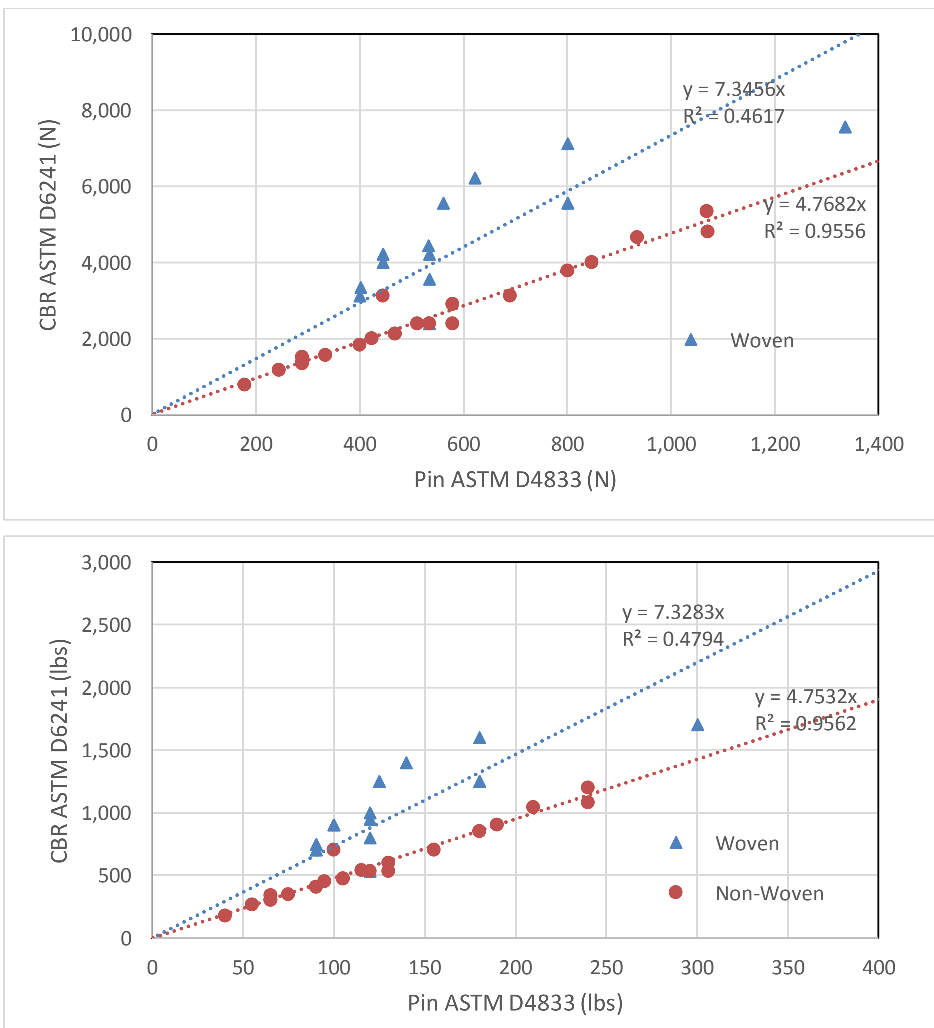


Figure 6.1 Industry data shown for comparative purposes (in SI and U.S. customary units)

Table 6.4 Current and proposed WisDOT specification limits

Geotextile Type	Minimum Puncture Strength (Average)			
	Current WisDOT Specifications Based on ASTM D4833 (Pin)		Proposed WisDOT Specifications Based on ASTM D6241 (CBR)	
	lbs.	N	lbs.	N
Subgrade Aggregate Separation (SAS)	70	300	340	1500
Marsh Stabilization (MS)	NA	NA	NA	NA
Drainage Filtration (DF), Schedule A	40	175	190	840
Drainage Filtration (DF), Schedule B	70	300	340	1500
Drainage Filtration (DF), Schedule C	70	311	340	1500
Subgrade Reinforcement (SR)	NA (145)*	NA (650)*	NA (700)**	NA(3100)**
Riprap (R)	80	350	390	1700
Heavy Riprap (HR)	100	440	490	2100
Modified Subgrade Aggregate Separation Type C (SAS-C)	70	300	340	1500
Embankment Stabilization (ES)	NA	NA	NA	NA
UV Radiation Stabilization ASTM D4355 for 500 hours of exposure – 50% Retention of Strength				

* Specification values are obtained from WisDOT project documents.

** Based on same data from WisDOT project documents

Chapter 7

Summary

The results from Phase 1 and II show that the CBR puncture strength can possibly be predicted for woven and nonwoven PP materials. The Woven PP materials exhibit a CBR puncture strength approximately double that of nonwoven PP materials with the same mass per unit area. The CBR displacement/elongation at puncture failure is determined by weave type rather than mass per unit area for PP materials. D6241 appears to correlate more with the weight of the fabric. We also found that the CBR puncture strength failure of a woven material is likely a function of filament tensile strength and CBR failure of nonwoven materials is a function of fiber-fiber contact area. When the results from D4833 are compared with the obtained values from WisDOT using the same standard, we see similar results obtained. Industry obtained minimum average roll value (MARV) numbers for both methods show similar correlations to the results obtained. The results also show consistent higher values for D6241 compared to the values from D4833. The outliers with high strength from the D6241 approach sometimes correlate with the higher strength (e.g. Group5 SAS), however in other cases (e.g. in the DF) series we do not see this correlation. Finally, in the proposed specifications in Chapter 6 we recommend values based on the correlations obtained in this report to enable and justify transitions to the new ASTM D6241 standard.

References

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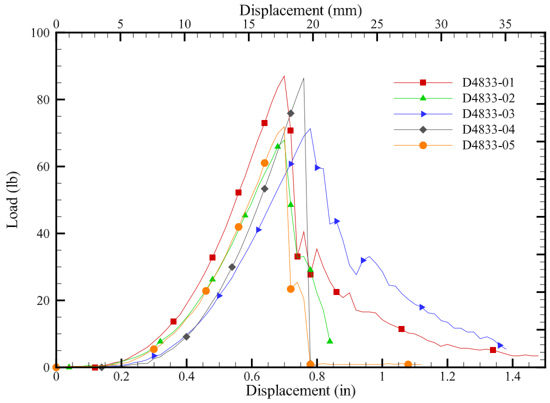
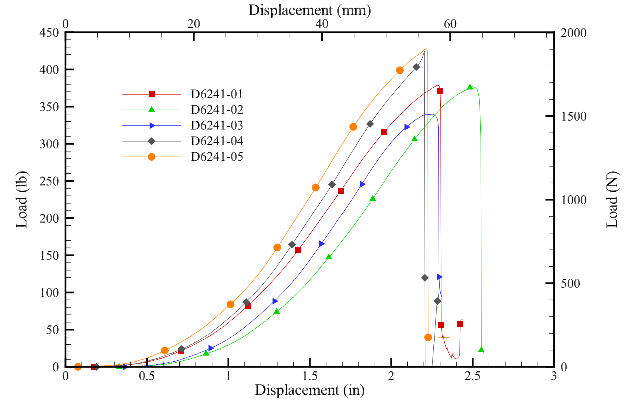
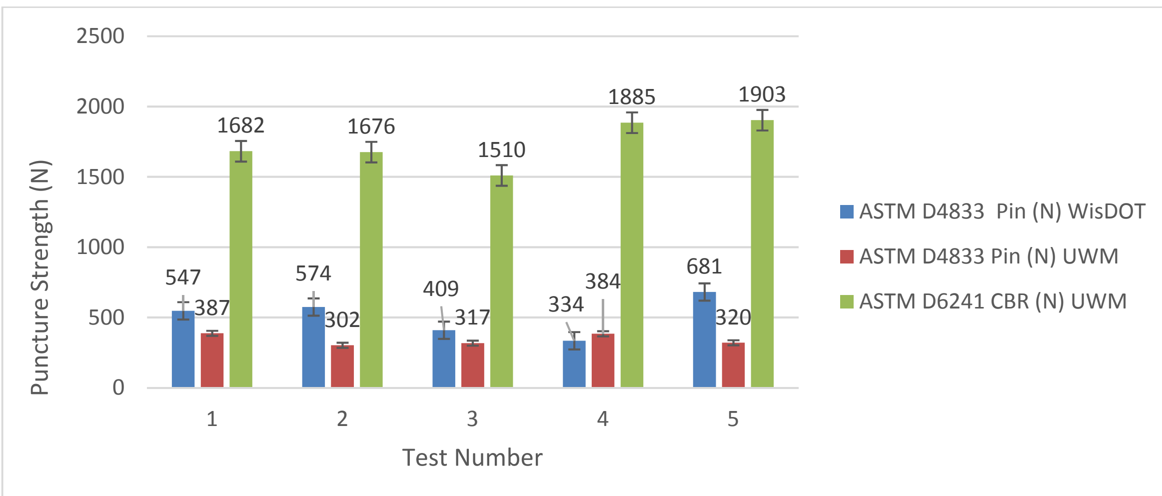


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

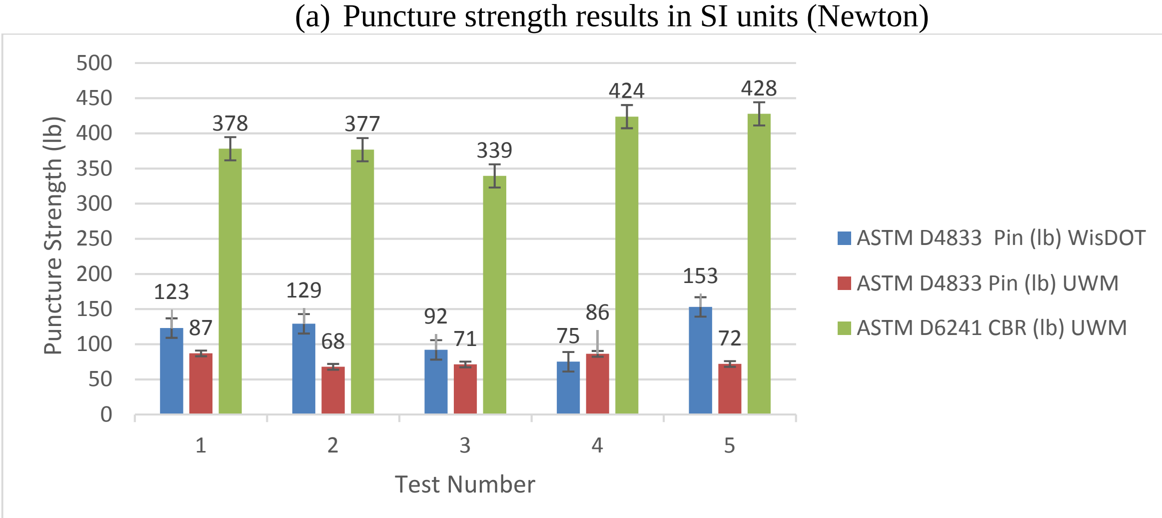


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-1: Pin and CBR puncture strength tests for geotextile specimens – fabric type SAS, project number 1133-03-71 – manufactured by PROPEX701

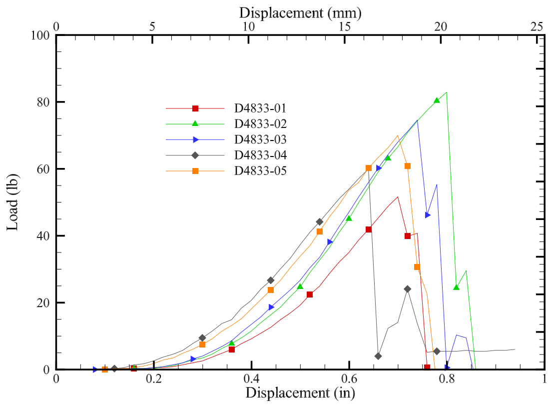


(a) Puncture strength results in SI units (Newton)

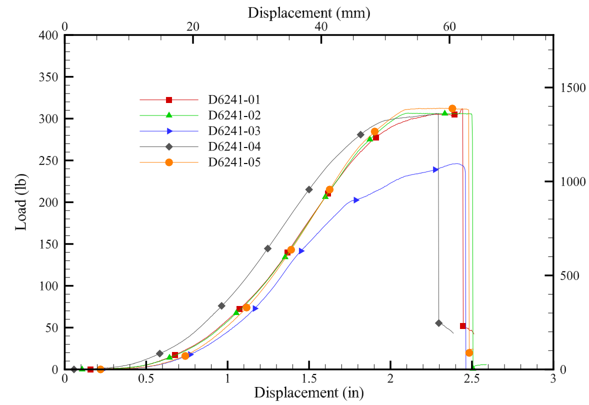


(b) Puncture strength results in U.S. units (Pound)

Figure A-2: Pin and CBR puncture strength tests for geotextile specimens – fabric type SAS, project number 1133-03-71 – manufactured by PROPEX701



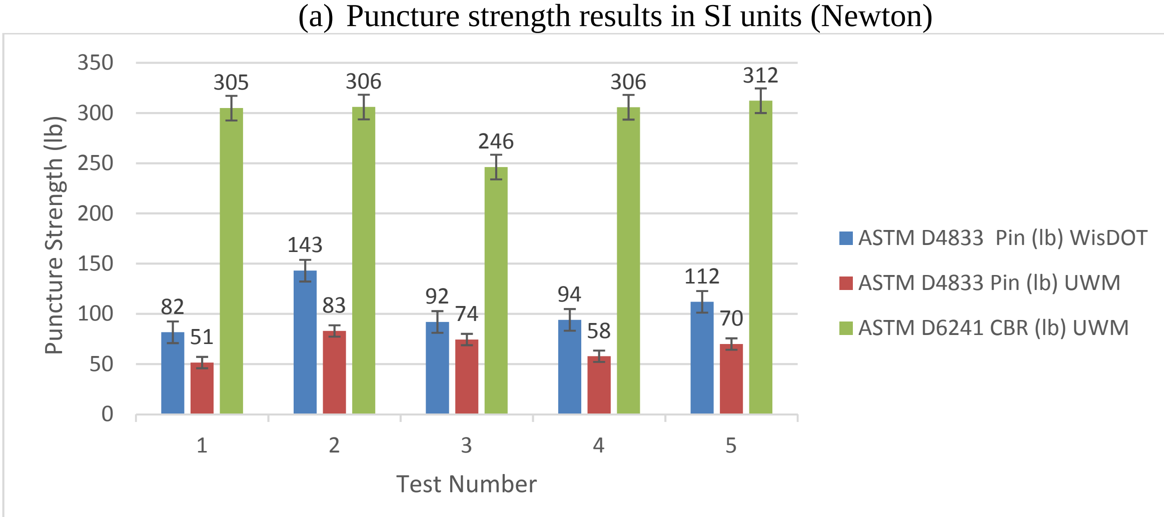
(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test



(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

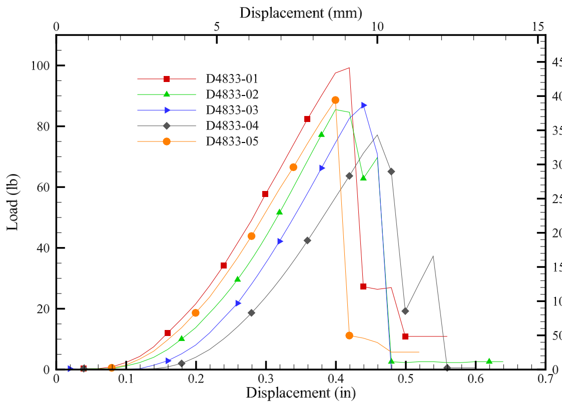
Figure A-3: Pin and CBR puncture strength tests for geotextile specimens – fabric type SAS, project number 8160-14-71 – manufactured by Geo Synthetics-LLC

(a) Puncture strength results in SI units (Newton)

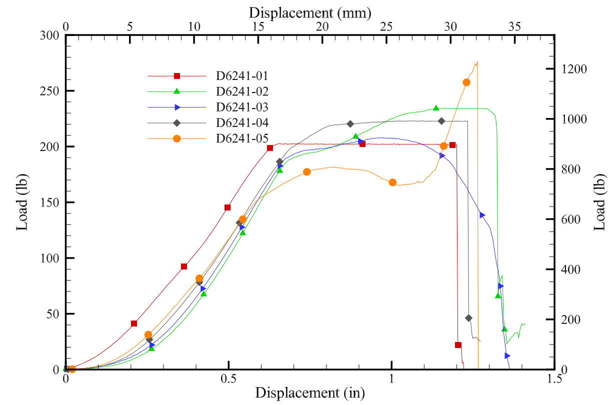


(b) Puncture strength results in U.S. units (Pound)

Figure 4.A-4: Pin and CBR puncture strength tests for geotextile specimens – fabric type SAS, project number 8160-14-71 – manufactured by Geo Synthetics-LLC

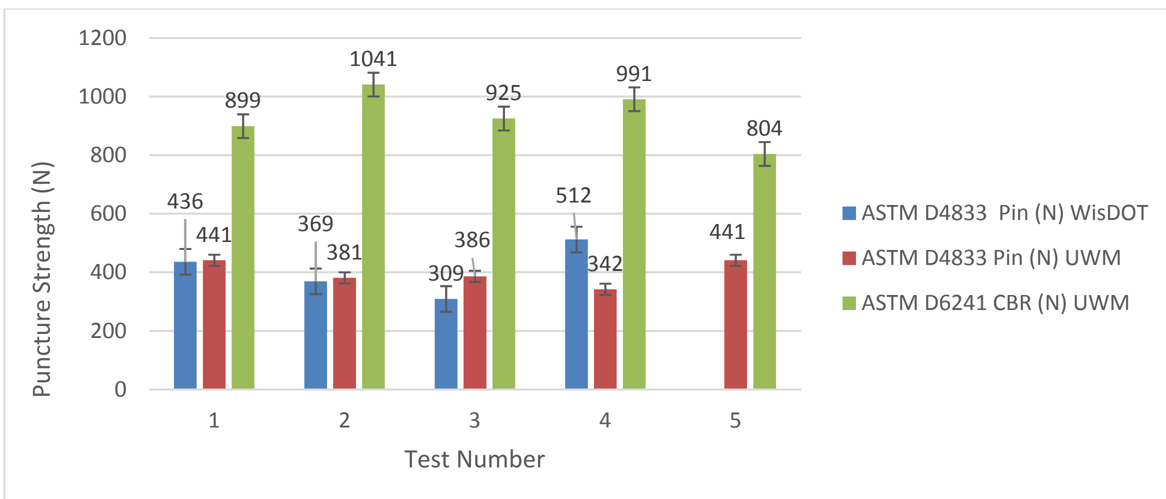


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

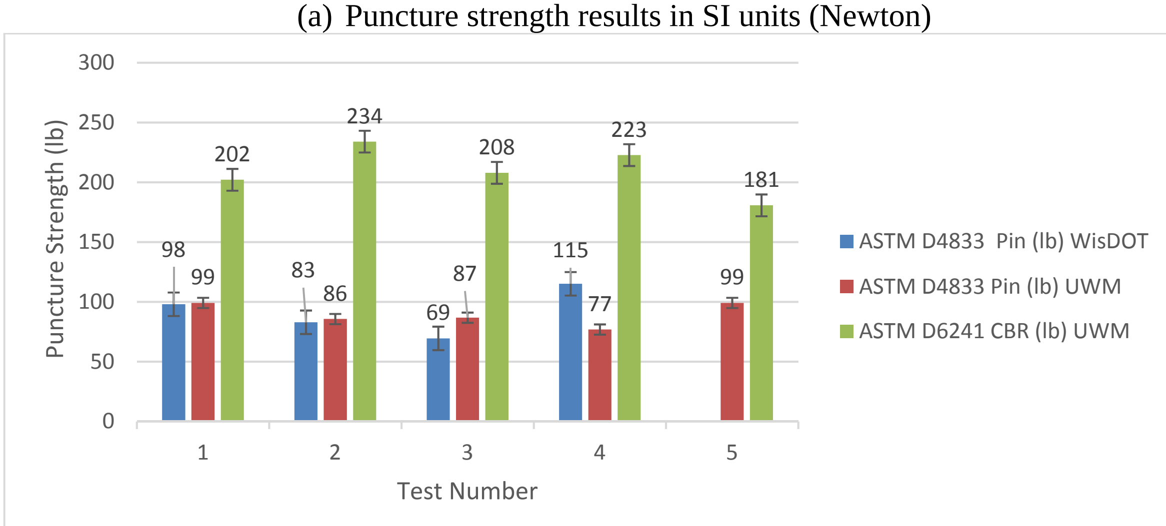


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-5: Pin and CBR puncture strength tests for geotextile specimens – fabric type SAS, project number 5658-00-75 – manufactured by Tencate Mirafi 600x

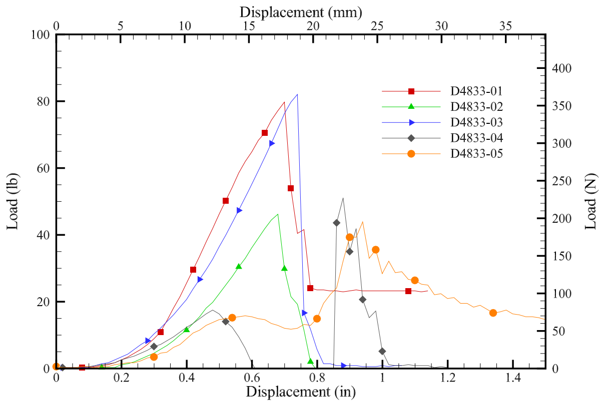


(a) Puncture strength results in SI units (Newton)

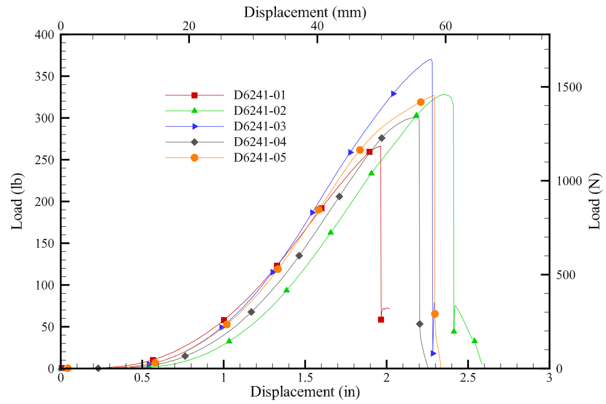


(b) Puncture strength results in U.S. units (Pound)

Figure A-6: Pin and CBR puncture strength tests for geotextile specimens – fabric type SAS, project number 5658-00-75 – manufactured by Tencate Mirafi 600x

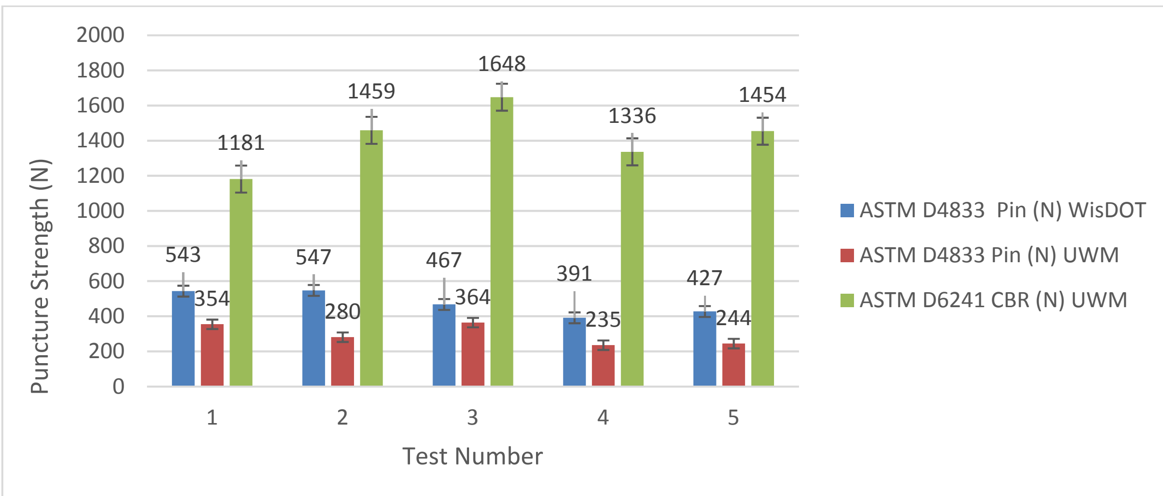


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

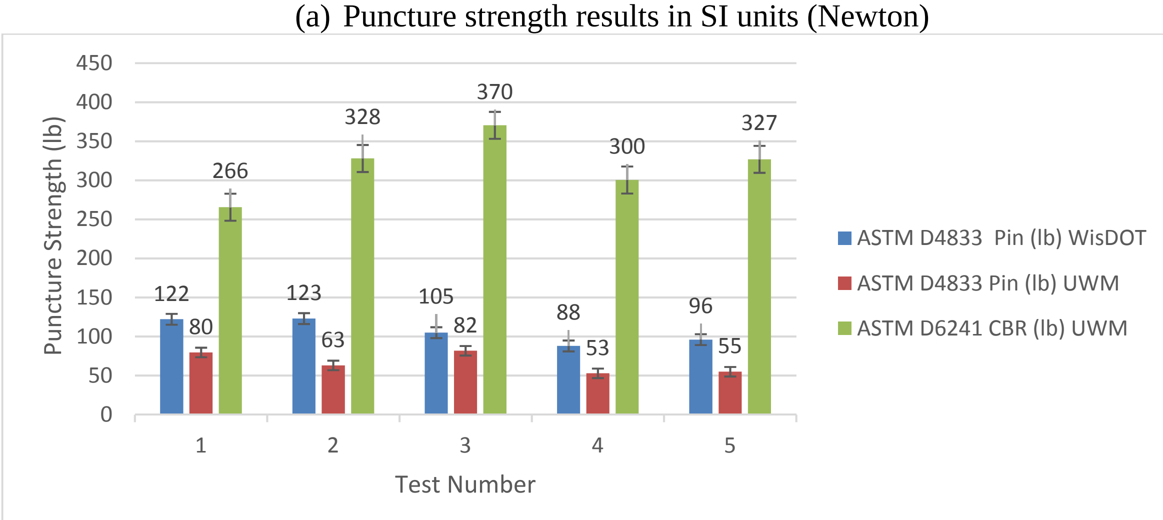


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-7: Pin and CBR puncture strength tests for geotextile specimens – fabric type SAS, project number – manufactured by X1

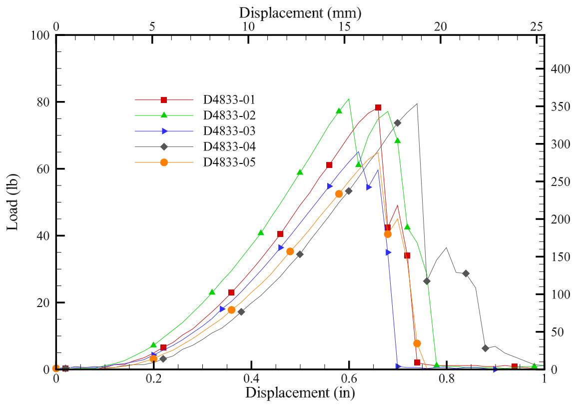


(a) Puncture strength results in SI units (Newton)

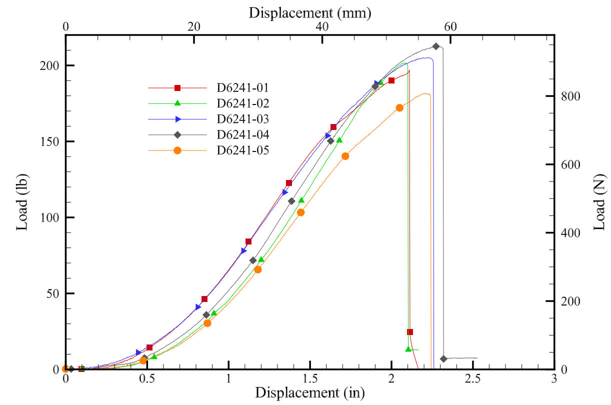


(b) Puncture strength results in U.S. units (Pound)

Figure A-8: Pin and CBR puncture strength tests for geotextile specimens – fabric type SAS, project number – manufactured by X1

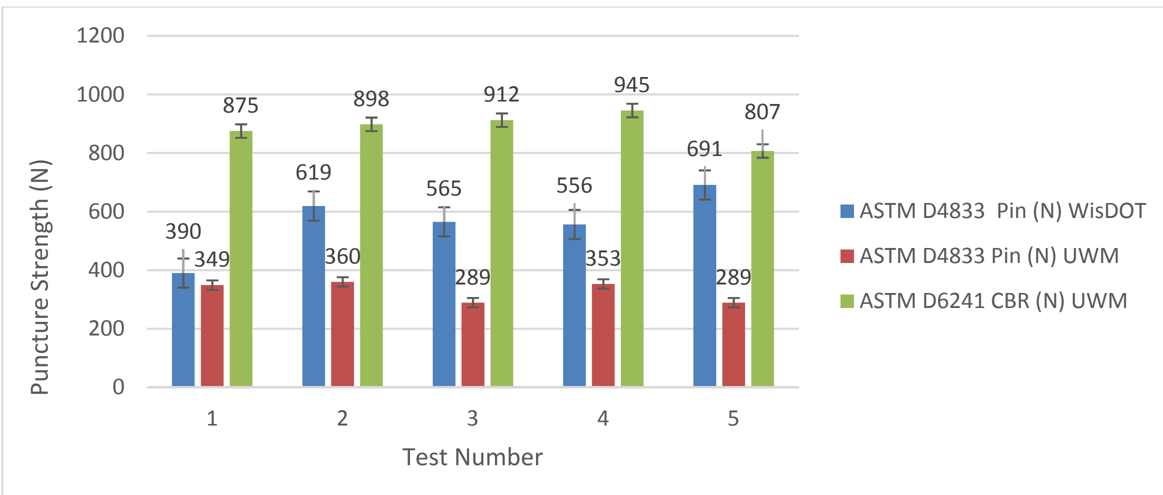


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

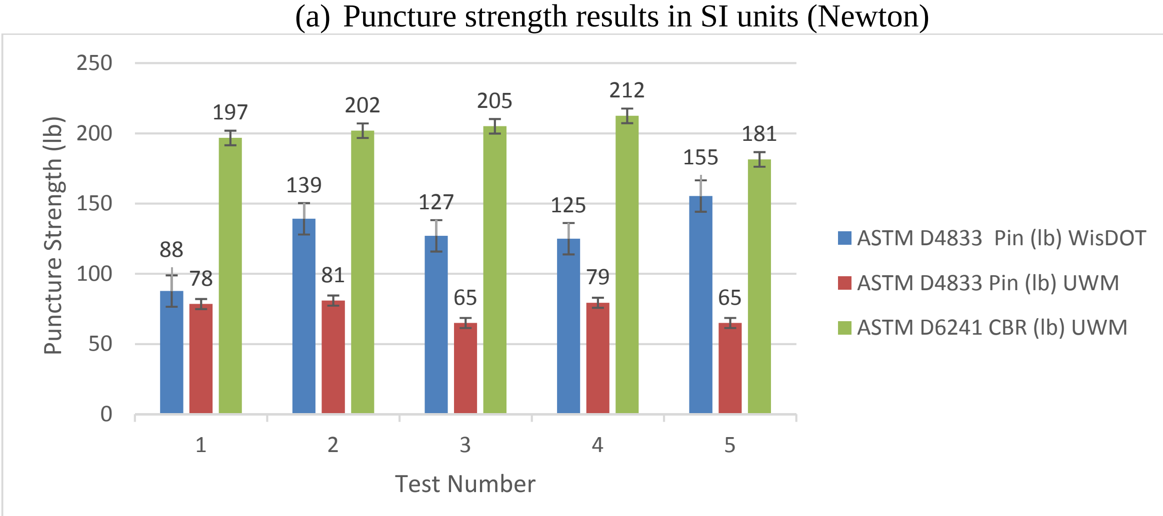


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-9: Pin and CBR puncture strength tests for geotextile specimens – fabric type SAS, project number 1030 -11 -70– manufactured by X1

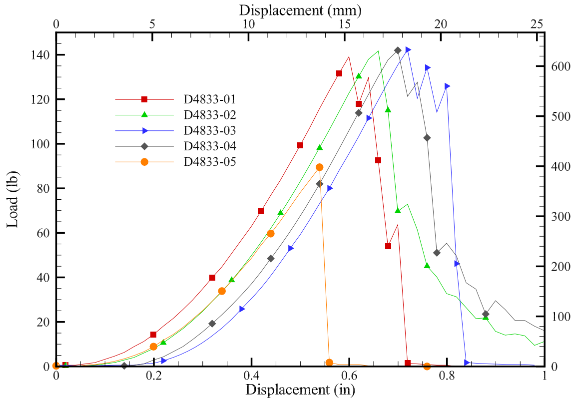


(a) Puncture strength results in SI units (Newton)

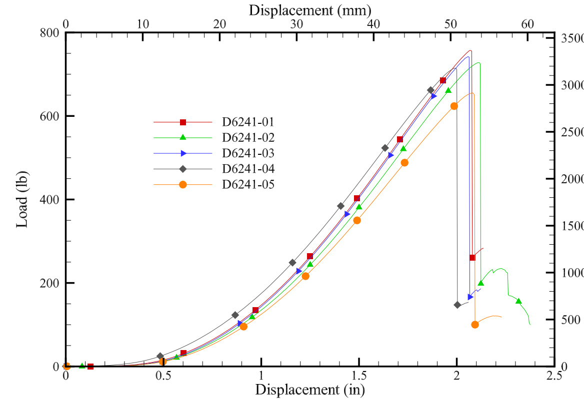


(b) Puncture strength results in U.S. units (Pound)

Figure A-10: Pin and CBR puncture strength tests for geotextile specimens – fabric type SAS, project number 1030 -11 -70– manufactured by X1

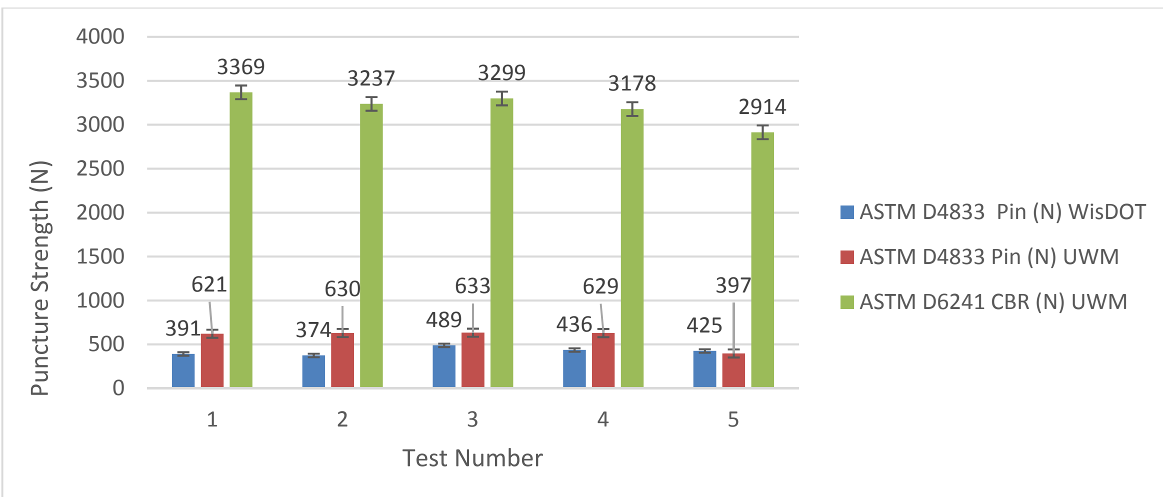


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

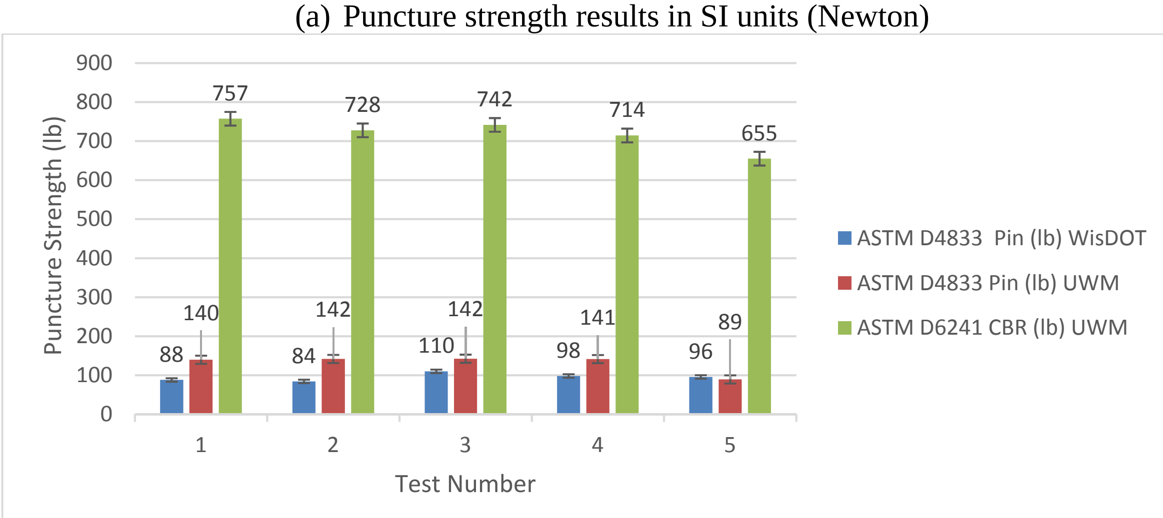


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-11: Pin and CBR puncture strength tests for geotextile specimens – fabric type SAS, project number – manufactured by WESTERN EXCELSIOR CORP

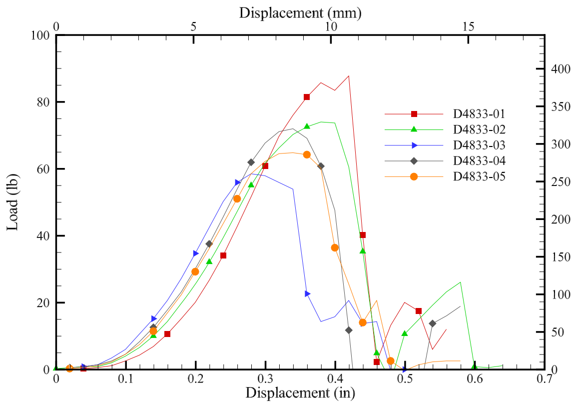


(a) Puncture strength results in SI units (Newton)

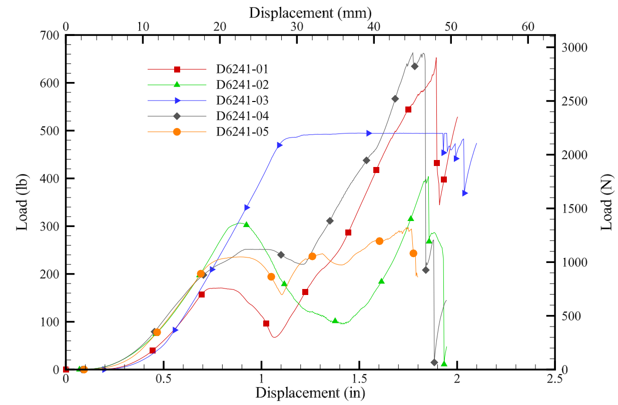


(b) Puncture strength results in U.S. units (Pound)

Figure A-12: Pin and CBR puncture strength tests for geotextile specimens – fabric type SAS, project number – manufactured by WESTERN EXCELSIOR CORP

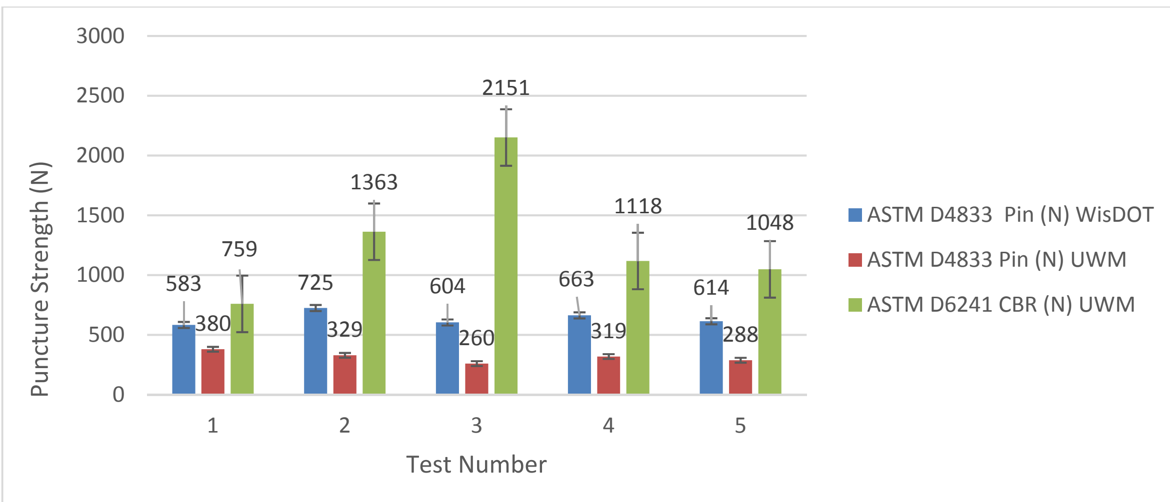


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

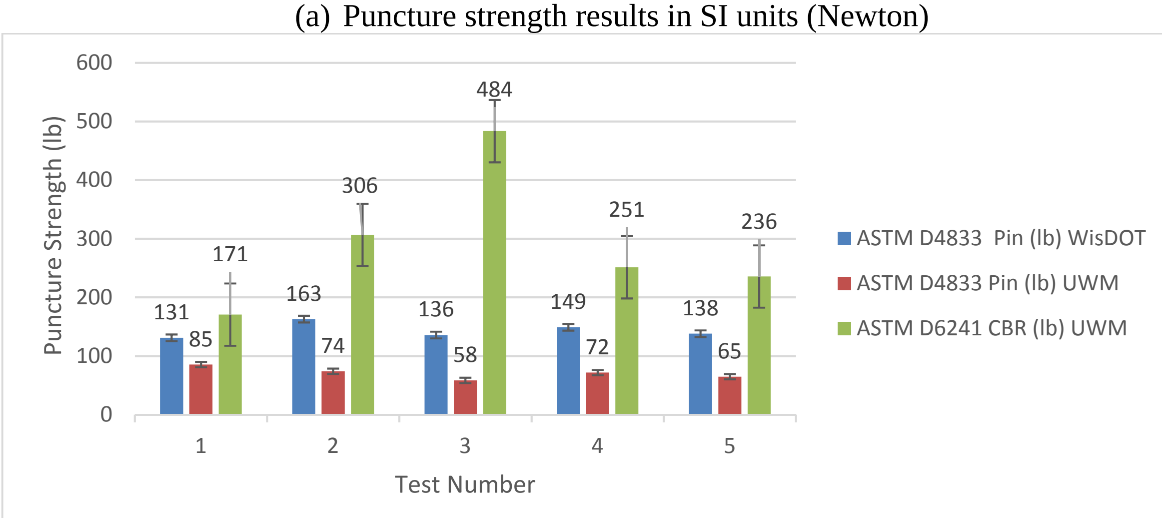


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-13: Pin and CBR puncture strength tests for geotextile specimens – fabric type MS, project number 6968-01-70– manufactured by TENCATE MIRAT

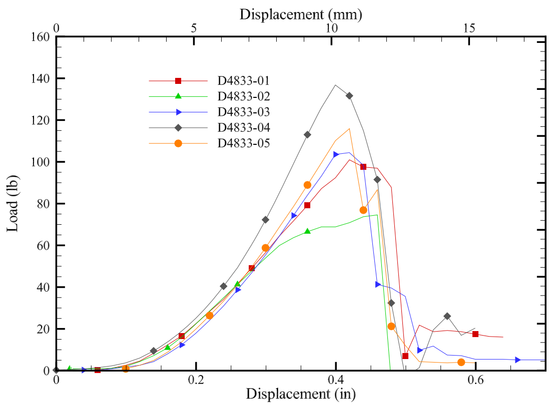


(a) Puncture strength results in SI units (Newton)

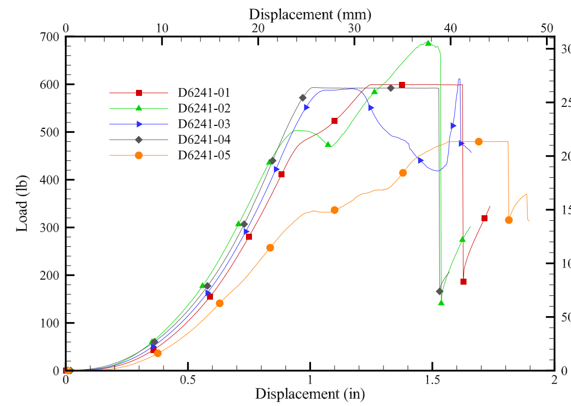


(b) Puncture strength results in U.S. units (Pound)

Figure A-14 Pin and CBR puncture strength tests for geotextile specimens – fabric type MS, project number 6968-01-70– manufactured by TENCATE MIRAT

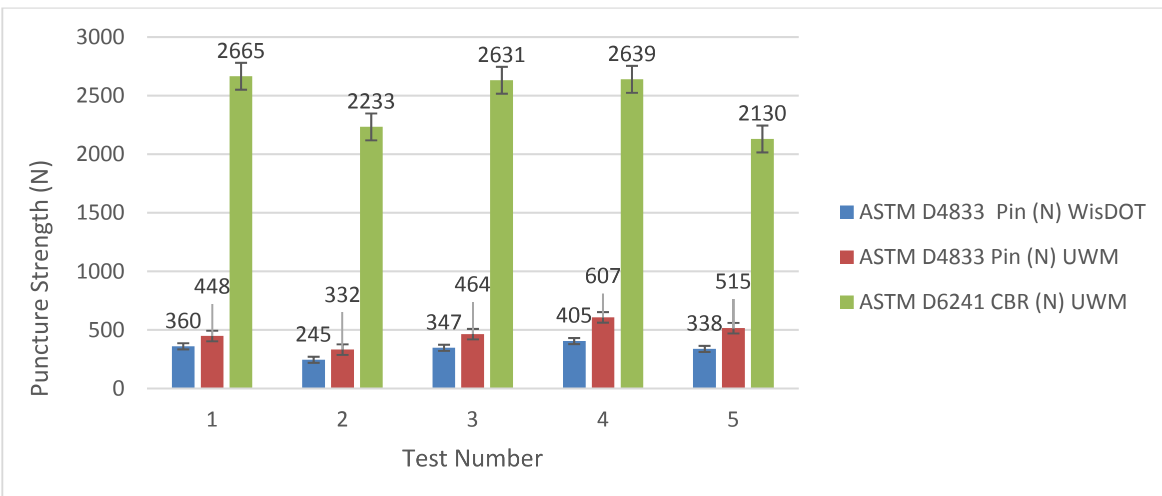


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

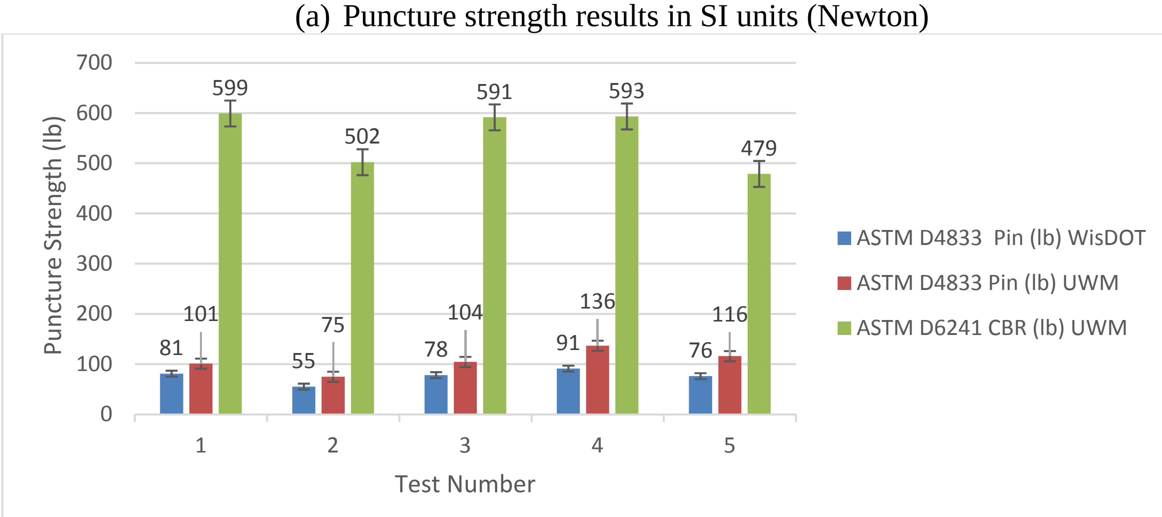


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-15: Pin and CBR puncture strength tests for geotextile specimens – fabric type MS, project number– manufactured by TENCATE

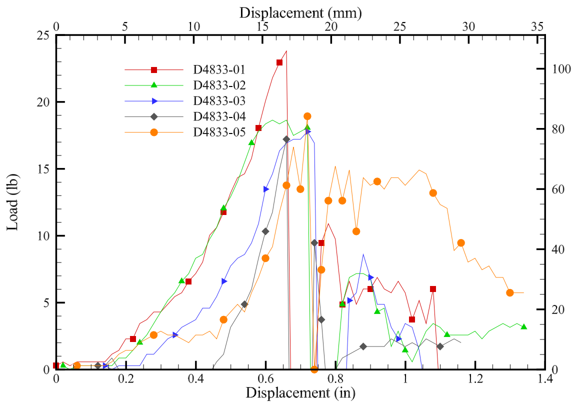


(a) Puncture strength results in SI units (Newton)

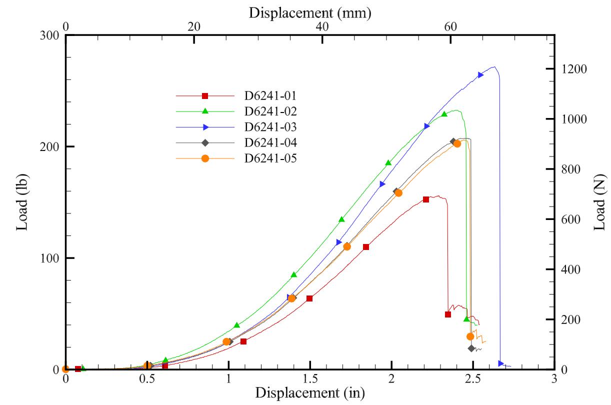


(b) Puncture strength results in U.S. units (Pound)

Figure A-16 Pin and CBR puncture strength tests for geotextile specimens – fabric type MS, project number– manufactured by TENCATE

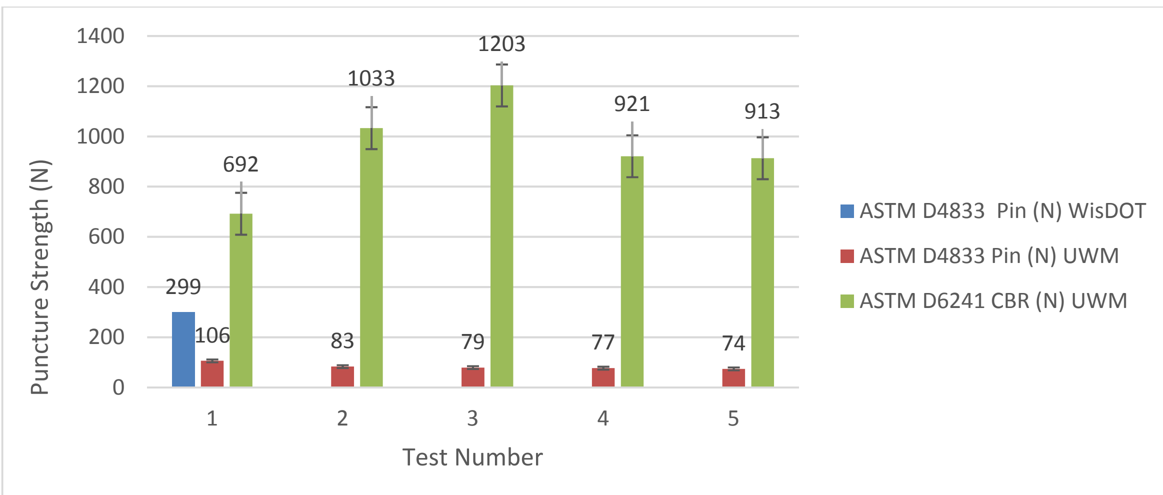


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

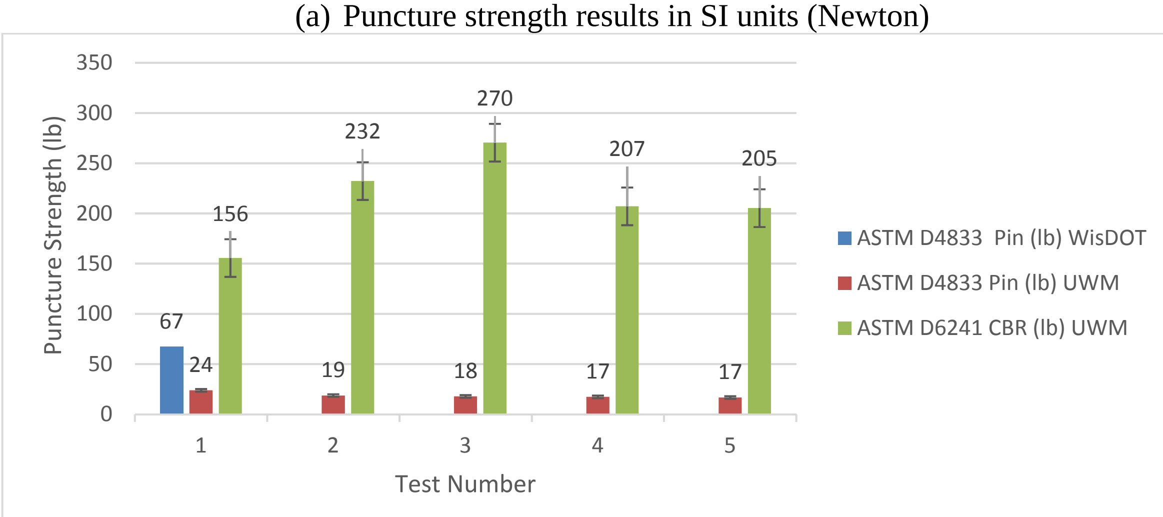


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-17: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1195-13-71– manufactured by PROPEK GEOTEX

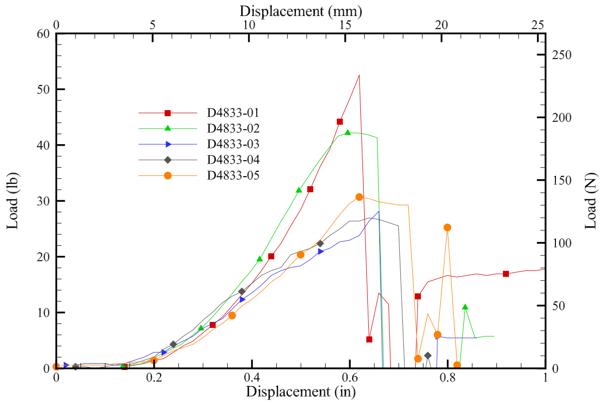


(a) Puncture strength results in SI units (Newton)

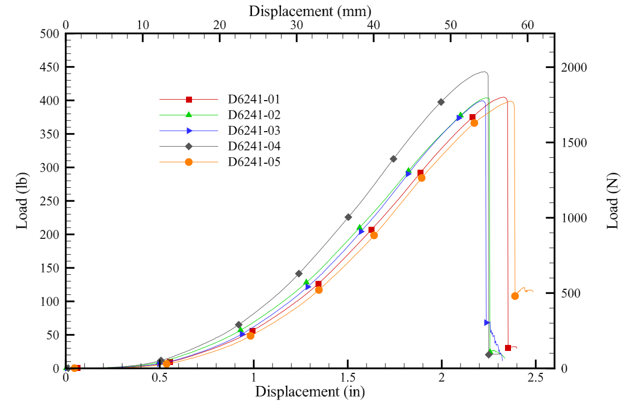


(b) Puncture strength results in U.S. units (Pound)

Figure A-18: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1195-13-71– manufactured by PROPEK GEOTEX

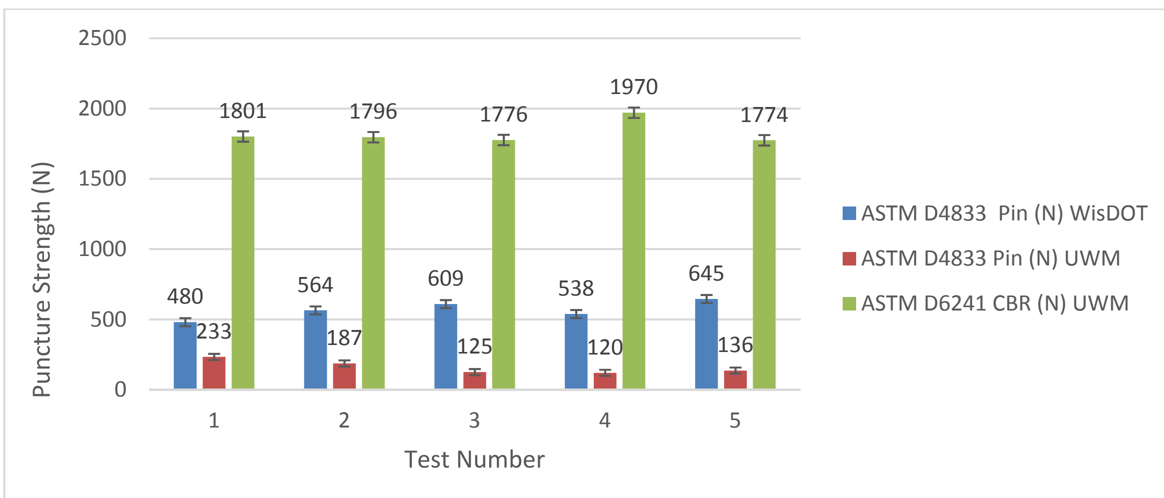


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

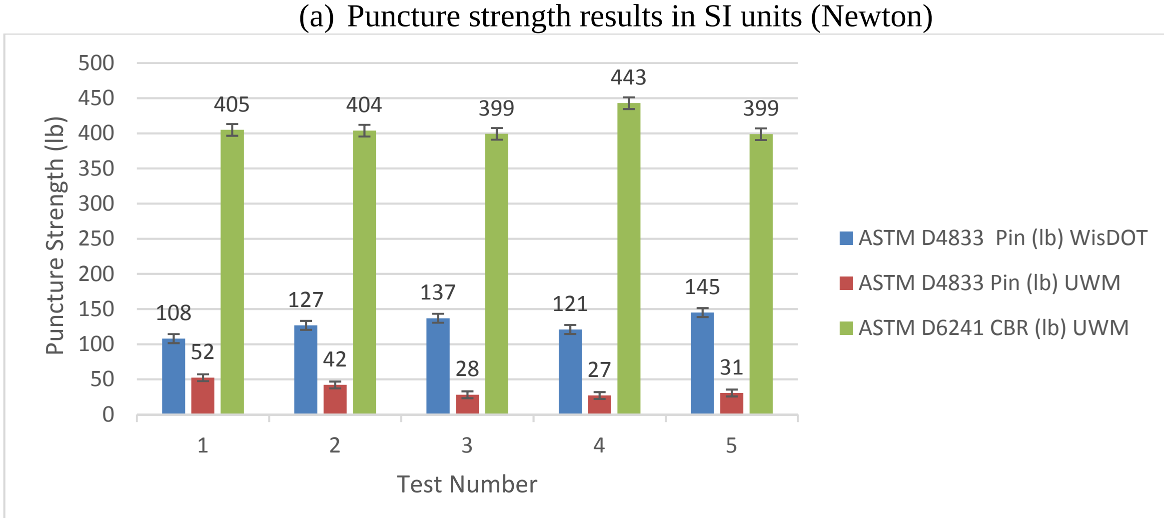


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-19: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1030-11-70 – manufactured by TENCATE

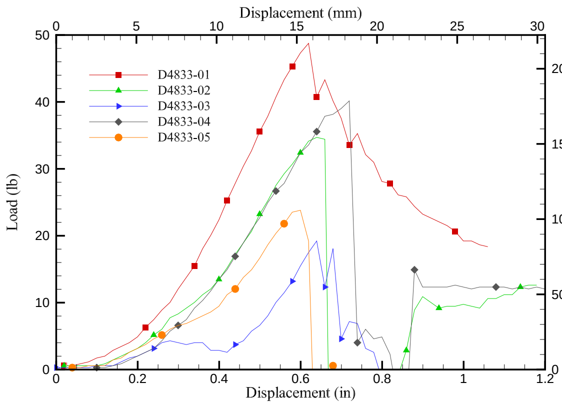


(a) Puncture strength results in SI units (Newton)

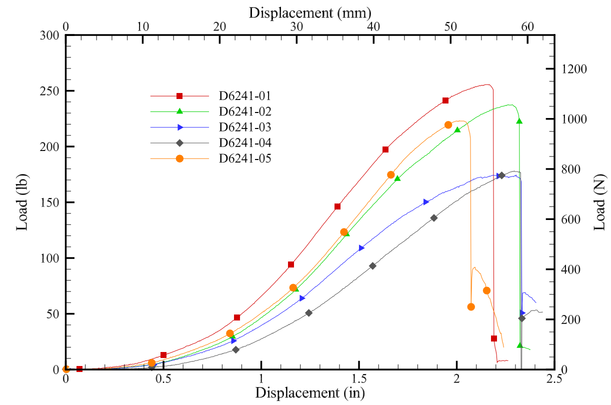


(b) Puncture strength results in U.S. units (Pound)

Figure A-20: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1030-11-70 – manufactured by TENCATE

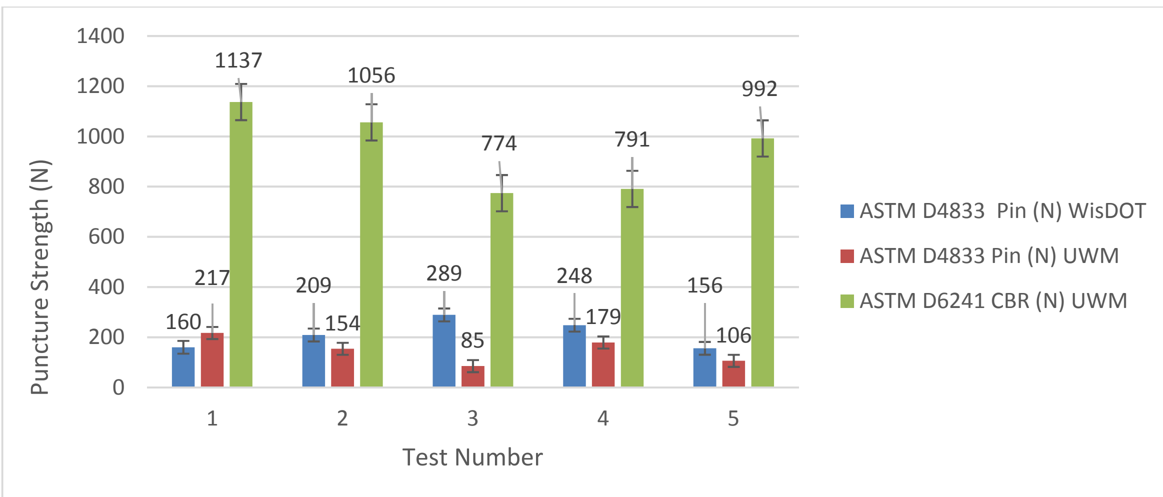


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

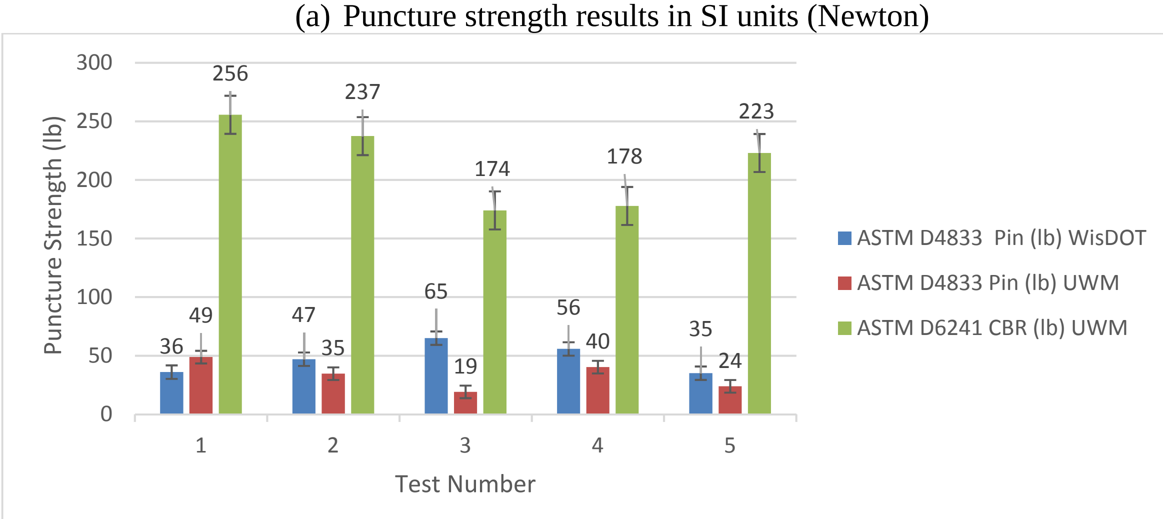


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-21: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1195-13-71 – manufactured by PROPEX GEOTEX 401

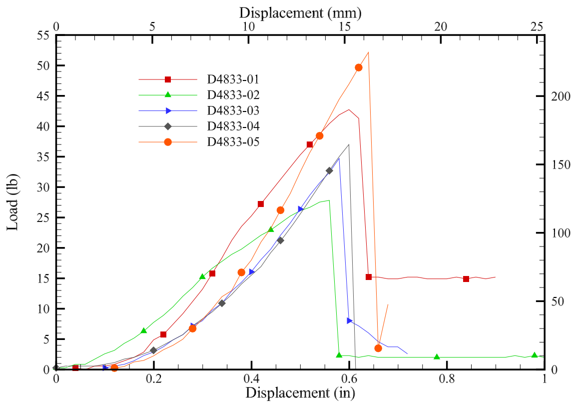


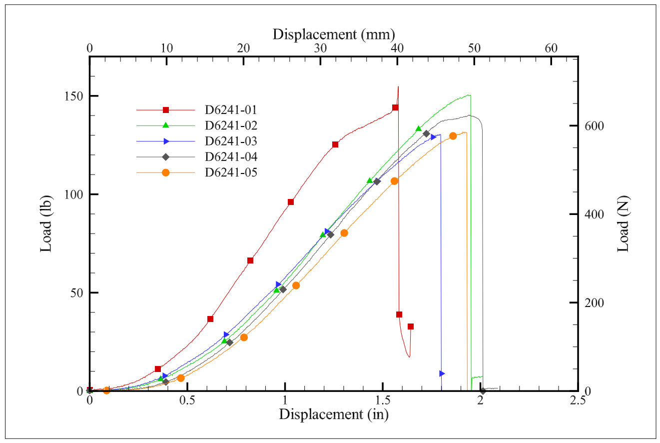
(a) Puncture strength results in SI units (Newton)



(b) Puncture strength results in U.S. units (Pound)

Figure A-22: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1195-13-71 – manufactured by PROPEX GEOTEX 401

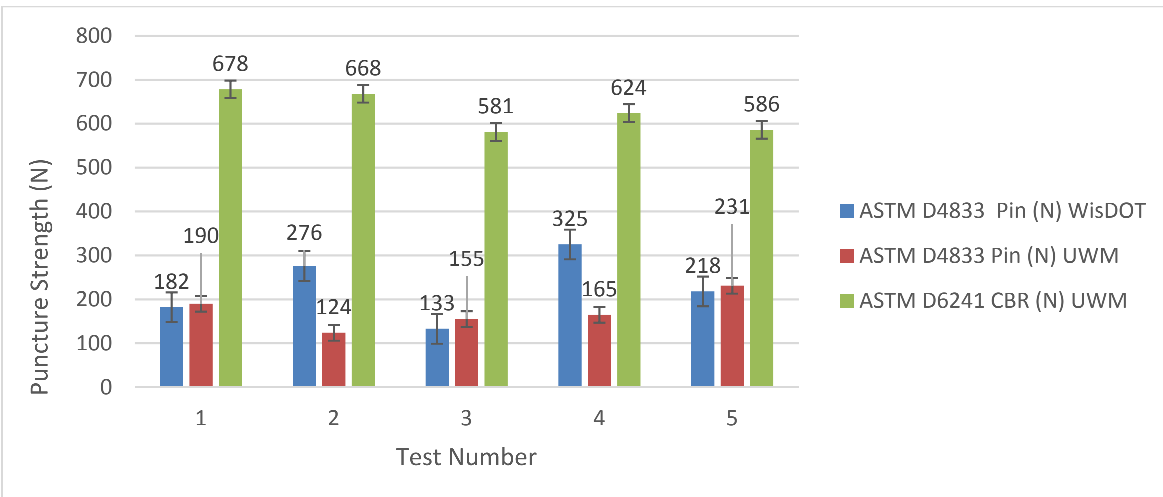




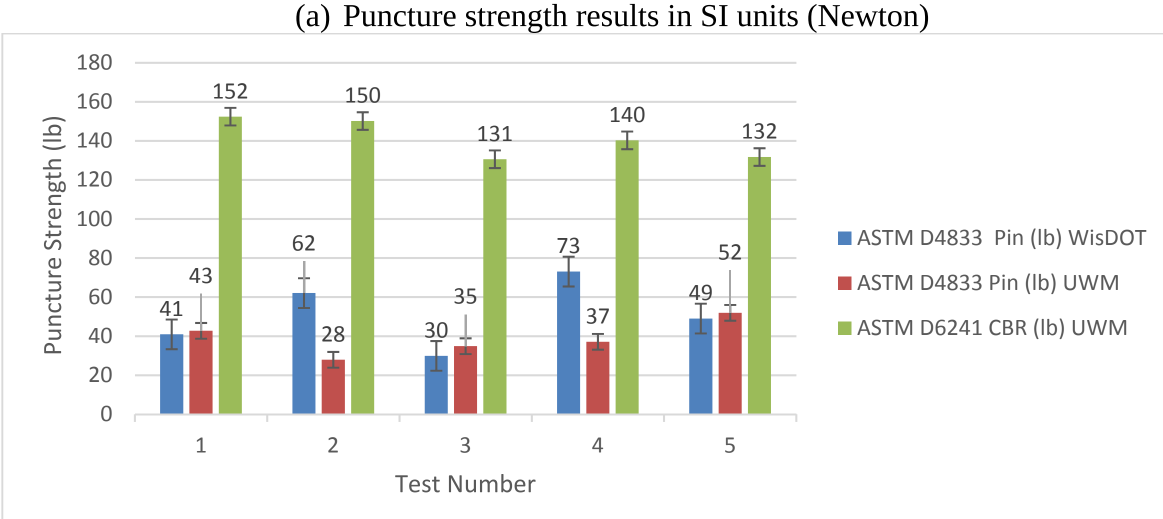
(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-23: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1170-01-70– manufactured by WILLACOOCHEE INDUSTRIAL FABRICS

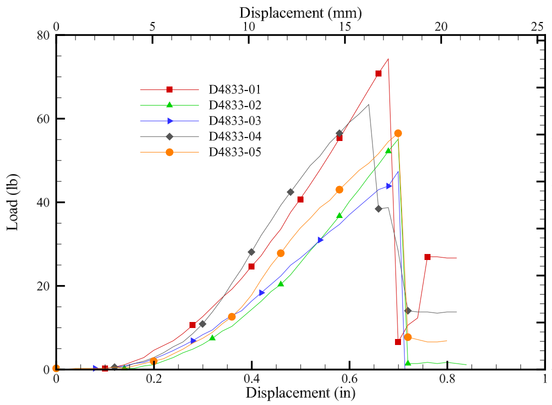


(a) Puncture strength results in SI units (Newton)

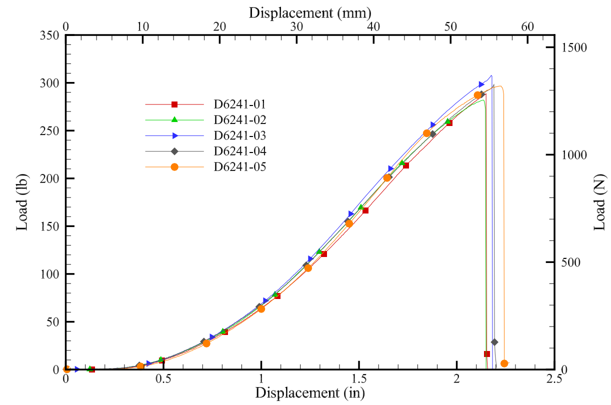


(b) Puncture strength results in U.S. units (Pound)

Figure A-24: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1170-01-70– manufactured by WILLACOOCHEE INDUSTRIAL FABRICS

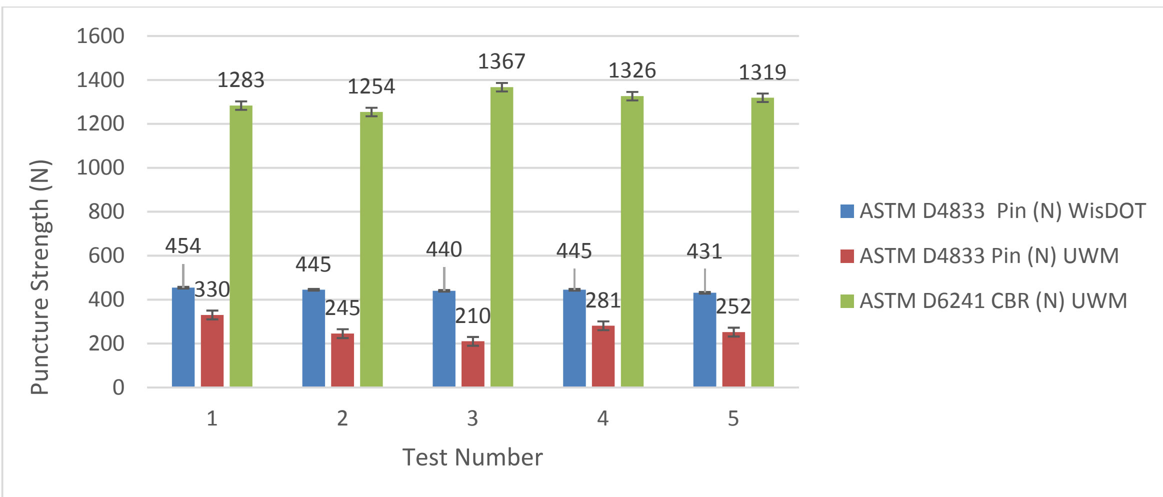


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

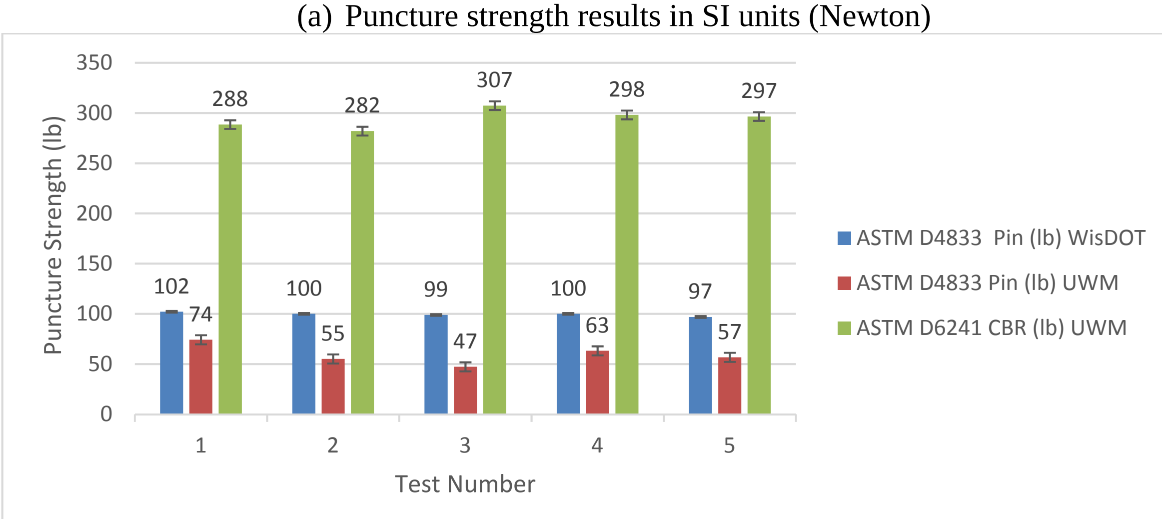


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-25: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1206-07-77 – manufactured by THRACE LINQ

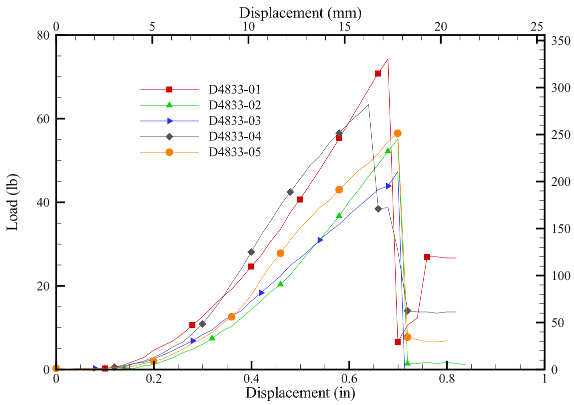


(a) Puncture strength results in SI units (Newton)

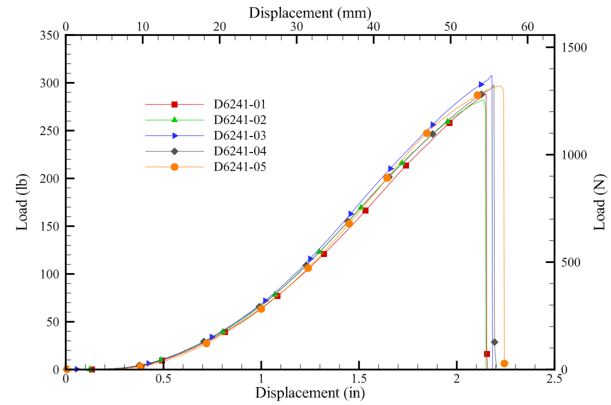


(b) Puncture strength results in U.S. units (Pound)

Figure A-26: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1206-07-77 – manufactured by THRACE LINQ

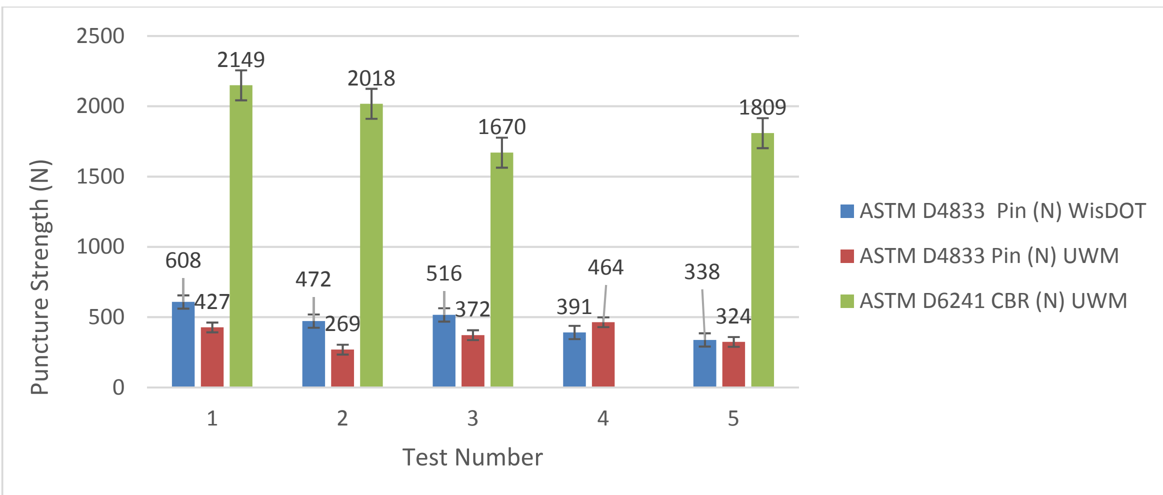


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

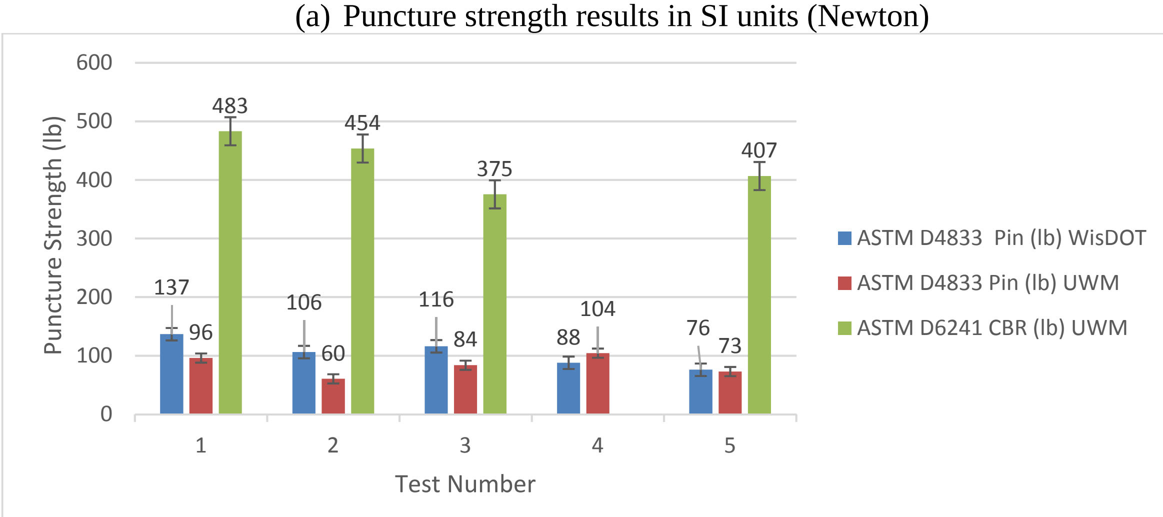


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-27: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number – manufactured by TENCATE

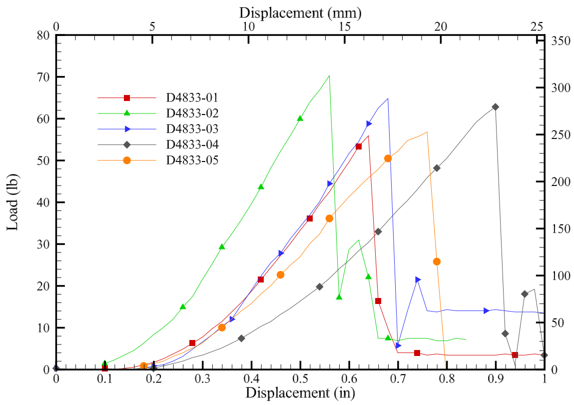


(a) Puncture strength results in SI units (Newton)

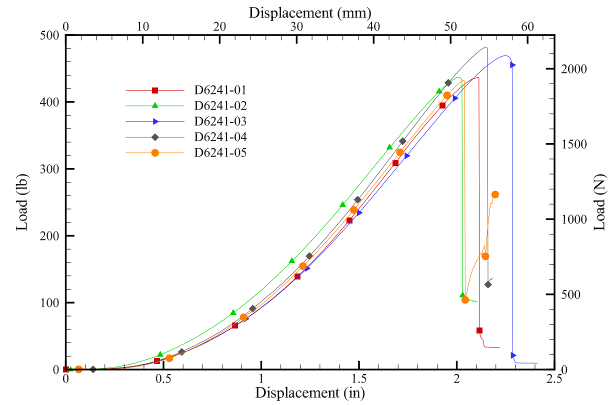


(b) Puncture strength results in U.S. units (Pound)

Figure A-28: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number – manufactured by TENCATE

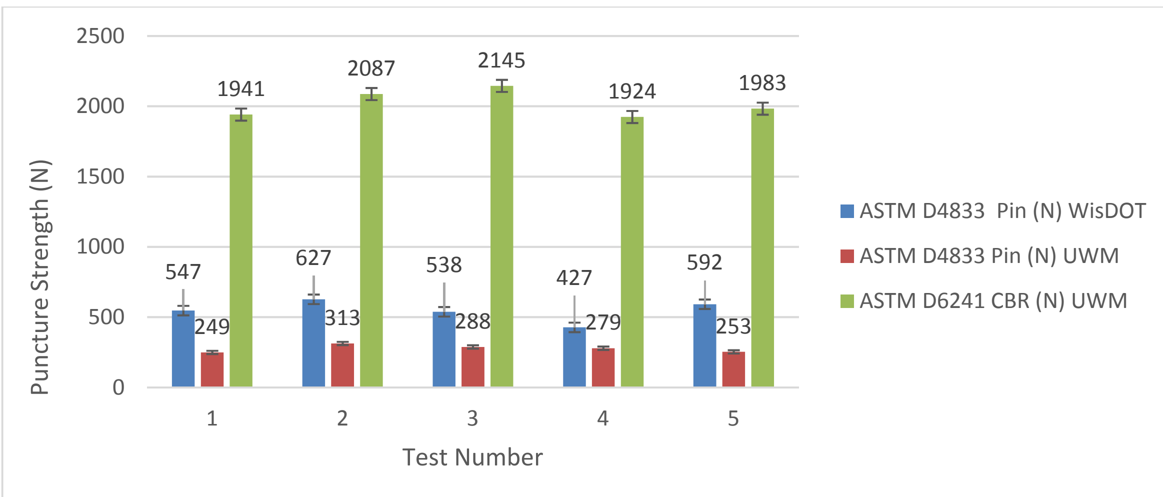


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

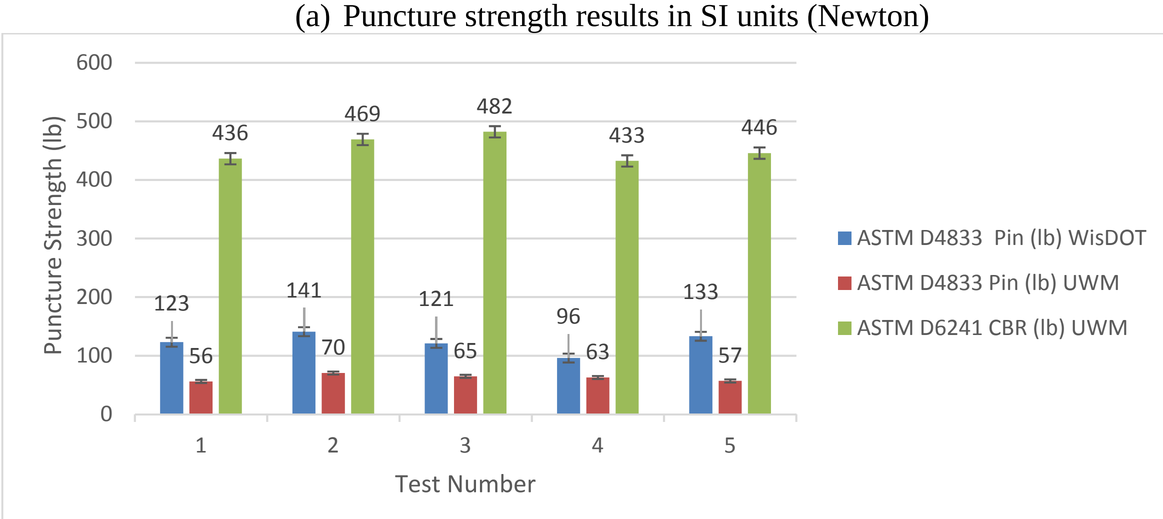


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-29: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number – manufactured by X1

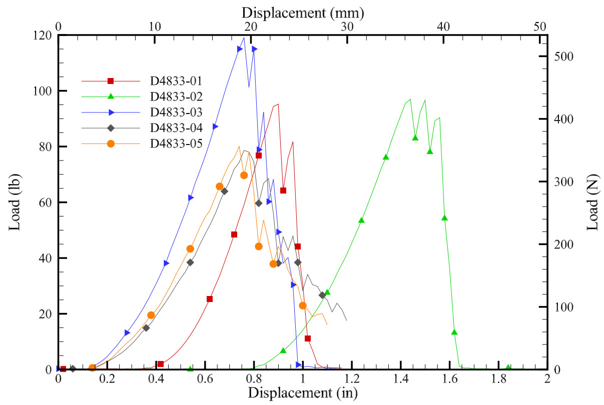


(a) Puncture strength results in SI units (Newton)

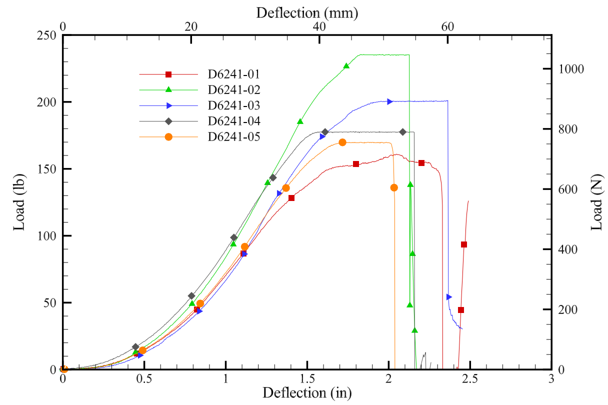


(b) Puncture strength results in U.S. units (Pound)

Figure A-30: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number – manufactured by X1

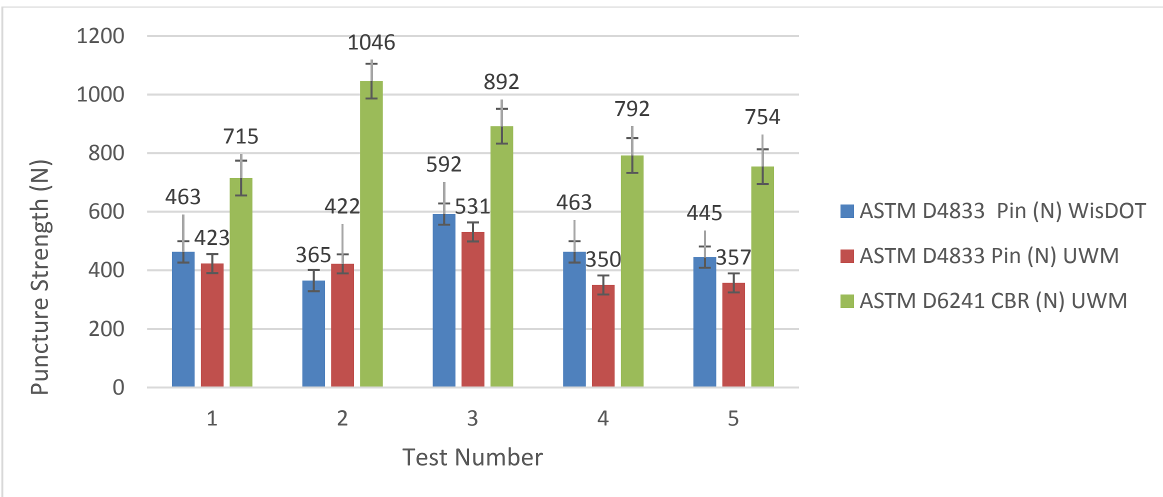


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

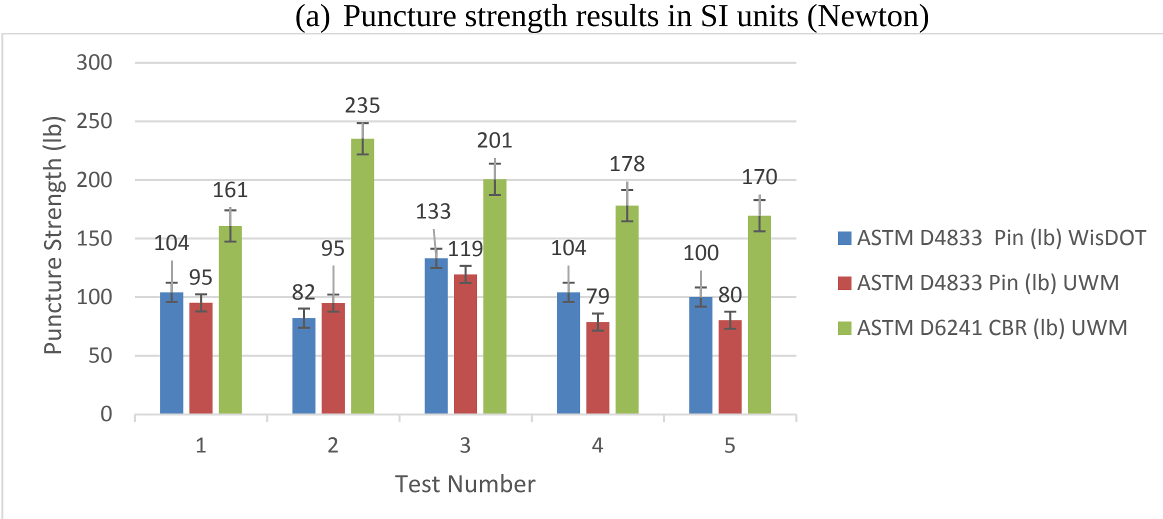


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-31: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1060-33-70– manufactured by SKAPS Industries

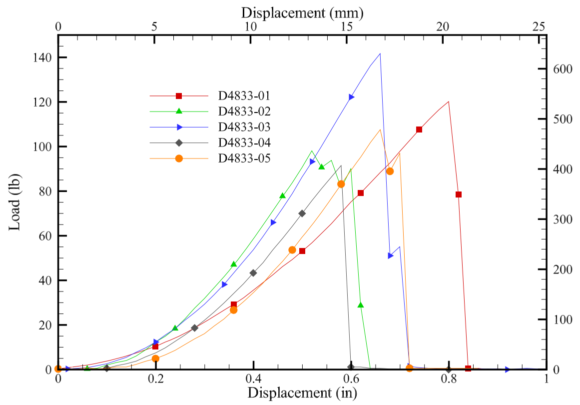


(a) Puncture strength results in SI units (Newton)

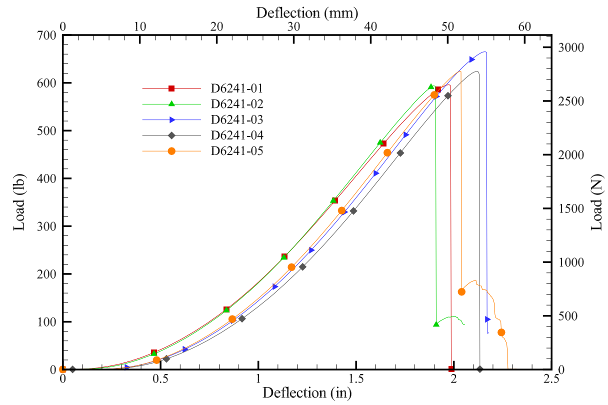


(b) Puncture strength results in U.S. units (Pound)

Figure A-32: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1060-33-70– manufactured by SKAPS Industries

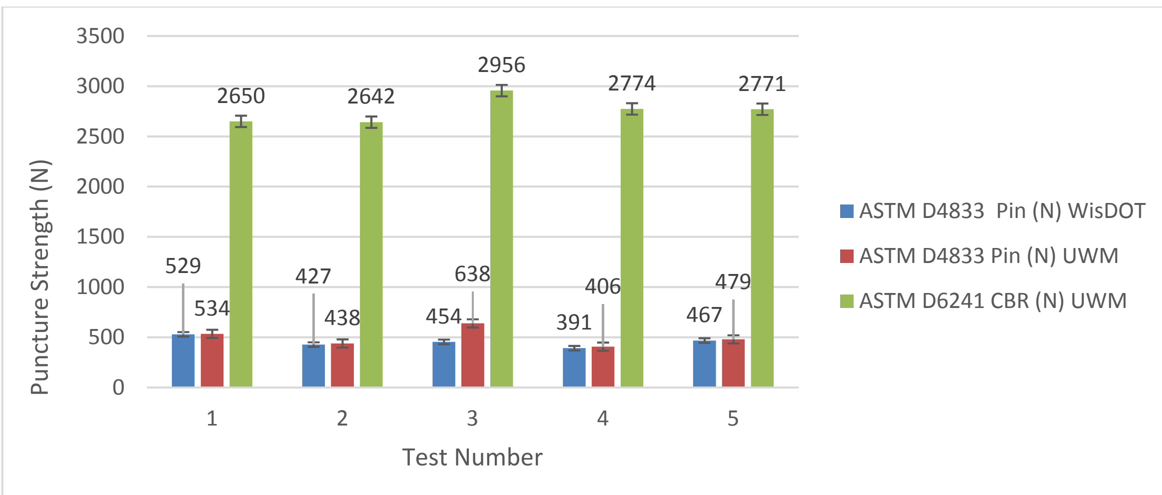


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

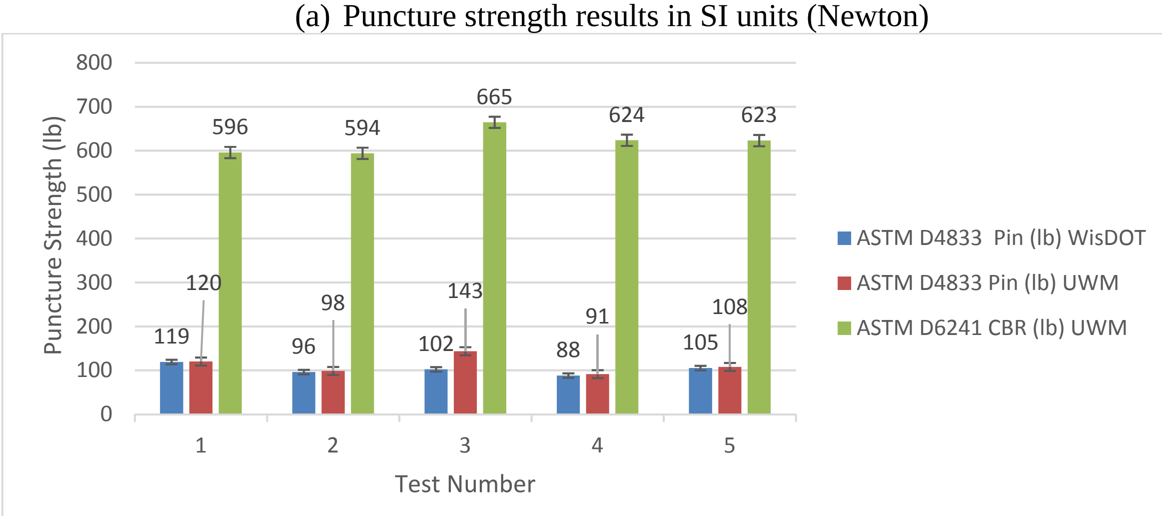


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-33: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 9200-04-71– manufactured by HONES GEO Component

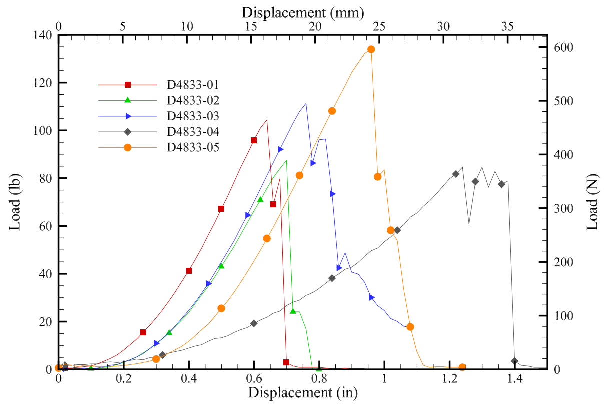


(a) Puncture strength results in SI units (Newton)

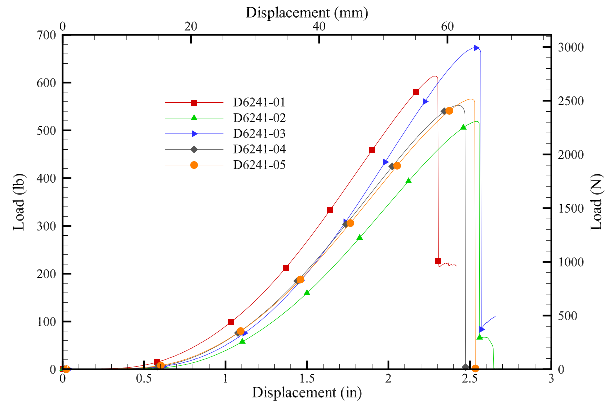


(b) Puncture strength results in U.S. units (Pound)

Figure A-34: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 9200-04-71– manufactured by HONES GEO Component

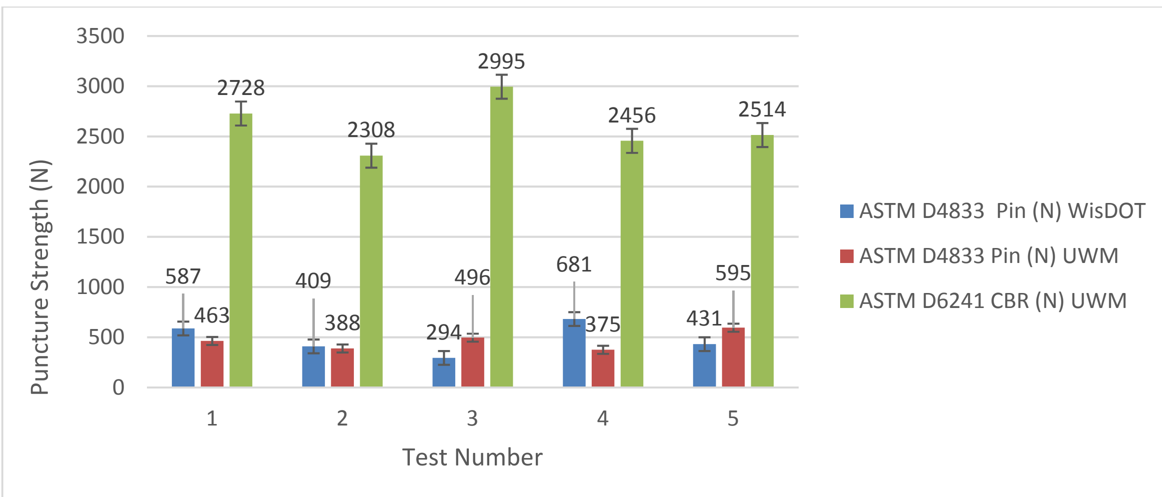


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

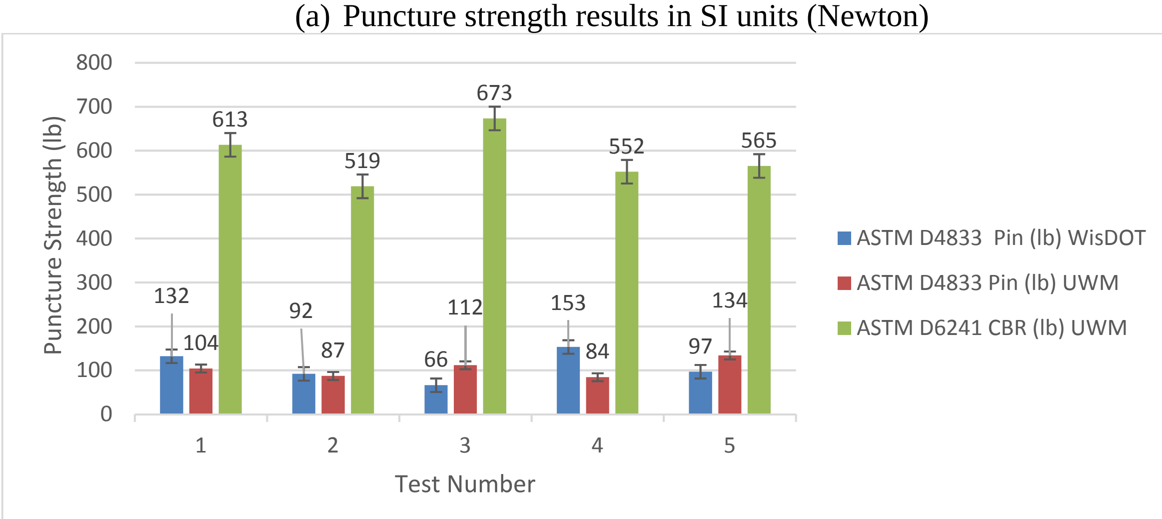


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-35: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1030-11-70 – manufactured by TENCATE

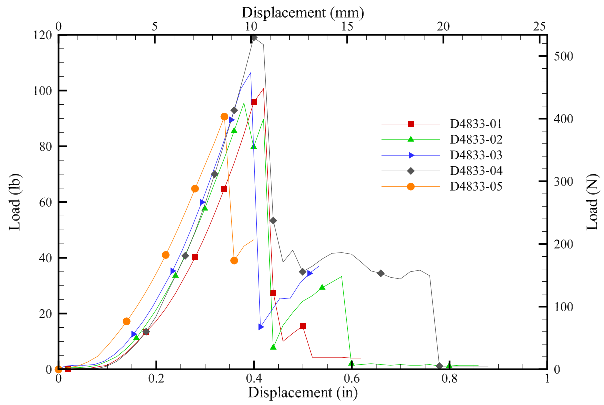


(a) Puncture strength results in SI units (Newton)

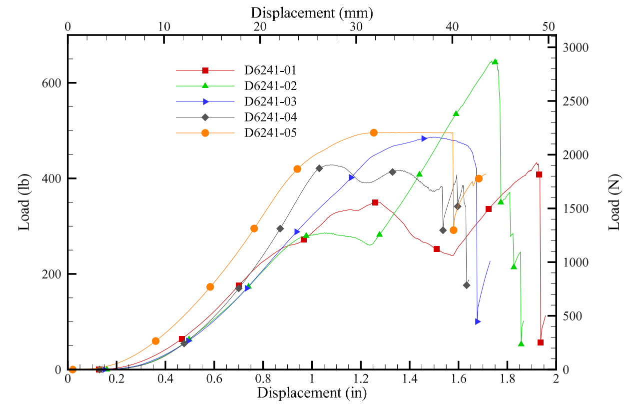


(b) Puncture strength results in U.S. units (Pound)

Figure A-36: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1030-11-70 – manufactured by TENCATE

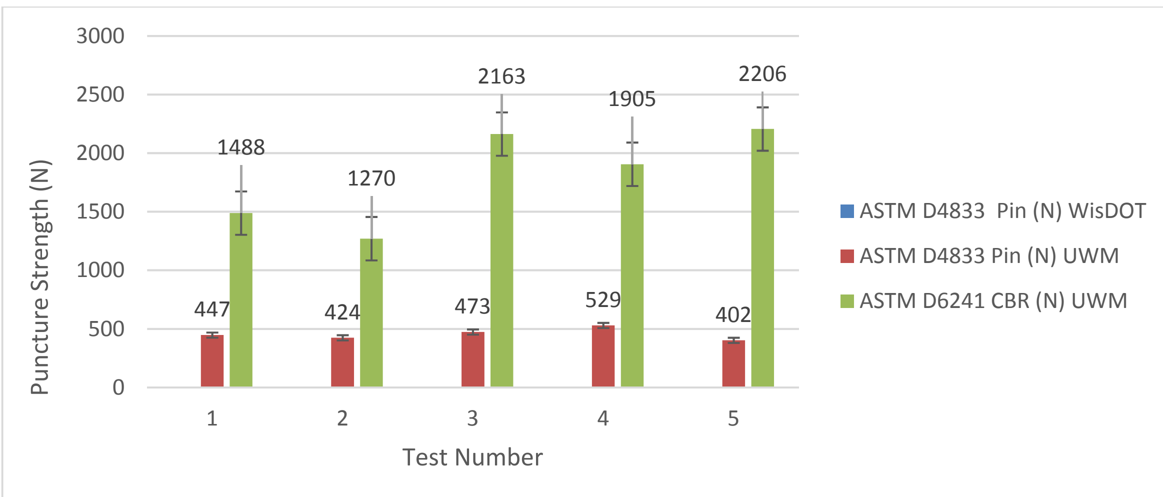


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

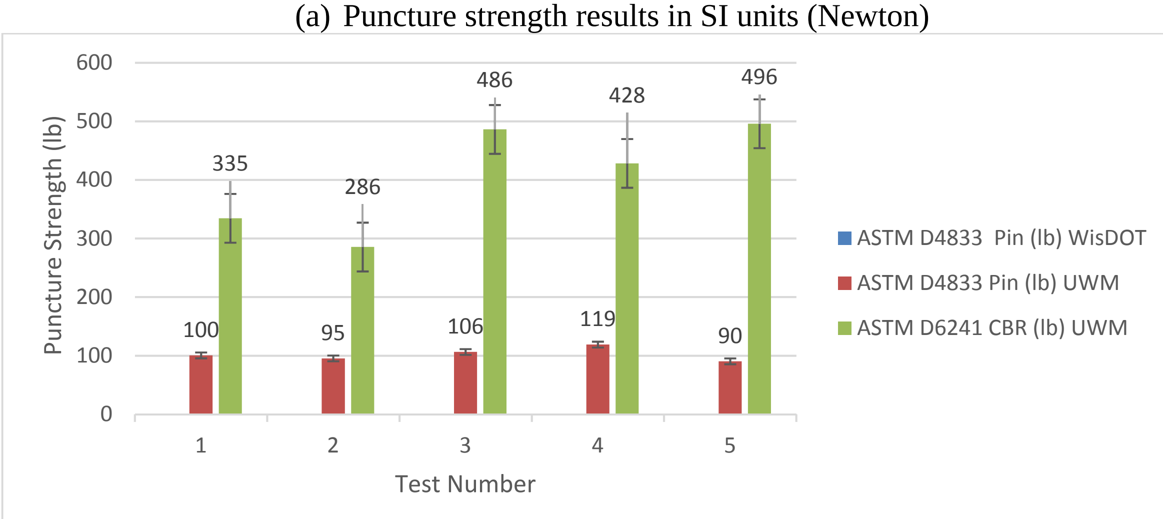


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-37: Pin and CBR puncture strength tests for geotextile specimens – fabric type SR, project number 5994-00-72 – manufactured by WILLACOOCHEE

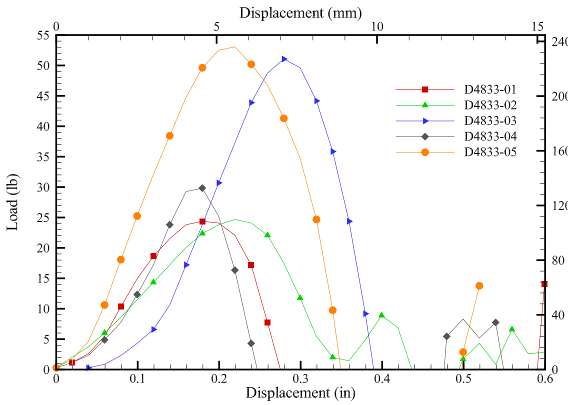


(a) Puncture strength results in SI units (Newton)

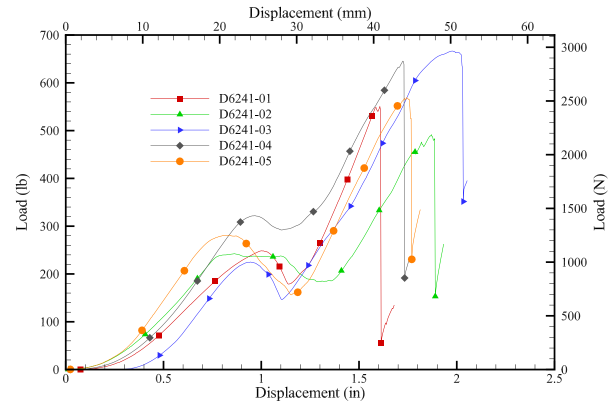


(b) Puncture strength results in U.S. units (Pound)

Figure A-38: Pin and CBR puncture strength test results for geotextile specimens – fabric type SR, project number 5994-00-72 – manufactured by WILLACOOCHEE

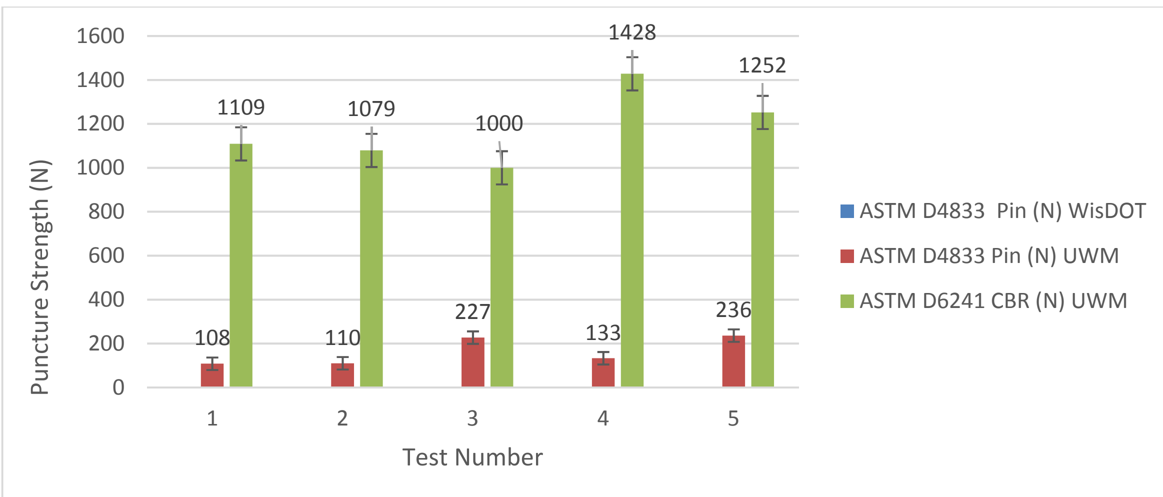


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

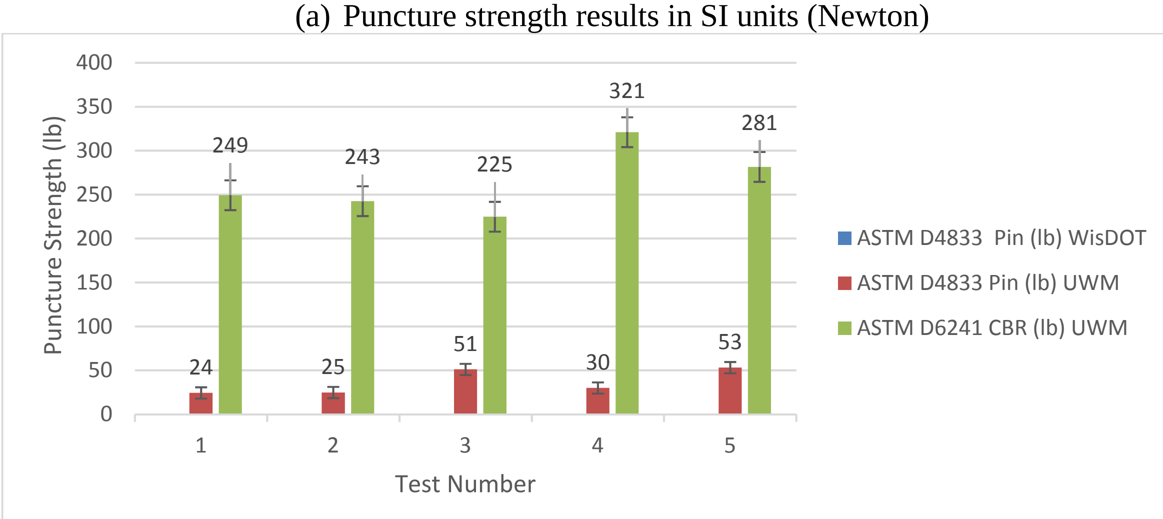


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-39: Pin and CBR puncture strength tests for geotextile specimens – fabric type SR, project number 5994-00-72– manufactured by WILLACOOCHEE

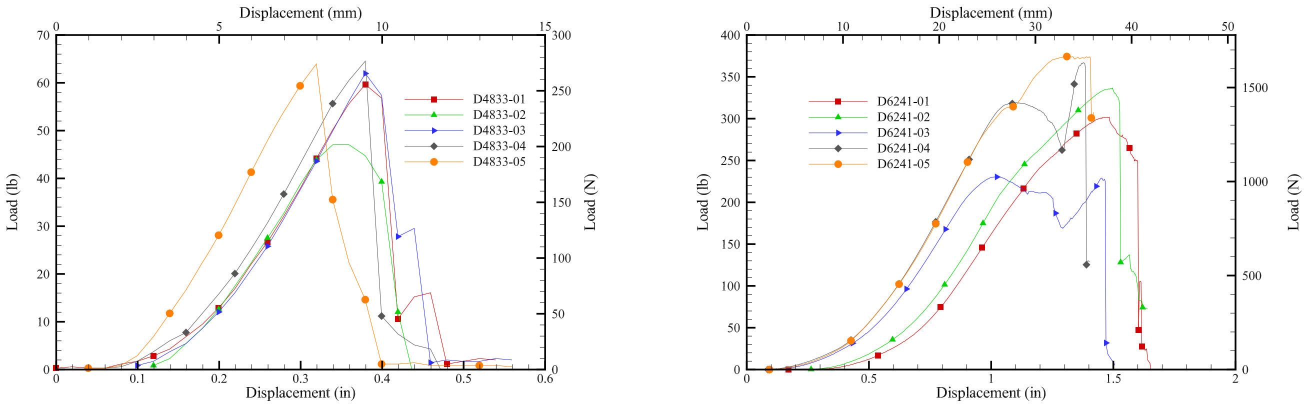


(a) Puncture strength results in SI units (Newton)



(b) Puncture strength results in U.S. units (Pound)

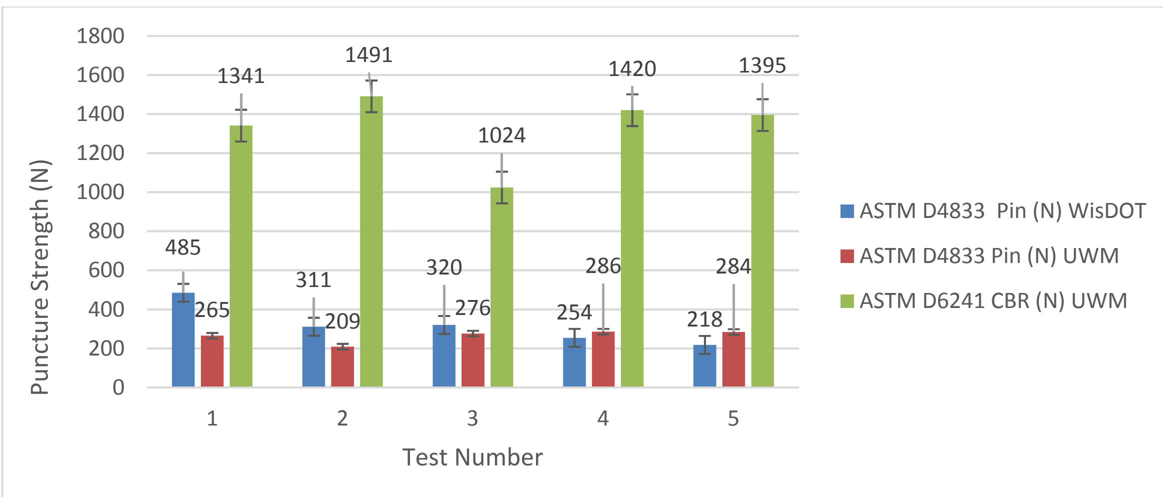
Figure A-40: Pin and CBR puncture strength tests for geotextile specimens – fabric type SR, project number 5994-00-72– manufactured by WILLACOOCHEE



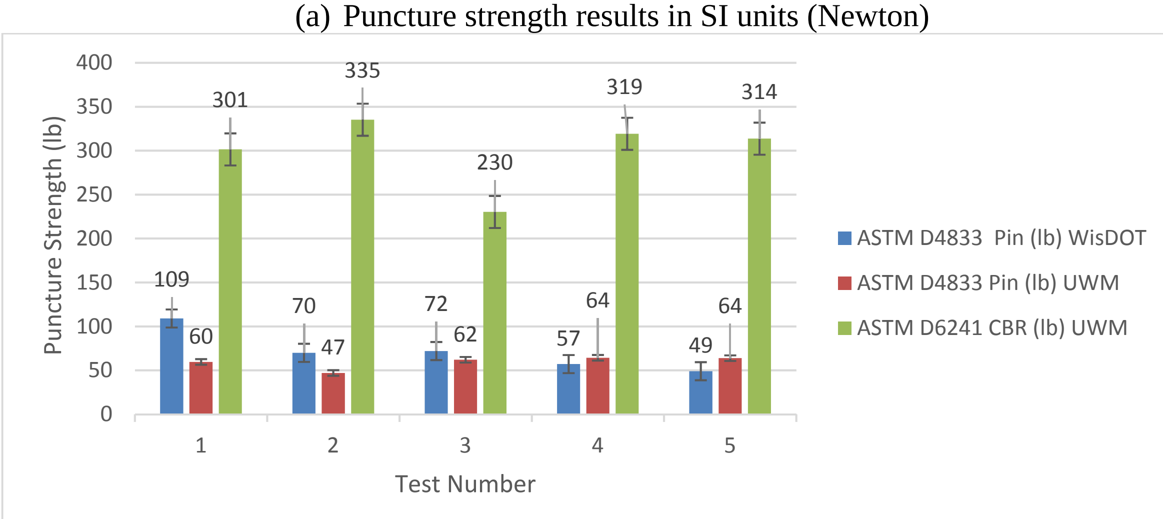
(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-41: Pin and CBR puncture strength tests for geotextile specimens – fabric type HR, project number– manufactured by X1

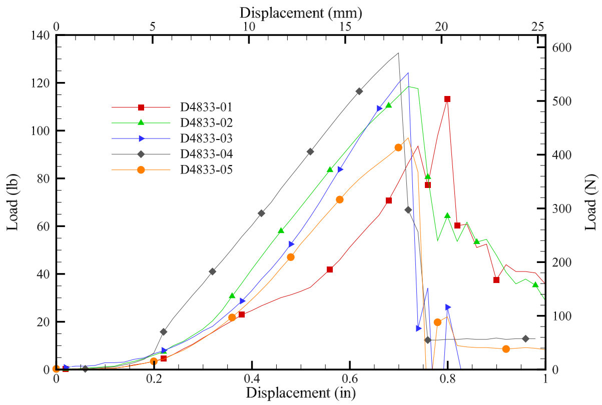


(a) Puncture strength results in SI units (Newton)

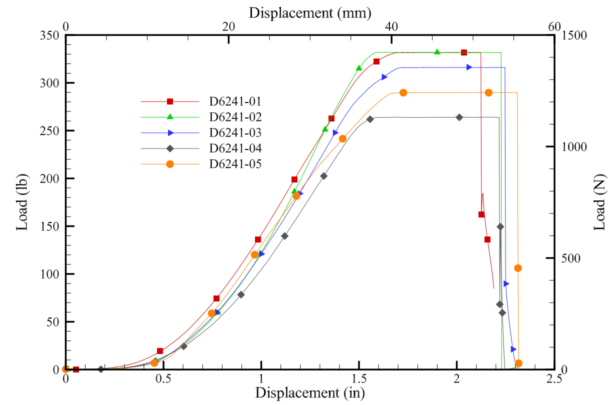


(b) Puncture strength results in U.S. units (Pound)

Figure a-42: Pin and CBR puncture strength tests for geotextile specimens – fabric type HR, project number– manufactured by X1

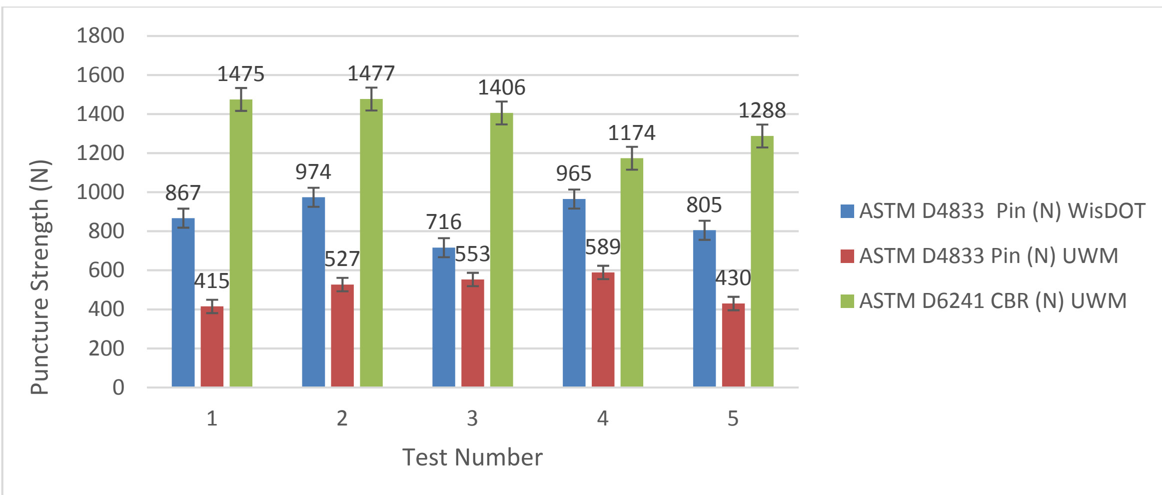


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

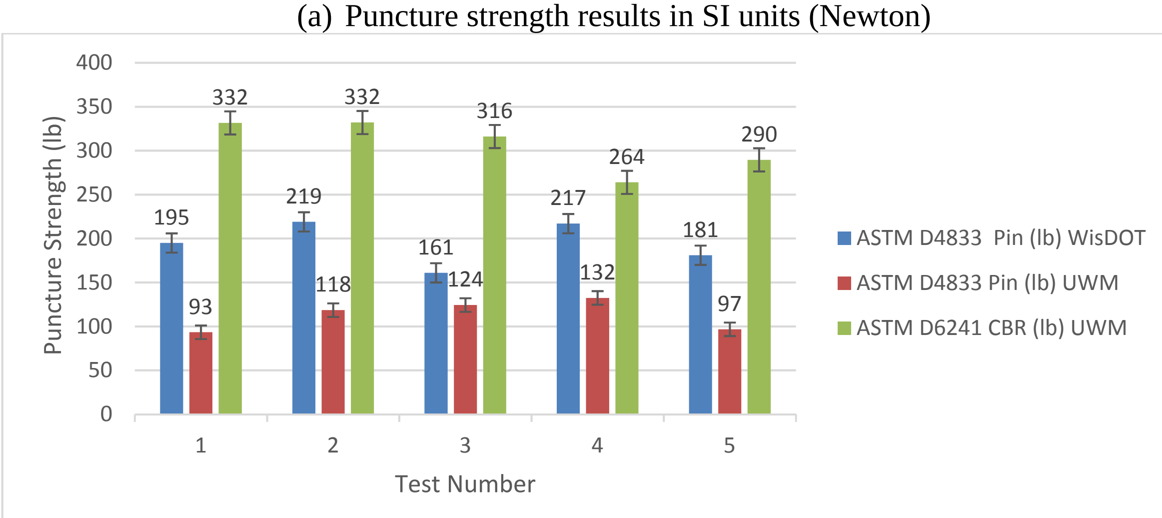


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-43: Pin and CBR puncture strength tests for geotextile specimens – fabric type HR, project number– manufactured by Advanced Geosynthetics 120 NW

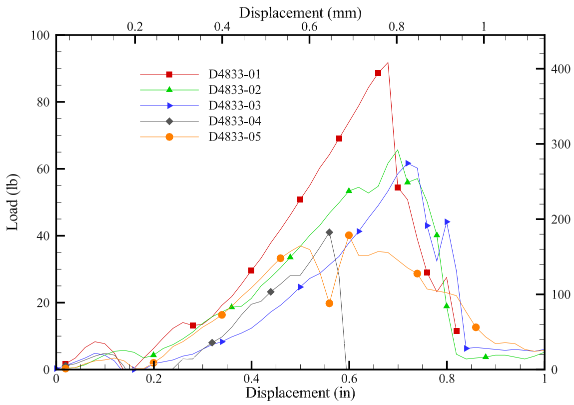


(a) Puncture strength results in SI units (Newton)

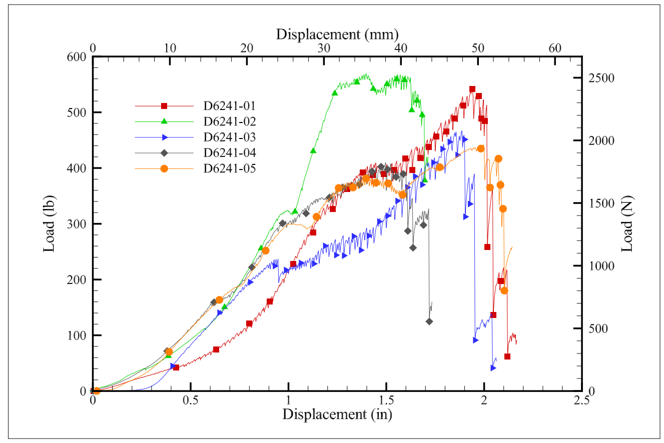


(b) Puncture strength results in U.S. units (Pound)

Figure A-44: Pin and CBR puncture strength tests for geotextile specimens – fabric type HR, project number– manufactured by Advanced Geosynthetics 120 NW

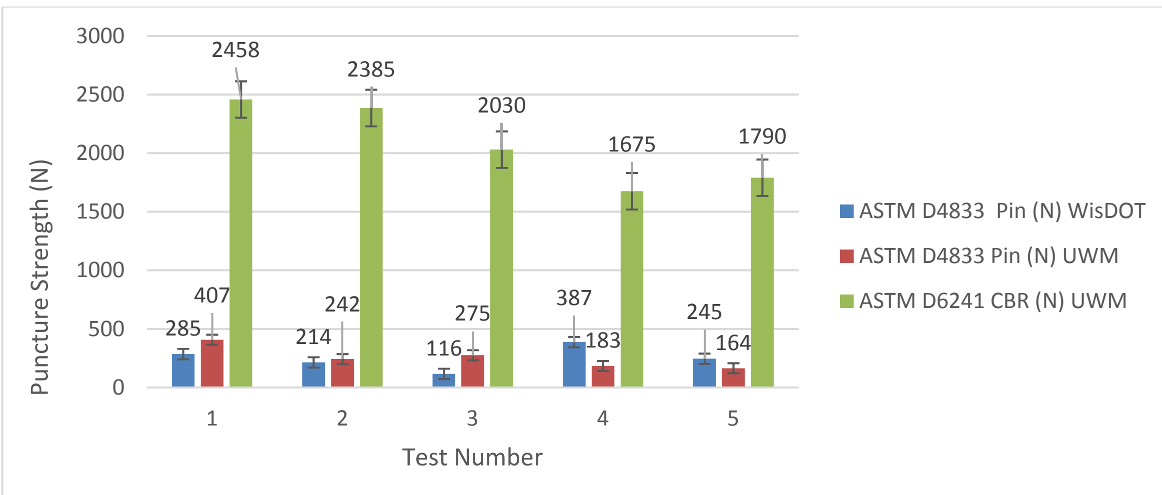


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

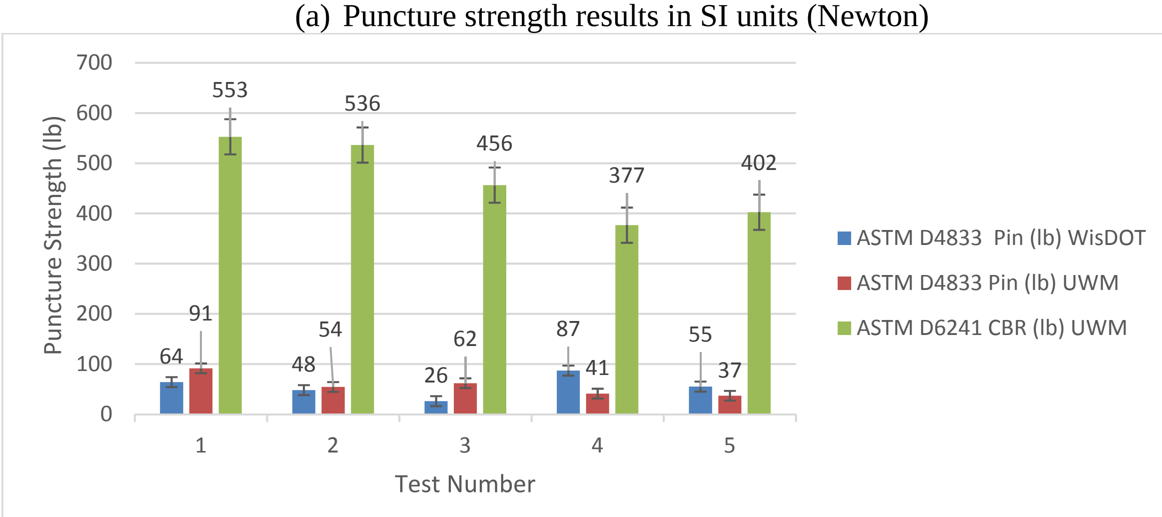


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-45: Pin and CBR puncture strength tests for geotextile specimens – fabric type ES, project number 1133-11-74– manufactured by HUESKER INC

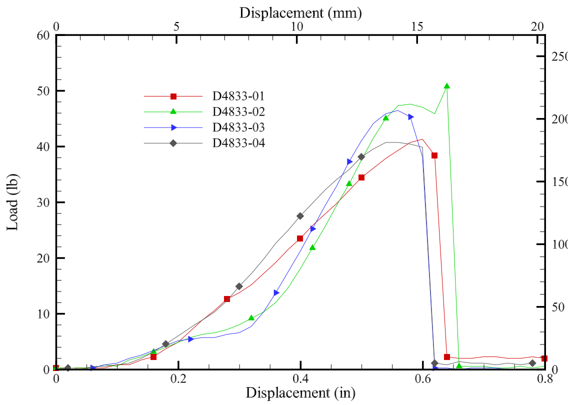


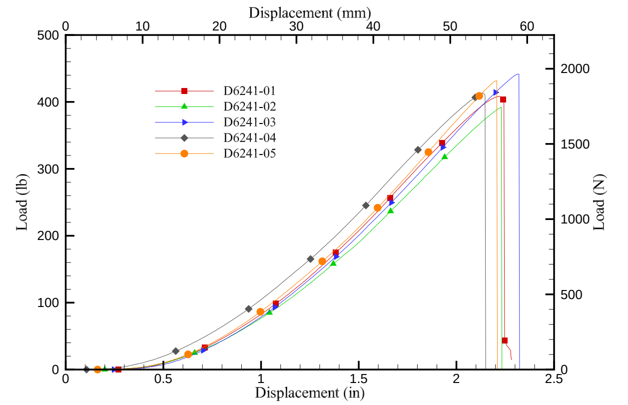
(a) Puncture strength results in SI units (Newton)



(b) Puncture strength results in U.S. units (Pound)

Figure A-46: Pin and CBR puncture strength tests for geotextile specimens – fabric type ES, project number 1133-11-74– manufactured by HUESKER INC

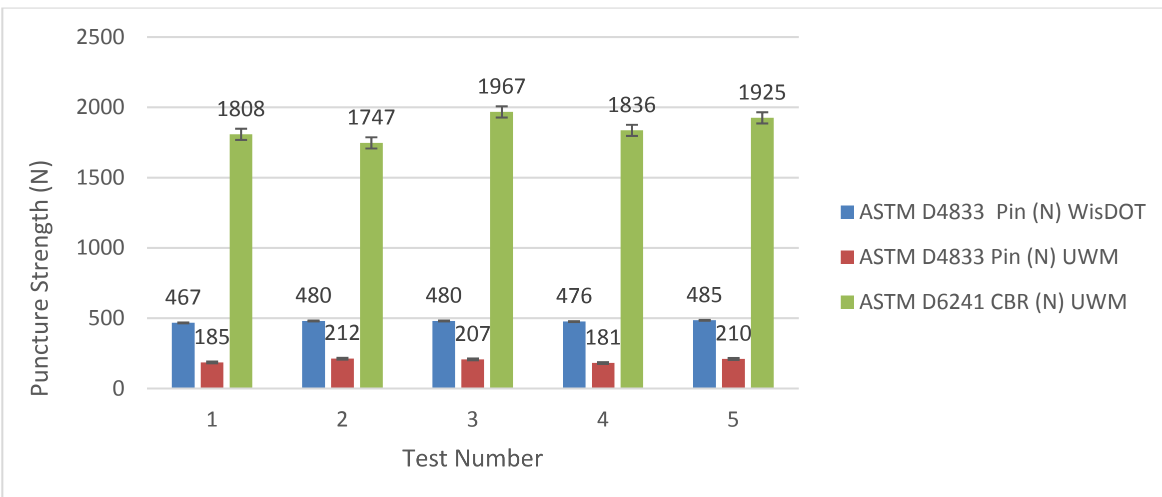




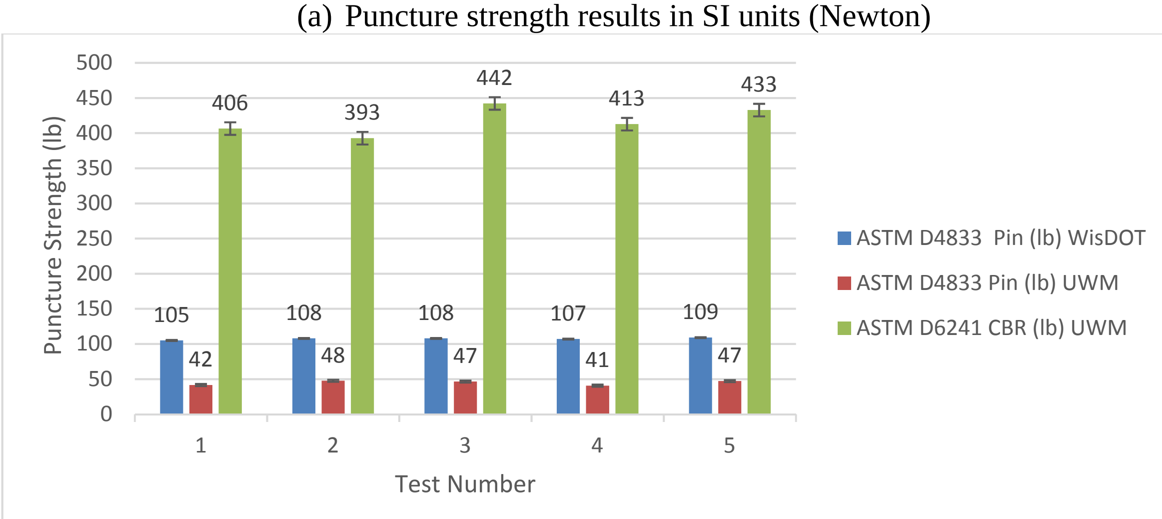
(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-47: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1206-07-77– manufactured by X1

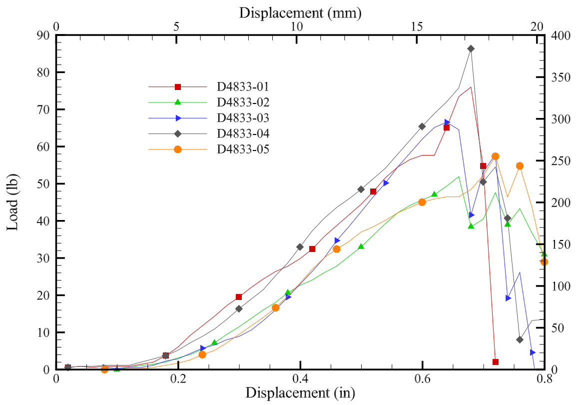


(a) Puncture strength results in SI units (Newton)

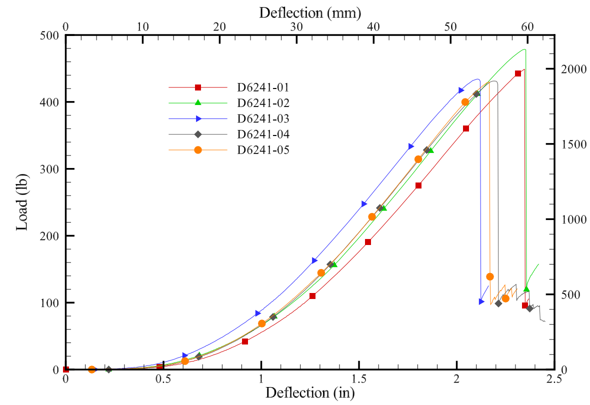


(b) Puncture strength results in U.S. units (Pound)

Figure A-48: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1206-07-77– manufactured by X1

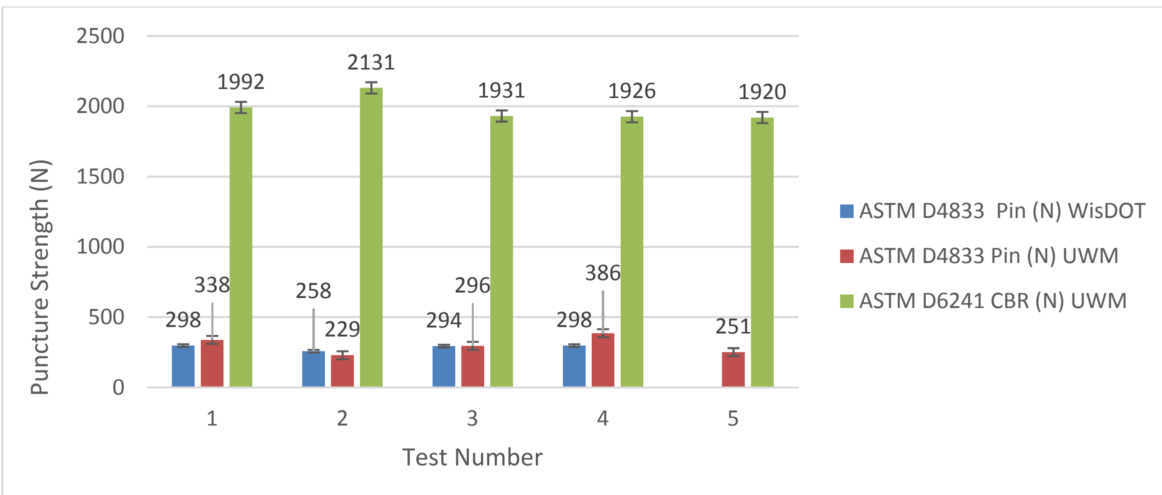


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

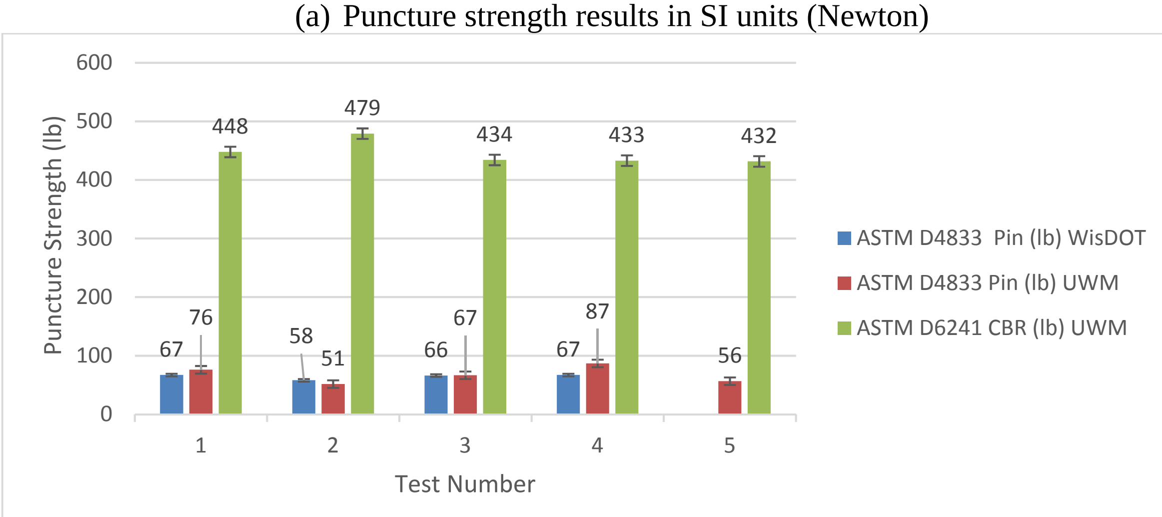


(b) Load vs. deflection relationships for ASTM D6241 (CBR) puncture strength test

Figure A-49: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1030-11-70– manufactured by TENCATE GEOSYNTHETICS AMERICAS

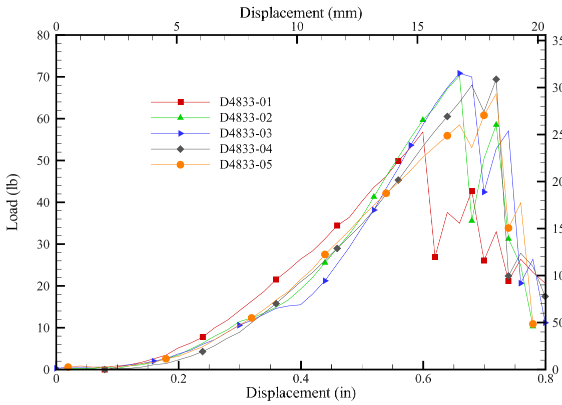


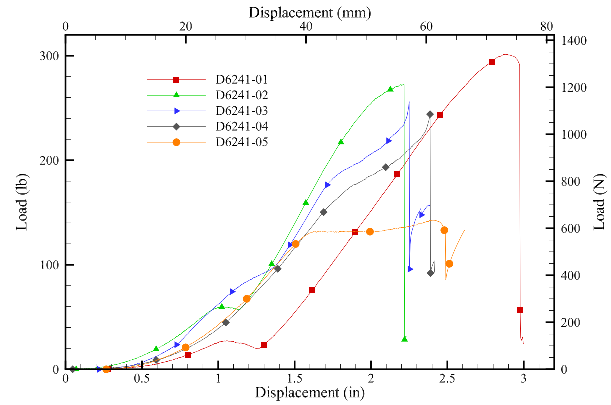
(a) Puncture strength results in SI units (Newton)



(b) Puncture strength results in U.S. units (Pound)

Figure A-50: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1030-11-70– manufactured by TENCATE GEOSYNTHETICS AMERICAS

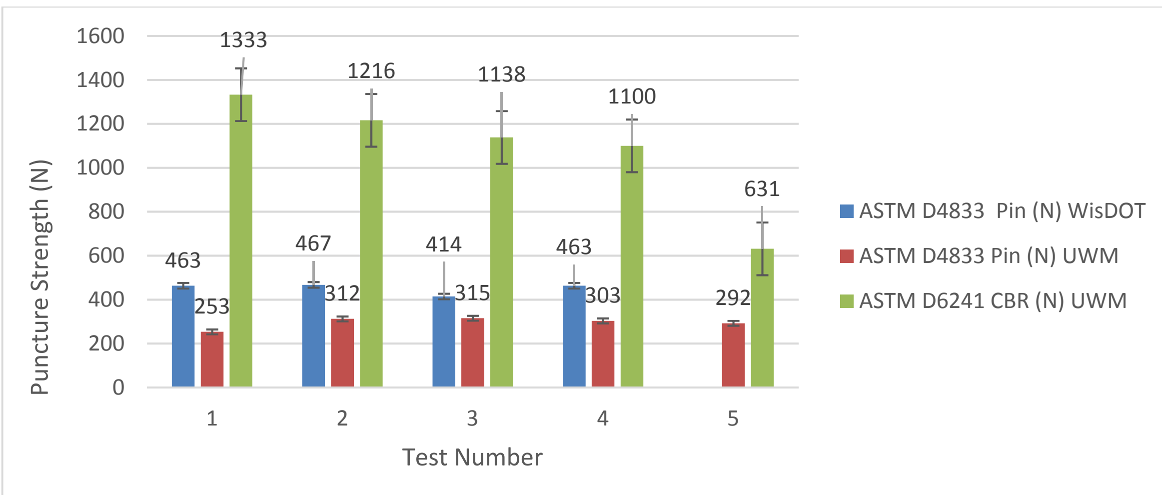




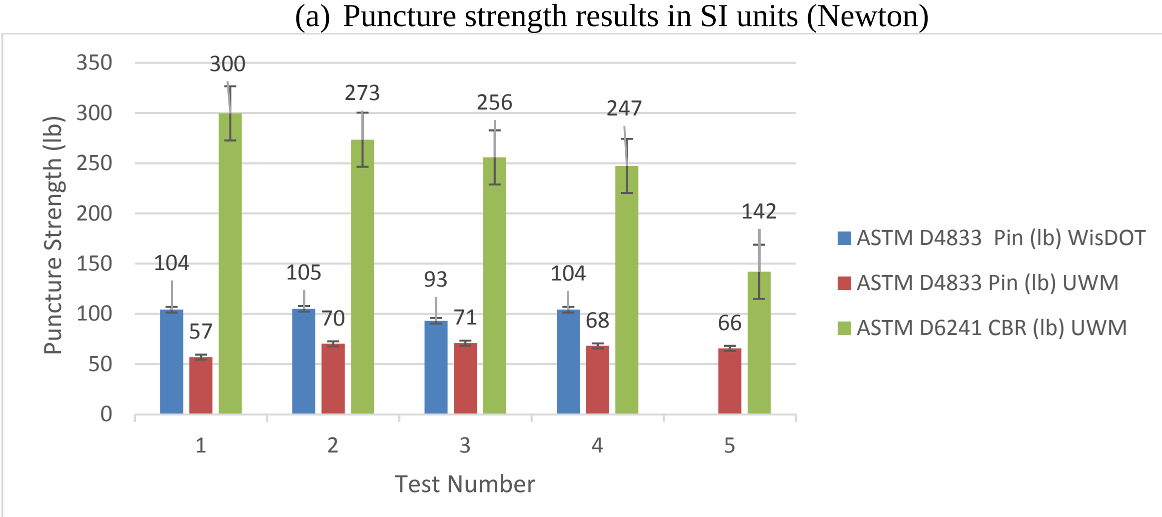
(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-51: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 2753-06-71– manufactured by SKAPS

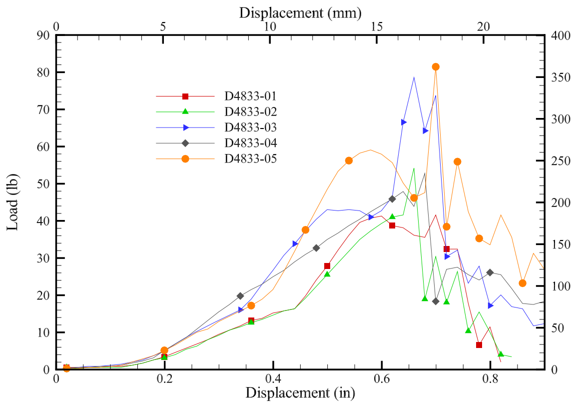


(a) Puncture strength results in SI units (Newton)

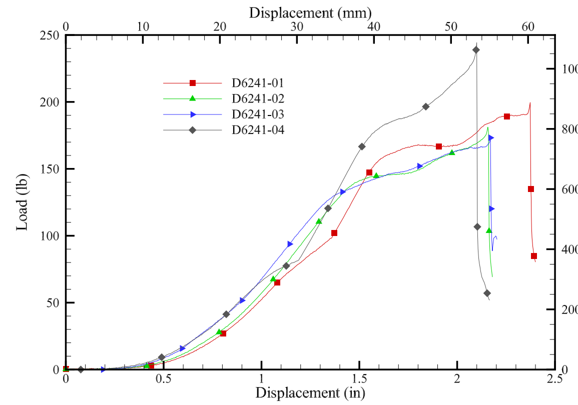


(b) Puncture strength results in U.S. units (Pound)

Figure A-52: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 2753-06-71– manufactured by SKAPS

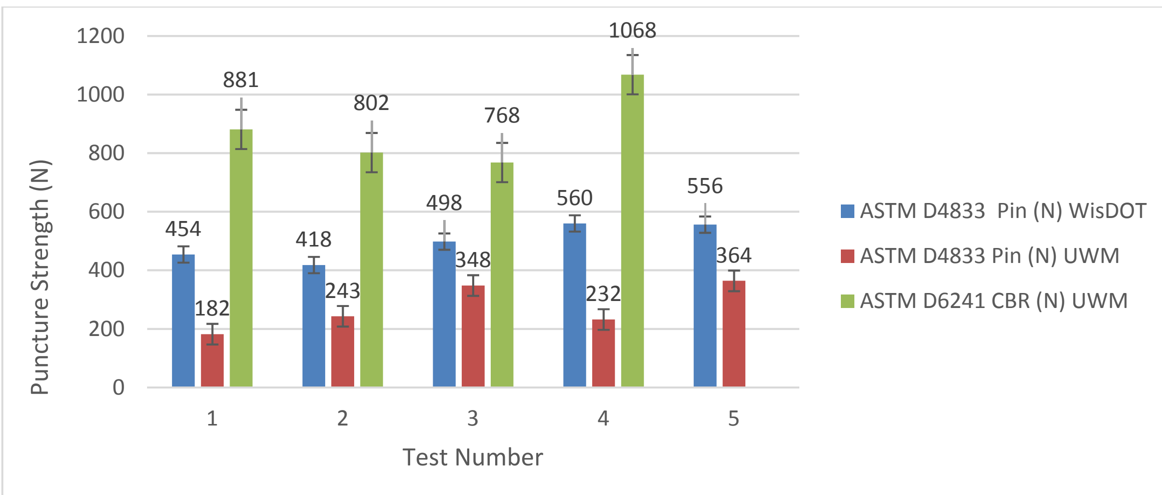


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

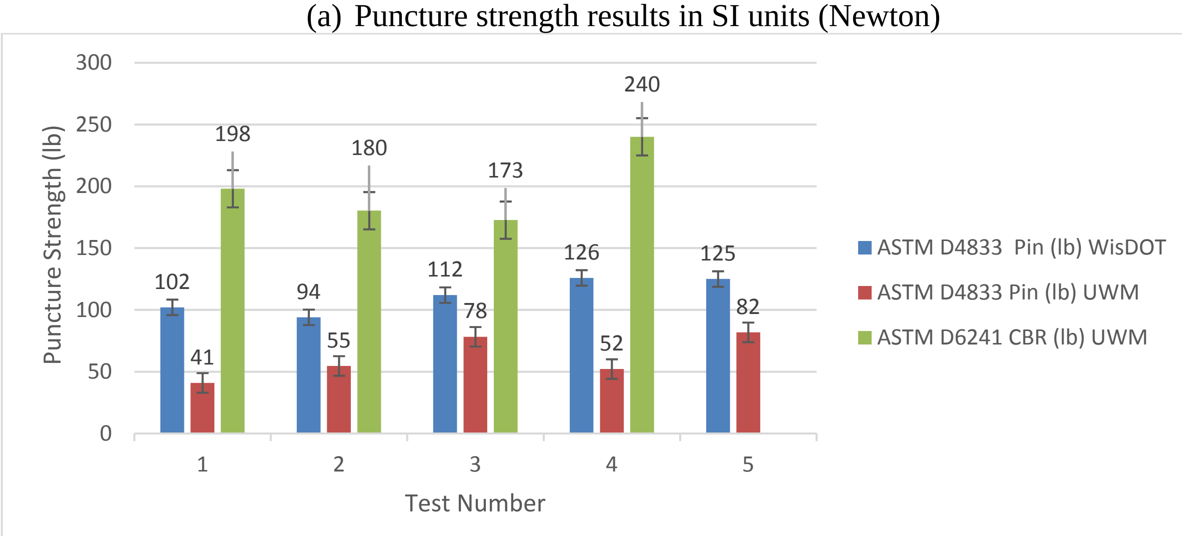


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-53: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1060-33-73– manufactured by PROPEX

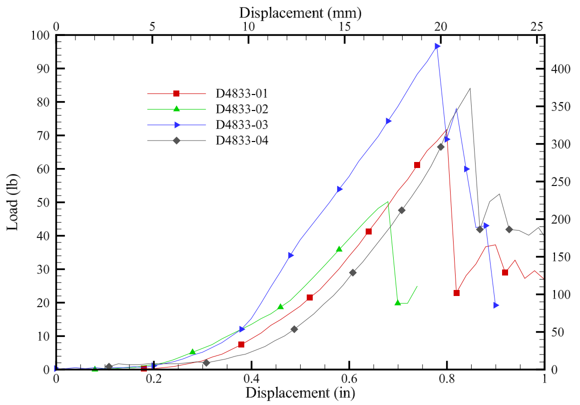


(a) Puncture strength results in SI units (Newton)

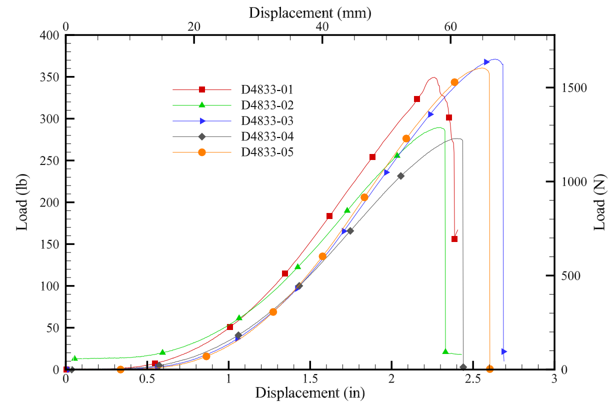


(b) Puncture strength results in U.S. units (Pound)

Figure A-54: Pin and CBR puncture strength tests for geotextile specimens – fabric type DF, project number 1060-33-73– manufactured by PROPEX

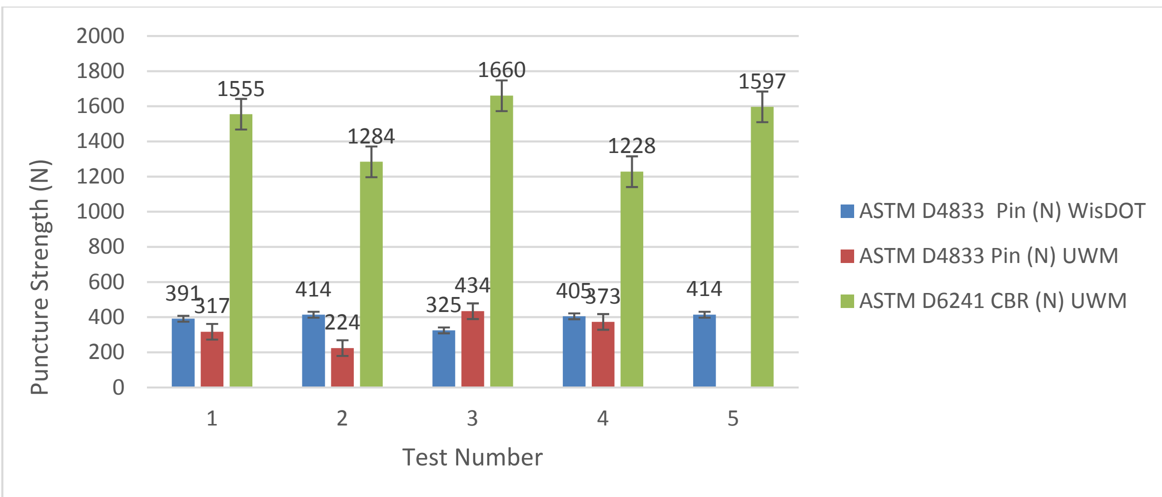


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

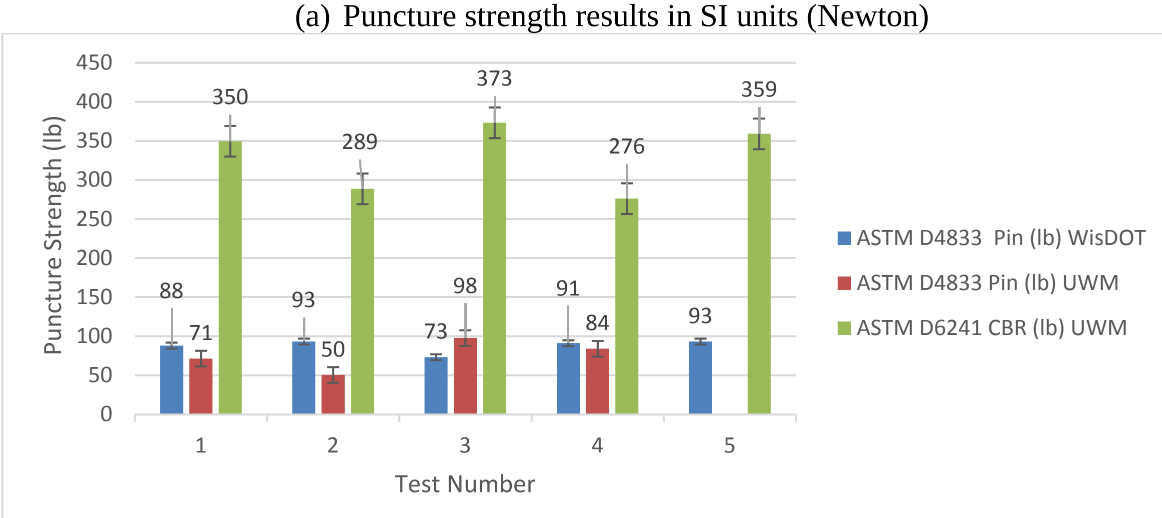


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-55: Pin and CBR puncture strength tests for geotextile specimens – fabric type SAS, project number 9240-10-61– manufactured by PROPEX

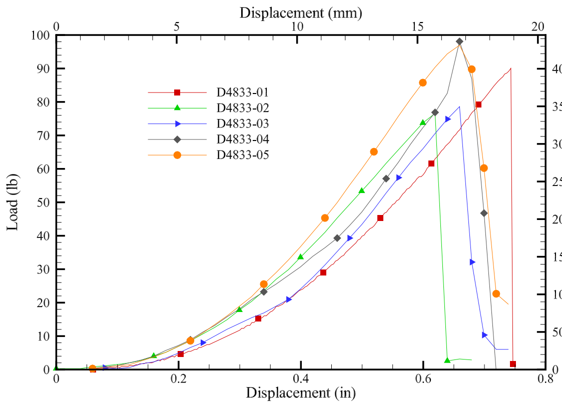


(a) Puncture strength results in SI units (Newton)

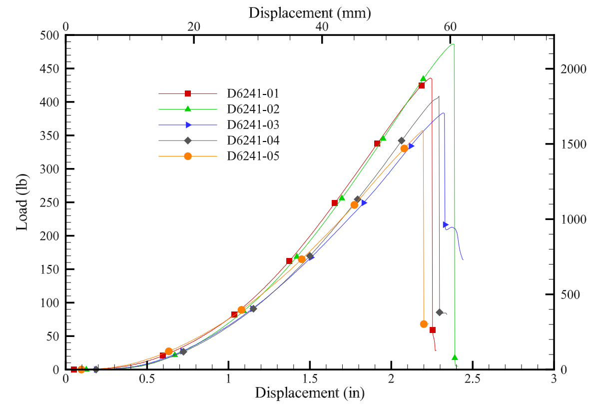


(b) Puncture strength results in U.S. units (Pound)

Figure A-56: Pin and CBR puncture strength tests for geotextile specimens – fabric type SAS, project number 9240-10-61– manufactured by PROPEX

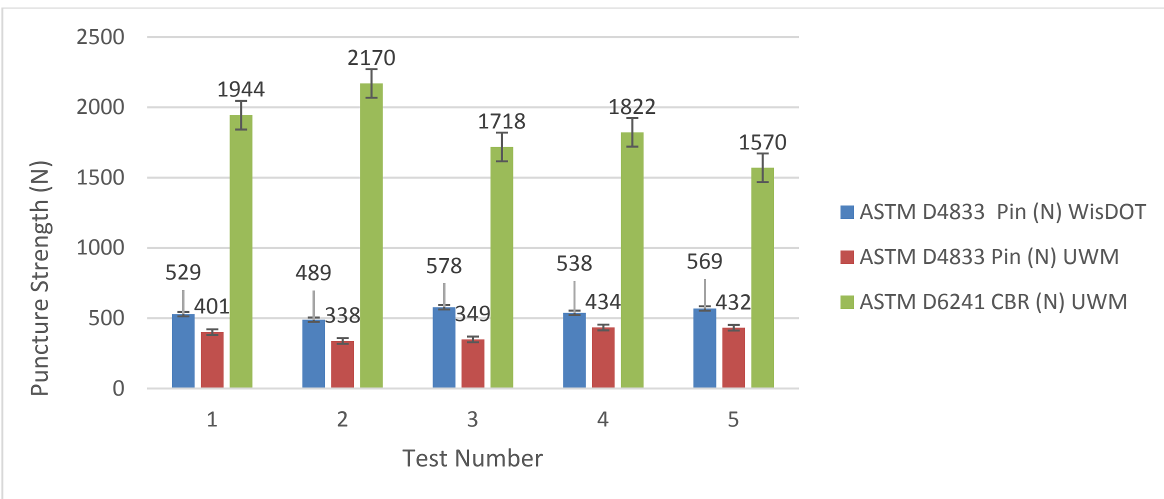


(a) Load vs. displacement relationships for ASTM D4833 (Pin) puncture strength test

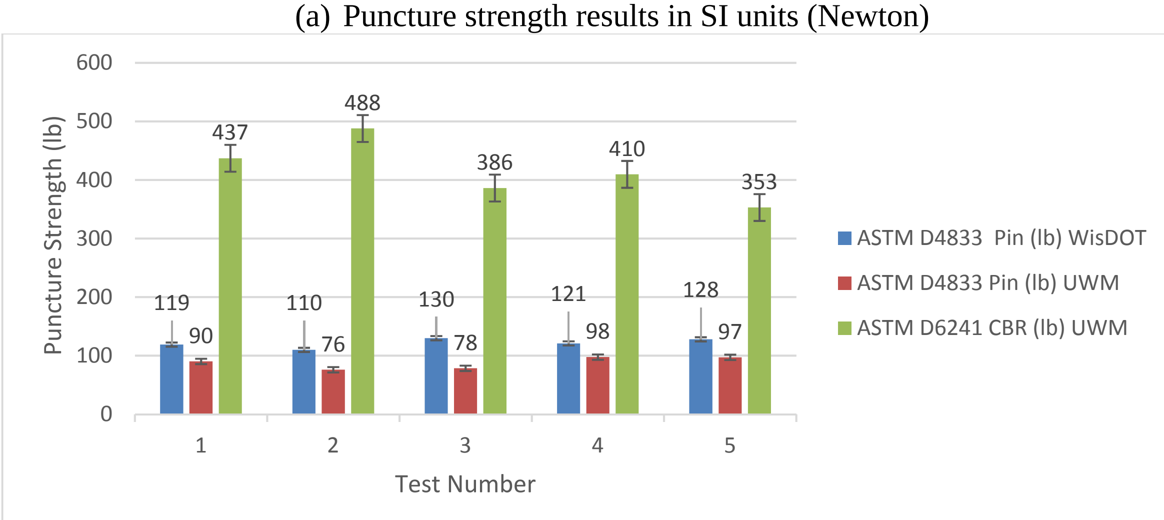


(b) Load vs. displacement relationships for ASTM D6241 (CBR) puncture strength test

Figure A-57: Pin and CBR puncture strength tests for geotextile specimens – fabric type SAS, project number 1060-33-75– manufactured by TENCATE



(a) Puncture strength results in SI units (Newton)



(b) Puncture strength results in U.S. units (Pound)

Figure A-58: Pin and CBR puncture strength tests for geotextile specimens – fabric type SAS, project number 1060-33-75– manufactured by TENCATE

Table B1: Pin and CBR Puncture Strength Values Reported by the Geotextile Industry (TenCate) for Needle punched Nonwoven (NPNW) Polypropylene (PP) Fabric.

	Number	Pin ASTM D4833 lb	Pin ASTM D4833 N (From site)	Pin ASTM D4833 N(Calculated)	CBR ASTM D6241 lb	CBR ASTM D6241 N (From Site)	CBR ASTM D6241 N(Calculated)	Type	Fiber Type	Designed for				
										Separation	Drainage	Protection	Filtration	Erosion Protection
TenCate Mirafi® N-Series	135N	NA	NA	NA	175	779	778.44	Needlepunched nonwoven	Polypropylene	✓	✓			
	140NL	NA	NA	NA	250	1113	1112.05	Needlepunched nonwoven	Polypropylene	✓	✓			
	140NC	NA	NA	NA	250	1113	1112.05	Needlepunched nonwoven	Polypropylene	✓	✓			
	140N	NA	NA	NA	310	1380	1378.94	Needlepunched nonwoven	Polypropylene	✓	✓			
	150N	NA	NA	NA	350	1558	1556.87	Needlepunched nonwoven	Polypropylene	✓	✓			
	160N	NA	NA	NA	410	1825	1823.76	Needlepunched nonwoven	Polypropylene		✓			
	170N	NA	NA	NA	450	2003	2001.69	Needlepunched nonwoven	Polypropylene	✓	✓			
	180N	NA	NA	NA	500	2224	2224.10	Needlepunched nonwoven	Polypropylene	✓	✓			
	180NC	NA	NA	NA	550	2224	2446.51	Needlepunched nonwoven	Polypropylene	✓	✓			
	1100N	NA	NA	NA	700	3115	3113.74	Needlepunched nonwoven	Polypropylene	✓	✓			
	1100NC	NA	NA	NA	600	2670	2668.92	Needlepunched nonwoven	Polypropylene	✓	✓			
	1100NPA	100	445	444.82	700	3115	3113.74	Needlepunched nonwoven	Polypropylene	✓	✓			
	1120N	NA	NA	NA	800	3560	3558.56	Needlepunched nonwoven	Polypropylene	✓	✓			
	1160N	NA	NA	NA	1025	4561	4559.41	Needlepunched nonwoven	Polypropylene	✓	✓			
TenCate Mirafi® S-Series	S600	NA	NA	NA	450	2003	2001.69	Needlepunched nonwoven	Polypropylene	✓	✓			
	S800	NA	NA	NA	600	2670	2668.92	Needlepunched nonwoven	Polypropylene	✓	✓			
	S1000	NA	NA	NA	725	3226	3224.945	Needlepunched nonwoven	Polypropylene	✓	✓			
	S1200	NA	NA	NA	900	4005	4003.38	Needlepunched nonwoven	Polypropylene	✓	✓			
	S1600	NA	NA	NA	1200	5340	5337.84	Needlepunched nonwoven	Polypropylene	✓	✓			
	S2000	NA	NA	NA	8900	8900	39588.98	Needlepunched nonwoven	Polypropylene	✓		✓		
	S2400	250	1113	1112.05	8900	8900	39588.98	Needlepunched nonwoven	Polypropylene	✓		✓		
	S2600	275	1224	1223.255	2000	8900	8896.4	Needlepunched nonwoven	Polypropylene	✓		✓		
	S2800	300	1335	1334.46	2100	9345	9341.22	Needlepunched nonwoven	Polypropylene	✓		✓		
	S3200	350	1558	1556.87	2200	9790	9786.04	Needlepunched nonwoven	Polypropylene	✓	✓			
Mirafi® Delineation	140NL/O	NA	NA	NA	310	1380	1378.942	Orange nonwoven geotextile	Polypropylene		✓			
	160N/O	NA	NA	NA	480	2136	2135.136	Orange nonwoven geotextile	Polypropylene		✓			
	180N/O	NA	NA	NA	630	2802	2802.366	Orange nonwoven geotextile	Polypropylene		✓			
TenCate Mirafi® FW-Series	FW300	NA	NA	NA	1250	5563	5560.25	woven	Polypropylene	✓			✓	✓
	FW402	NA	NA	NA	675	3004	3002.535	woven	Polypropylene	✓			✓	✓
	FW403	NA	NA	NA	1340	5963	5960.588	woven	Polypropylene	✓			✓	✓
	FW404	NA	NA	NA	1150	5118	5115.43	woven	Polypropylene	✓			✓	
	FW500	NA	NA	NA	1200	5340	5337.84	woven	Polypropylene	✓			✓	✓
	FW700	NA	NA	NA	950	4228	4225.79	woven	Polypropylene	✓			✓	✓
TenCate Mirafi® X-Series	500X	NA	NA	NA	700	3115	3113.74	woven	Polypropylene	✓				
	600X	NA	NA	NA	900	4005	4003.38	woven	Polypropylene	✓				
	650X	NA	NA	NA	1000	4450	4448.2	woven	Polypropylene	✓				
	830X	140	623	622.748	1500	6675	6672.3	woven	Polypropylene	✓				
	850X	200	890	889.64	NA	NA		woven	Polypropylene	✓				

Table B2: Pin and CBR Puncture Strength Values Reported by the Geotextile Industry (US Fabric) for Woven and Needle punched Nonwoven (NPNW) Polypropylene (PP) Fabric

	Number	Pin ASTM D4833 lb	Pin ASTM D4833 N(From site)	CBR ASTM D6241 lb	CBR ASTM D6241 N(From Site)	Type	Fiber Type	Designed For					
								French Drain	Filtration	Drainage	Separation	Stabilization	Erosion Control
Light Weight Nonwoven	US 100NW	65	289	300	1,335	Nonwoven Needlepunched	PP	√	√				
	US 120NW	65	289	340	1,513	Nonwoven Needlepunched	PP	√		√	√	√	
	US 135NW	75	334	350	1,557	Nonwoven Needlepunched	PP			√			
	US 80NW	40	178	175	779	Nonwoven Needlepunched	PP	√	√				
	US 90NW	55	245	265	1,179	Nonwoven Needlepunched	PP	√	√				
Medium Weight Nonwoven	US 160NW	90	400	410	1,824	Nonwoven Needlepunched	PP			√	√	√	√
	US 180NW	105	467	475	2,114	Nonwoven Needlepunched	PP		√		√	√	
	US 205NW	130	579	535	2,381	Nonwoven Needlepunched	PP			√	√	√	√
Heavy Weight Nonwoven	US 250NW	155	690	700	3,115	Nonwoven Needlepunched	PP				√	√	
	US 270NW	100	445	700	3,115	Nonwoven Needlepunched	PP		√		√	√	
	US 300NW	180	801	850	3,782	Nonwoven Needlepunched	PP				√	√	
	US 380NW	240	1,070	1080	4,806	Nonwoven Needlepunched	PP				√	√	
Environmental Nonwoven	US 105NWE	65	289	305	1,360	Nonwoven Needlepunched	PP		√				
	US 165NWE	95	423	450	2,000	Nonwoven Needlepunched	PP			√			
	US 200NWE	115	511	540	2,400	Nonwoven Needlepunched	PP						
	US 225NWE	130	578	600	2,900	Nonwoven Needlepunched	PP						
	US 270NWE	NA	NA	725	3,226	Nonwoven Needlepunched	PP						
	US 330NWE	190	846	900	4,000	Nonwoven Needlepunched	PP						
	US 390NWE	210	935	1,045	4,650	Nonwoven Needlepunched	PP						
	US 425NWE	240	1,068	1,200	5,340	Nonwoven Needlepunched	PP						
Spunbond Nonwoven	US SF20	18	80	NA	NA	Nonwoven Spunbonded	PP	√	√				
	US SF32	30	134	NA	NA	Nonwoven Spunbonded	PP		√	√			
	US SF40	41	182	NA	NA	Nonwoven Spunbonded	PP		√	√			
	US SF49	56	249	NA	NA	Nonwoven Spunbonded	PP		√	√			
	US SF65	79	352	NA	NA	Nonwoven Spunbonded	PP		√		√	√	
Paving	US 100P	NA	NA	300	1,335	Nonwoven Needlepunched	PP						
	US 90P	NA	NA	275	1,224	Nonwoven Needlepunched	PP						

Table B2: Pin and CBR Puncture Strength Values Reported by the Geotextile Industry (US Fabric) for Woven and Needle punched Nonwoven (NPNW) Polypropylene (PP) Fabric (cont'd)

	Number	Pin ASTM D4833 lb	Pin ASTM D4833 N(From site)	CBR ASTM D6241 lb	CBR ASTM D6241 N(From Site)	Type	Fiber Type	Designed For: French Drain	Filtration	Drainage	Separation	Stabilization	Erosion Control
Woven Reinforcement	US 2600	NA	NA	NA	NA	Woven	PP				√	√	
	US 2700	NA	NA	1,000	4,448	Woven	PP				√	√	
	US 3300ND	180	801	1,250	5,560	Woven	PP				√	√	
	US 3600	NA	NA	NA	NA	Woven	PP						
	US 3600/3600	180	800	1,600	7,120	Woven	PP				√	√	
	US 4000	NA	NA	1,200	5,338	Woven	PP				√	√	
	US 4800	NA	NA	1,400	6,228	Woven	PP				√	√	
	US 4800/30	NA	NA	2,200	9,790	Woven	PP				√	√	
	US 4800F	NA	NA	1,574	7,002	Woven	PP				√	√	
	US 6200	300	1,335	1,700	7,562	Woven	PP				√	√	
	US 7200	NA	NA	NA	NA	Woven	PP				√	√	
Woven Stabilization and Seperation	US 200	90	400	700	3115	Woven	PP				√	√	
	US 250	100	445	900	4,005	Woven	PP				√	√	
	US 270	100	444	900	4,230	Woven	PP				√	√	
	US 315	120	533	1,000	4,450	Woven	PP				√	√	
	US 400	225	1,000	NA	NA	Woven	PP				√	√	
	US 500	200	890	NA	NA	Woven	PP				√	√	
Woven Filtration	US 1540	90	401	750	3,336	Woven	PP		√				√
	US 2020	NA	NA	1,000	4,448	Woven	PP		√				√
	US 230	NA	NA	1,150	5,118	Woven	PP		√				√
	US 230C	140	622	1,400	6,230	Woven	PP		√				√
	US 350	NA	NA	1,200	5,340	Woven	PP		√				√
	US 640	120	534	800	3,559	Woven	PP		√				√
	US 670	120	534	950	4,228	Woven	PP			√			√
	US 830	125	560	1,250	5,563	Woven	PP		√				√
	US 840	NA	NA	1,340	59,638	Woven	PP		√				√
Orange Warning Barrier	US 65HVO	NA	NA	NA	NA	Nonwoven Needlepunched	PP						
	US 100NW-HVO	NA	NA	310	1,380	Nonwoven Needlepunched	PP						
	US 160NW-HVO	NA	NA	480	2,136	Nonwoven Needlepunched	PP						
	US 205NW-HVO	NA	NA	630	2,802	Nonwoven Needlepunched	PP				√		
Aeromodeling	US 230	NA	NA	1,150	5,118	Woven	PP						
Cow Carpet	Cow Carpet	105	467	475	2,114	Nonwoven Needlepunched	PP						
Marine Recovery	US 205NW	120	534	535	2,381	NA	PP						
Polyurea	PG 1	NA	NA	1,080	4,806	Nonwoven Needlepunched	PP						
	PG 2	NA	NA	870	3,871	Nonwoven Needlepunched	PP						
	PG 3	NA	NA	760	3,382	Nonwoven Needlepunched	PP						

Table B2: Pin and CBR Puncture Strength Values Reported by the Geotextile Industry (US Fabric) for Woven and Needle punched Nonwoven (NPNW) Polypropylene (PP) Fabric (cont'd)

	Number	Designed For													
		Rip-rap	Railroad Ballast	Geomembrane Cushion	Paving	Heavyweight Separation	Reinforcement	Lightweight Seperation	Mediumweight Seperation	Bulkhead	Warning Barrier	Aeromodel	Cow Carpet	Marine Recovery	Polyurea
Light Weight Nonwoven	US 100NW														
	US 120NW														
	US 135NW														
	US 80NW														
	US 90NW														
Medium Weight Nonwoven	US 160NW														
	US 180NW	√													
	US 205NW														
Heavy Weight Nonwoven	US 250NW	√	√												
	US 270NW														
	US 300NW	√	√												
	US 380NW	√	√												
Environmental Nonwoven	US 105NWE														
	US 165NWE			√											
	US 200NWE			√											
	US 225NWE			√											
	US 270NWE			√											
	US 330NWE			√											
	US 390NWE			√											
	US 425NWE			√											
Spunbond Nonwoven	US SF20														
	US SF32														
	US SF40														
	US SF49														
	US SF65														
Paving	US 100P				√										
	US 90P				√										

Table B2: Pin and CBR Puncture Strength Values Reported by the Geotextile Industry (US Fabric) for Woven and Needle punched Nonwoven (NPNW) Polypropylene (PP) Fabric (cont'd)

	Number	Designed For													
		Rip-rap	Railroad Ballast	Geomembrane Cushion	Paving	Heavyweight Separation	Reinforcement	Lightweight Seperation	Mediumweight Seperation	Bulkhead	Warning Barrier	Aeromodel	Cow Carpet	Marine Recovery	Polyurea
Woven Reinforcement	US 2600					✓									
	US 2700					✓									
	US 3300ND														
	US 3600														
	US 3600/3600					✓	✓								
	US 4000					✓	✓								
	US 4800					✓	✓								
	US 4800/30					✓	✓								
	US 4800F						✓								
	US 6200					✓	✓								
	US 7200					✓	✓								
Woven Stabilization and Seperation	US 200							✓							
	US 250							✓							
	US 270							✓							
	US 315								✓						
	US 400								✓						
	US 500								✓						
Woven Filtration	US 1540	✓								✓					
	US 2020	✓								✓					
	US 230	✓								✓					
	US 230C	✓								✓					
	US 350	✓								✓					
	US 640	✓								✓					
	US 670	✓								✓					
	US 830	✓								✓					
	US 840	✓								✓					
Orange Warning Barrier	US 65HVO										✓				
	US 100NW-HVO										✓				
	US 160NW-HVO										✓				
	US 205NW-HVO										✓				
Aeromodeling	US 230											✓			
Cow Carpet	Cow Carpet												✓		
Marine Recovery	US 205NW													✓	
Polyurea	PG 1														✓
	PG 2														✓
	PG 3														✓

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